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Numerical and experimental Analysis of Solar Injera Baking with a PCM Heat Storage

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ABSTRACT

Today, many developing countries are using biomass as their primary energy supply. However, this energy affects the environment, health and safety of women and children. In addition, utilization of this energy using traditional cooking stoves is causing indoor air pollution and in turn health problems to millions of people. To overcome such problems, efforts are being made by researchers globally and are suggesting alternative safe energy sources. This paper demonstrates solar cooker with an integrated PCM thermal storage and heat transportation loop system suitable for high temperature applications. The system has designed to address Injera baking application. Injera, a fermented flat bread type, is the most common food type served three to four times a day in Ethiopia. Other countries like Eritrea, Somalia, Sudan and Yemen also use this food. The storage system has storing capacity of heat up to 250^{0}C and it can retain this heat for about two days. The storage has coupled to a polar mounted concentrator, fixed receiver and used steam heat transfer fluid. The steam circulates naturally between the evaporator and condenser in a closed loop. The paper focuses on indirect charging, simultaneous charging-discharging and discharging of the stored heat for the purpose of Injera baking. The frying pan is a custom-made aluminum plate casted by embedding a 10mm coiled stainless steel steam pipe as heating element. The pan is 500mm in diameter and 30mm thick; and the fins are 20mm in diameter and 140mm long. The fins have immersed into a 20kg PCM, which is coupled to a 1.8m diameter parabolic dish collector. The solar fryer demonstrates Injera baking for average family size. Baking is tested from the stored heat, while storage is charging. A fully charged storage has supplied enough heat to baked average household Injera demands about 19Injeras and additional breads with the remaining heat.

Keywords: Solar Injera baking, PCM charging, PCM storage, Solar Injera stove design, Solar cooking, Ethiopia.

1. INTRODUCTION

1.1.Background on Solar Cooker and Thermal Storage

Ethiopia like many developing countries depends on biomass as its primary household energy supply. Women and children are often in charge of fetching firewood and cooking where they spent most of their valuable energy and time. In addition, they are also the most affected from indoor air pollution that is produced by using traditional cooking stoves to convert this energy.

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On the other hand, the progress of solar cookers technology is very slow in spite of their benefits. One reason for this is lack of synergy on crosscutting researches. Secondly, the outreaches of these cookers often do not consider the active participation of end users. Moreover, many studies of solar cooker focus on direct cooking and with low temperature heat storage for low temperature applications. Many developing countries, which are dependent on biomass, have huge potentials of solar energy that can potentially substitute the role of biomass. However, solar energy technologies have rarely introduced in these places. Moreover, solar thermal technologies in general have not reached a robust stage of mass production and distribution. Although some countries have introduced solar box cookers, their success has been limited due to technological and social factors in which none of the cookers enabled night cooking and indoor use. Such technical limitations also affect users' norm of cooking, which may cause a social ban on the adoption of new technology.

To improve acceptance of solar cookers and assure their widespread use, a continuous improvement in technical development, social awareness and thermal storage is required. The storage helps to store the surplus solar energy during the day and keep it for late evening or early morning use. In this regard, robust design of storage heat exchangers for melting and solidifying PCM materials is very important as discussed in the works of Abduljalil et al. (2014). In addition, it helps to supply nearly uniform heat during the process of cooking. Some solar cooker design features allow charging and discharging simultaneously. For example, the solar cooker designed by Antonio et al. (2013) could cook family lunch, while charging the storage simultaneously. The stored heat of this cooker allows dinner cooking and breakfast heating for the following day. Such design features help to expand the acceptance of solar cooking. Another solar cooker design, which has used heat pipes, flat-plate collector and integrated indoor phase change material (PCM) storage, has able to cook food at noon, evening and keep the food warm at night and the following day morning, (Hussein et al., 2008). The solar fryer presented in this paper has solved the mismatch of time and the availability of energy and enable users to perform any time indoor cooking practice. The use of PCM storage for cooking is increasing and diversifying with time. For example, Hussein et al. (2008) have tested a PCM storage coupled to flat plate collectors for indoor cooking and heating of food during the evening. In addition, portable solar cooker with PCM storage enables day and nighttime cooking at a small-scale level (Antonio et al., 2013). This paper is to design an indirect solar cooker with latent heat storage, for baking Injera, Ethiopian food using a thermosiphon loop to transport heat (Dobson and Ruppersberg, 2007).

Injera is yeast-risen flat bread with slightly spongy texture. It is the most common food type of Ethiopia and served 3 to 4 times a day. Injera is also eaten in Eritrea (Injera), Somalia (Canjeero), Sudan and Yemen (Lahoh), (Wikipedia, 2014). Injera is prepared by baking on a clay stove called "Mitad". The baking process needs significant amount of energy. It is obtained from biomass as majority population live without access to electricity. Biomass produces full of smoke and soot that affects the health of people. The solar stove designed in this study has tried to give a clean, competitive, and affordable stove solution.

2. MATERIALS AND METHODOLOGY

2.1. Heat Storage

The heat storage in this paper is designed to accommodate 20 kg of solar salt (nitrate salt mixture of 40% KNO_3 and 60% $NaKO_3$), which is sufficient to supply heat for an average household size. This PCM is selected based on the baking temperature requirement of Injera. The storage configuration contains a baking plate with embedded stainless steel steam pipe and down-going aluminum fins. These fins are design to transport optimal conduction heat to the PCM. This design avoids any direct contact of the steam and the PCM. Moreover, the storage has 10% vacant space to avoid any pressure development and volume variation during phase transition of PCM (Fig 1). The thermos syphon loop is designed to simplify the heat transfer mechanisms over long distances.

