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Design and development of solar thermal *Injera* baking: steam based direct baking

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Abstract

Ethiopia, the second most populated country in Africa, meets 96% of its energy need from bio-mass and majority of this energy goes entirely to *Injera* baking. Injera, a pan-cake like bread that is consumed by most of the population, demands a temperature of 180-220 ^{o}C to be well baked. Both traditional and newly developed biomass Injera stoves are energy inefficient; besides the kitchen environment is highly polluted with soot and smoke that affect the health of household inhabitants. This article introduces new technology that enables Injera baking using indirect solar stove. A parabolic dish with an aperture area of 2.54 m^2, a well-insulated stainless steel pipe of 10mm, a coiled stainless steel heat exchanger, a pressure relief valve and three gate valves were equipped in the system and K-type thermocouples were used to record the temperature. The heat transfer process has been governed by the principle of natural circulation boiling-condensation between receiver and stove. A preset pressure relief valve is used to control the self-circulating working heat transfer fluid (steam at a temperature of 250 ^{o}C). The system was developed and tested for steam based direct baking in the same fashion as the traditional Injera stove. In this experiment, heat transport without significant loss from the receiver for baking at some distance is demonstrated. The challenge with manual tracking and direct steam based baking model indicates the performance of the technology can be improved. It can also win more acceptances if it is equipped with auto trackers and heat storage mechanism. In conclusion, unlike previous efforts, the experiment demonstrated that a high temperature indirect baking of Injera is possible.

Keywords: Steam based Injera baking stove; fixed focus parabolic concentrator; polar mount two axis tracking parabolic dish

1. Introduction

The main energy source of developing countries comes from biomass. Generally biomass is considered as renewable source of energy; however, this is a misleading concept for developing countries where deforestation and afforestation actions are not balanced. Studies show about 800 million people who are dependent on this form of energy are exposed to death and critical health problems [1]. This is worse in

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the Sub-Saharan Africa (SSA) region where there is high biomass energy demand with a steady population growth. Biomass accounts for 71.5 % of average total primary energy in Africa with as high as 90 % in some countries of the continent [2]. Generally it accounts for 70 % to 90 % of primary energy for most SSA countries. The energy estimation of 2030 shows one billion Africans will depend on traditional biomass and half a million will die from its impact [3]. During this period the world's population is projected to reach 8.2 billion; in which 90 % of the population and 90 % energy demand will come from developing countries [4]. Clean energy supply was set as the motto for Millennium Development Goals (MDGs); however, the 715.4 million metric tons of oil equivalent energy production in SSA which is under the target [5]. Regardless of the huge potential of clean energy in the developing world, it remains unutilized due to market barrier, lack of technical, economic, political and social factors [6]. Nowadays, it is common to hear "revolution towards clean energy" in the agenda of world leaders promoting solar energy. However, the efforts so far are more in favor of PV technology although majority the world's generated power is utilized for thermal needs.

Many people in Ethiopia, like other developing countries choose biomass as their primary energy supply because they are exposed to immature technology of other clean energy sources and it is collected for free or is cheap. In addition, the rural community of most developing countries live far from the national grid where biomass based energy is a prominent option. On the other hand, the urban communities with access to electricity still depend on the rural for fuel supply. For example, Zenebe's study on urban fuel demand of Ethiopia shows the dependency of urban on rural for energy supply was started as of 1000 B.C when there was no electricity but continues until today [7]. This trend continues even today while electricity is chipper to fire wood supply. The author took the pictures shown in Fig1 in February 2013, from one of the market places of Mekelle city, northern Ethiopia, to show the impact of biomass based energy supply on deforestation. Such illegal biomass supplies come mainly during night from the source and reach the market early in the morning as shown on Fig 1 (a). The higher price and huge demand of urban for biomass based energy invited the rural to risk environmental rules to improve their income. Unless government efforts are intensified to create awareness and provide options for efficient clean energy, this may affect the ecosystem of the country shortly.

(a) (b)

Fig. 1. Urban - rural relation in biomass energy supply, (a) illegal firewood supply from by farmers; (b) city market of firewood and charcoal

Most developing countries are found within the solar belt where the solar radiation potential is the highest and it can be exploited for rural and urban multipurpose applications [8]. The most advantages of solar energy for developing countries include:

- It needs simple and low-cost technology to use the potential.
- It has a noticeable livelihood impact.
- It improves deforestation and motivates to build a green economy that favors to achieve the millennium development goal.

A study by Stephen and Waeni on renewable energy in Africa shows that many PV and solar water heaters have been distributed as compared to solar cookers [9]. This shows the research on solar thermal, especially on high temperature cookers has shown very little technological advancement. Nowadays one third of the world population cooks daily meals over open fires, though most of them are living with ample sunshine, where an estimated 500 million people urgently need~~s~~ solar cooking technologies [10]. The implementation of solar cookers show increasing benefits, for instance, they are acknowledged for their significant fuel and time saving in Ethiopian refugee camps with increasing acceptance [11]. In addition a research dissemination activity by the mechanical engineering department, Mekelle University, in solar cookers indicated increased acceptance and the versatility of the cooker kit was improved. This resulted in the attitude change of users manifested from being fully subsidized to partially finance in owning the cooking kit. Likewise, the interest for high temperature indoor cooking has been increasing. The size and acceptance of a solar cooker depends on household's size and the stagnation temperature of the system. Large scale reflector type solar cooker has been introduced since 1950's in India [12]; however, the technology has not developed enough to enable indoor and night cooking.

Injera, a common food type to some east African countries mainly Ethiopia, Eritrea, Somalia and to some extent Sudan, is known for its intensive energy and time consuming cooking. It has been baked widely over open fire of three stone stoves for centuries. Injera stove varies slightly in dimension and efficiency from place to place in Ethiopia but generally it is considered inefficient. Despite its being energy intensive, it remained rarely researched for alternative energy sources. However, recent energy crises motivated researchers to improve the stove efficiency and its possibility to work with other alternative energies such as biogas and solar. The research of solar energy for cooking has been studied for decades and yet a robust solution for high temperature indoor cooking is not met. The first trial of solar Injera baking was tested by illuminating the bottom part of the pan with solar radiation for conduction based baking [14], but this is still a direct cooker. Acceptance of solar Injera baking stove depends on its: simplicity, possibility of indoor and night cooking, and comparative baking time with biomass and electric stoves. The authors have been working to enable any time indoor Injera baking using solar thermal in which valuable energy and time of users can be saved. This article mainly addressed the possibility of high temperature indoor solar cooking (Injera baking) on a physically similar traditional stove. An accompanied paper of the Author discusses on a suitable thermal storage mainly for Injera baking purpose. The author's continuation work of these two papers is on integrated heat storage-stove, design optimization, performance improvement and scaling the model to average household demand size.

The objective of this research is to understand the actual Injera baking process (energy and time), design; construct and test a steam based solar Injera baking system. And meet its designed stagnation temperature, test actual Injera baking on the new system and study its application potential.

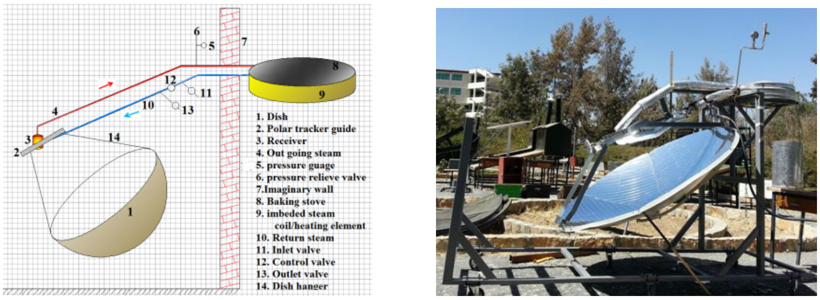
Nomenclature

A_a	aperture area [m^2]
A_o	Outer area [m^2]
A_{Io}	Outer area of Insulated pipe [m^2]
A_r	Receiver area [m^2]
D_i	inside diameter[m]
D_o	Outer diameter [m]
f	coefficient of friction
h	hydraulic head [m]
h_c	Coefficient of convective heat transfer [W/m^2K]
h_{max}	possible maximum hydraulic head[m]
h_{lv}	Latent heat of vaporization [J/kg]

I_b	Mean Insolation [W]
K	Thermal conductivity [W/m. K]
l	length [m]
Le	equivalent length[m]
P_{loss}	Pipe loss [W]
q	Heat transfer rate [W]
R_{loss}	Receiver loss [W]
S_{loss}	Stove loss [W]
t	insulation thickness[m]
T_a	Ambient Temperature [^oC]
T_{pipe}	Temperature of pipe [^oC]
T_{Ipipe}	Temperature of insulated pipe [^oC]
T_s	Temperature of steam [^oC]
UL	over all heat loss [W]
V	speed [m/s]
ρ	Density [kg/m^3]
σ	Stephan Boltzmann Constant ($5.67*10^{-8}$) [w/m^2k^4]
ε	Material emissivity
μ	Absolute viscosity [Pa.s]
η_t	Thermal efficiency
η_o	optical efficiency

2. Methodology

A fixed receiver-polar mounted parabolic concentrator with one axis auto tracker assisted by a manual secondary tracker was developed as shown in Fig 2. The system uses naturally circulating pressurized steam heat transfer fluid. The principle of boiling-condensing heat transfer in a closed loop is demonstrated. The tracker motor gets power from a 12V PV and clutch system was coupled to reverse evening position in to next day suitable position. The tracking was performed via photodiode sensor; however, this paper presents results of a manual tracking. Lab view was used to log temperature data from K-type thermocouples at different positions.



(a) (b)

Fig. 2. Polar mounted parabolic dish concentrator: (a) schematic drawing, and (b) actual rig during test

The following procedures should be followed when to work with this system

- Set the relief valve to 45bar
- Pressurize the system with water slightly above the working pressure to inspect leakage
- Flash the system from any trapped air
- Discharge two-third of the system total volume up on heating and
- Record charging temperature to see its development at different positions.

3. System design

A standard readymade six petal satellite dish of 1.8 m diameter and 0.684 m focal length was filmed with MIRO-SUN weather proof reflective 90 and tested. The geometric parameters of the dish given in table 1 were calculated in the same fashion followed by Kalbande [13] and Mohamed [15].

Table 1. Specification of parabolic collector

No.	Description	Unit	Value
1	Height	m	0.296
2	Rim angle	Degree	74.5
3	Surface area	m2	2.80
4	Arc length	m	1.92
5	Circumference	m	5.65
6	Aperture are	m2	2.54
7	Receiver area	m2	0.0078
8	Concentration ratio	--	325.6

3.1. Pipe line design and selection

A naturally circulating fluid flow is usually accompanied by pressure drop that is compensated by a hydraulic head between receiver and stove. An increase of hydraulic head beyond h_{max} of Fig 3 will enter in to two phase state which is not the interest of this study. The total pressure drop, summation of drop due to working fluid flow through evaporator, vapor line, condenser, and condensate line, of the system can be evaluated using eq.(1) [16]. The flow rate of the working fluid depends significantly on the value of the hydraulic head h; a design survey on solar water heater recommends the hydraulic head value can range from 0.2 to 2 m [17], where lower head has higher flow rate and smaller heat loss at elevated temperature.

$$\Delta P_t = (\rho_l - \rho_v)gh \tag{1}$$

While running the experiment during the first and second day, the author experienced the effect of un-insulated condensate line that lead into a two phase condition and took longer time to reach stagnation temperature. That was corrected by insulating it and made the system run in single phase. The pressure drop of the system is computed by eq. (2) [16].

$$\Delta P = f\frac{L_e}{d_i}\frac{\rho V^2}{2} \tag{2}$$

The coefficient of friction for smooth stainless steel pipe is 0.042 and the corresponding Reynolds number is in the order of $2*10^3$ i.e., 1524 as evaluated by eq. (3) [18].

$$f = \frac{64}{\mathrm{Re}} \tag{3}$$

The Reynolds number defined by eq. (4) [16] helps to estimate the flow velocity of the working fluid. The dynamic viscosity and density of steam at 40bar are; $18.24*10^6$ NS/m^2 and 20 kg/m^3 respectively.

$$\mathrm{Re} = \frac{\rho VD}{\mu} = \frac{4q}{h_{lv}\pi d_i \mu} \tag{4}$$

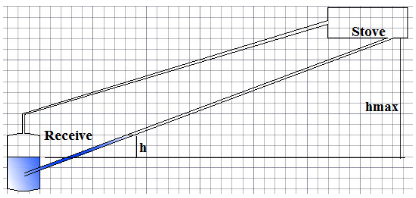


Fig. 3. Boiling condensing loop of the system

3.2. System heat loss

The heat loss includes loss in pipe line, receiver, and stove. The heat loss from the pipe line through conduction and radiation was computed using eq. (5) [19]. Where, thermal conductivity, thickness and surface emissivity of rock wool insulation are 0.07w/m.K, 0.05m and 0.05 respectively.

$$P_{loss} = \frac{2\pi kl}{\ln\left(\frac{D_o + 2t}{D_i}\right)}\left[T_{pipe} - T_a\right] + A_{Io}\sigma\varepsilon\left(T_{Ipipe}{}^4 - T_a{}^4\right) + h_c A_{Io}\left(T_{Ipipe} - T_a\right) \tag{5}$$

Convective and radiation losses from receiver and stove were computed by eq. (6) and (7). Where, average value of 350°C, 80°C and 25w/m^2.K were taken as receiver temperature (T_r), stove lead temperature (T_l) and h_c of air. Pipe conduction heat loss was neglected and the external wall temperature of the pipe (250 °C) is used as the temperature of the fluid.

$$R_{loss} = h_c A_r (T_r - T_a) + A_r \sigma\varepsilon \left(T_r^{\,4} - T_a^{\,4}\right) \tag{6}$$

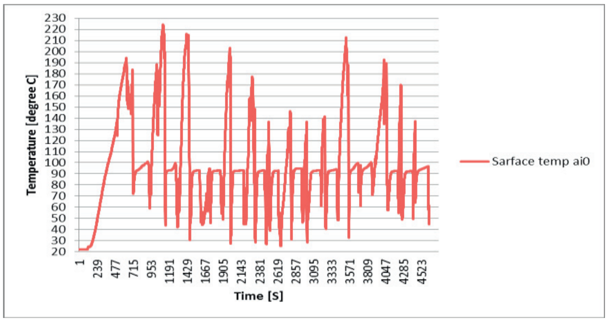
$$S_{loss} = h_c A_S (T_l - T_a) + A_S \sigma\varepsilon \left(T_l^{\,4} - T_a^{\,4}\right) \tag{7}$$

Theoretically computed heat losses at stagnation temperature of the system shows a maximum loss be encountered from receiver that accounts for 304.4 W when compared to the losses from stove and pipe line which contribute 269.95 and 94.8 w respectively. This suggests optimization should be done to decrease losses from the receiver to improve overall baking time of the system. Interestingly enough the theoretical losses from receiver shows the same result while pipe line loss becomes insignificant and stove loss lowered to 171.14W practically.

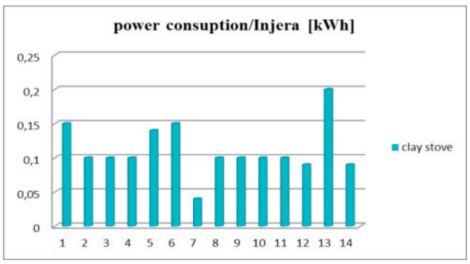
4. Results and discussions

The traditional electric Injera stove was tested for different ranges of baking temperature; the quality of Injera in the range of 135-220 °C remains the same, however, a slightly baking time difference was observed. Fig 3(a) shows well-cooked Injera and Fig 4 (b) presents the experimental values of Injera baking temperature in which the rise and fall of baking temperature during the baking cycle is clearly shown. Per Injera power and time requirements are shown in Fig 4 (c) and (d) respectively. One Injera needs an average of 0.1 kWh and 150 second to be well cooked. Looking at the range of 6th-9th cycles of Fig 4 (b), the literature value of Injera baking is far from actual value. While this test was running, the author was developing the polar mount solar stove in parallel that was tested for no-load, with load and its result is presented in Fig 5.

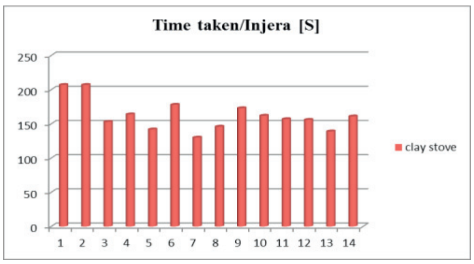
(a)



(b)



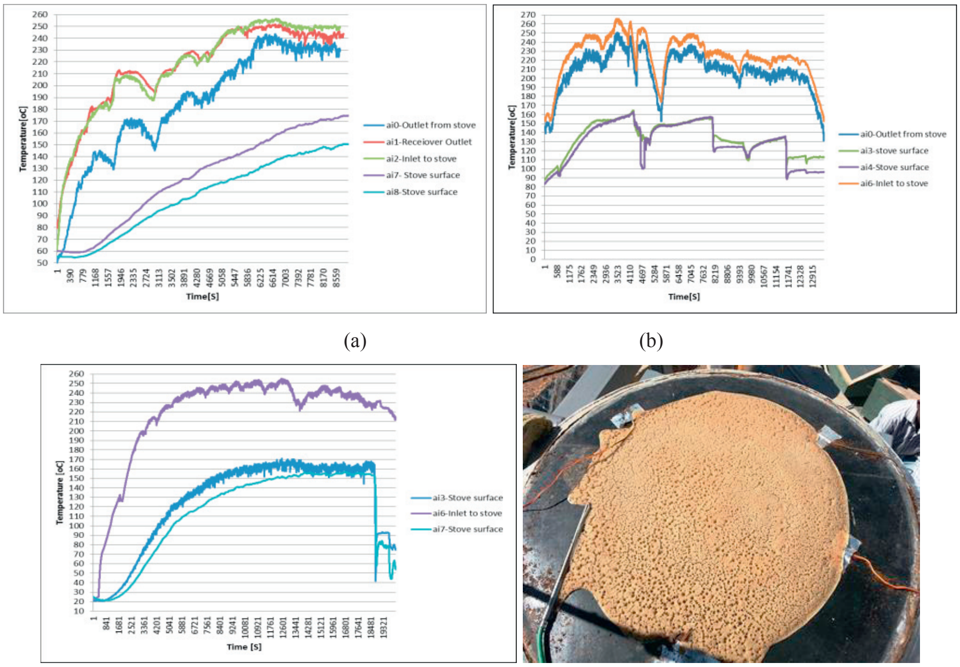
(c)



(d)

Fig. 4. Injera baking behavior, (a) fresh Injera; (b) baking Cycle, (c) baking power and (d) baking time

A no-load test was run to check if the stagnation temperature of the system is achieved as per the design. The result shown in Fig 5 (a) exhibits 255 ^{o}C stagnation temperature and 175 ^{o}C stove temperatures is recorded. The stove temperature is a little bit below the literature values of Injera baking. However, the author was running several parallel experiments on different electric stoves and his results show the literature value is higher than the actual baking temperature. Injera stoves need frequent polishing with oil or oil seeds to avoid sticking and produce good quality Injera. This practice takes considerable time and power; the power and time used to regain the lost heat during polishing may exceed the power and time required during bakes intervals. Polishing drops stove temperature from 165 to 100 ^{o}C and 158 to 120 ^{o}C as shown in Fig 5 (b). Finally, the stove is tested for baking and it successful bakes Injera between 135 and 160 ^{o}C as shown in Fig 5 (b) and (c) respectively. This baking temperature is below the lower marginal values cited in literature and strengthens the author investigation on electric stoves. Injera baking on new stove requires intensive heating, polishing and gives poor Injera quality for a couple of days. However, the Injera quality of new solar stove shown in Fig 5 (d) is not very far from the quality of the common Injera shown in Fig 4 (a).



(a) (b)

(c) (d)

Fig. 5. Temperature profile of baking stove (a) without load; (b) with load; (c) with load and (d) Solar steam baked Injera

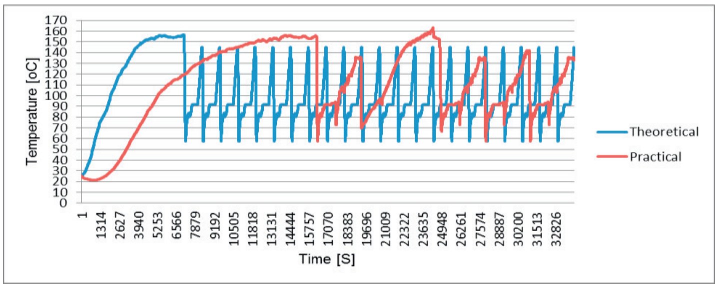


Fig. 6. Theoretical and experimental comparisons of solar stove

Theoretically the solar stove is expected to be competent with electric stove to favor energy switching. However, certain factors like intermittent nature of solar radiation, stove insulation, stove heating element and stove size affects its performance and are considered while developing the theoretical model shown in Fig 6. This model considered about two hours heating up time, 15 minutes baking interval and average family size Injeras as its main assumptions. The practical experience of this study is quite interesting in which variable heating up and baking time was recorded depending the starting time of the experiment. When the experiment was started early in the morning the system took longer time to reach its stagnation temperature and about four and half hours heating up time with 40-50 minutes of baking interval. However, if the experiment was started around 10:00-11:00 am the system's stagnation temperature was reached in about 45 minutes to one hour and the stove bakes in about 10-15 minutes with 30 minutes of baking interval. Similarly presence of thin layer of cloud has affected the heating up, baking, and baking interval of the system. The practical result shown in Fig 6 is a merged result of different days and more or less the cycles show a similar nature.

5. Conclusion and Recommendation

Injera stove stayed behind a closed door to alternative energy supply due to its intensive energy demanding nature perception though less researched. This piece of work will initiate many researchers to improve and make alternative clean energy like solar, as tried in this paper, is real candid energy source for Injera baking. In this study three important results were achieved. The first result shows direct solar steam based baking i.e., it proves indoor solar baking is possible. Secondly, Injera baking using solar energy was impossible due to its high temperature demand; this study can change this attitude and encourage researchers to go for improved indirect high temperature solar cooker in general. The third and important result is the possibility of Injera baking at 135-160 ^{o}C that will bring a significant impact in the revolution of Injera stove in Ethiopia. The third result may help to further improve the efficiency of existing designs of biomass and electric stoves. Generally, these results are important milestones for the growing home based design and technological development that is trying to addresses the rising energy price and need for clean energy. The author continues on design and development works of integrated stove –storage technology that enables indoor and night Injera baking using solar as the second level of his work in this paper and accompanied paper in heat storage.

The author wants to recommend the following points based on the result of this paper.

- Full scale direct steam based Injera stove should be tested before drawing any conclusion.
- The long time heating up, baking and baking interval time should be narrowed by scaling up the collector and enhance the heat conductivity of the stove.
- The intermittent heat supply and higher baking interval time observed in this technology must be addressed with compatible latent heat storage.
- The storage integrated concept should be implemented to all types of Injera stove design to increase their economical and versatile values.

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