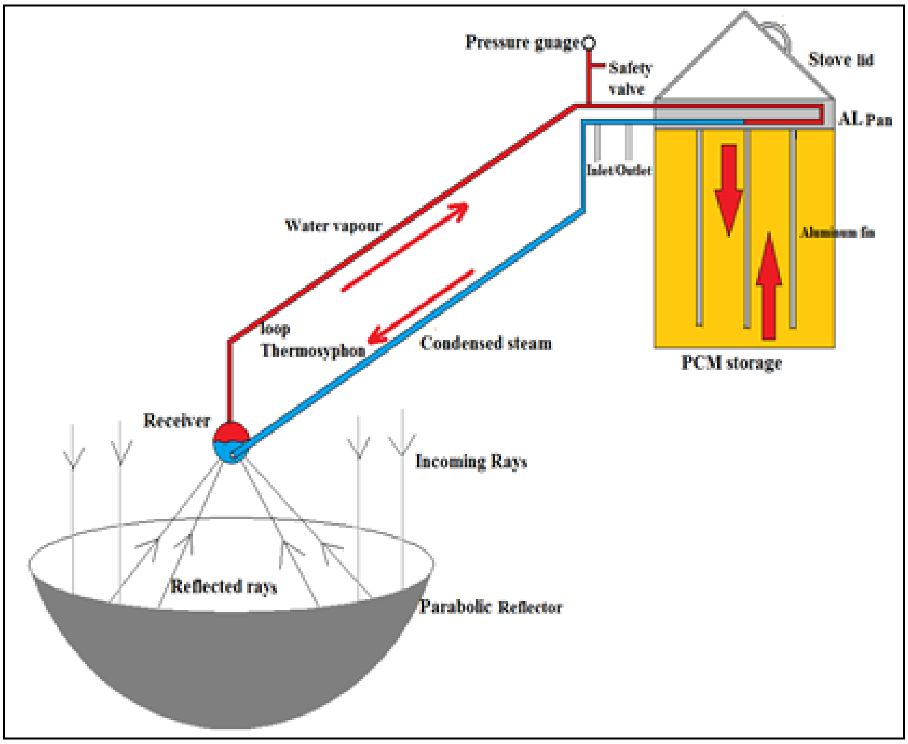

Figure 1. Schematic of the developed system.

The frying pan has an embedded stainless steel (SS) steam pipe, which is the heating element of the system and it resembles a heating element of modern electric stoves. The system was coupled to 1.8m parabolic dish collector filmed with alando solar reflector. This system was tested at Mekelle, Ethiopia (13°28'48.30"N latitude). The concentrator design has followed polar mounted reflector with fixed receiver philosophy. The list of sensors and equipment used during the experiment this research is given in table 1.

Table 1. System components.

Label	***Description***	***Label***	***Description***
A	Pressure relief valve	F	Inlet, out let and directional control valves
B	Pressure gauge	G	Parabolic dish reflector
C	Tracking sensor	H	Data logger
D	DC motor	I	K-Type Thermocouples
E	Solar PV source	J	Receiver

2.2.Parabolic Dish Concentrator Design

In solar power generation, the use of pressurized steam is a common practice. However, the use of high pressure steam for small-scale application such as cooking is new. In fact there exists some large-scale steam solar cookers; however, they use low-pressure steam. For example, Scheffler steam rice cooker uses steam in the range of 3bar. On the other hand, high-pressure steam solar cookers are not commonly used due to their technical and safety concerns while generating the steam.

2.2.1. Collector Design

The fixed receiver of this concentrator is used to generate steam and in return this steam was used to charge the heat storage. Parabolic dishes can be manufactured from optimized petal shaped sheets with due attention on precision design and manufacturing as studied by Lifang and Steven (2011). The other and easier way to get parabolic dish for solar concentration purpose is to customize the existing satellite dishes by filming them with appropriate reflector materials. The parabolic dish used in the study is a six petal satellite dishes, filmed with a self-adhesive aluminum reflector, Miro high reflective 95 and thicknesses of 0.5mm.

2.2.2. Receiver Design

The receiver is developed by welding of two cylindrical cups of black steel and the cups have 100mm diameter, 5mm thickness and 40mm height (Fig 2). Random temperature measurements in the illuminated area of the receiver lie between 300°C to 1150°C. However, larger part of the receiver is exposed to radiation loss.

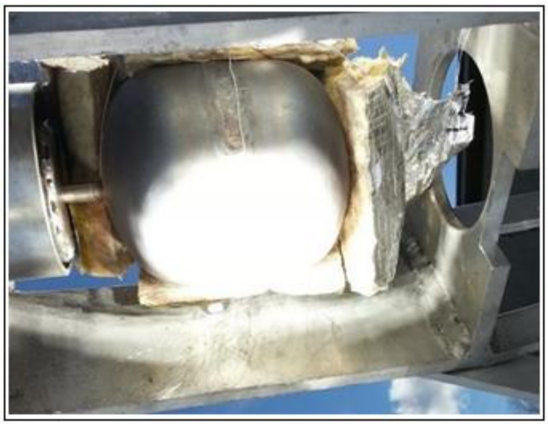

Figure 2. Receiver of a parabolic dish collector.

2.2.3. Thermal Performance

The thermal efficiency of the system has given by the ratio of the useful energy stored and the energy incident at the concentrator's aperture. The storage energy is the sum of the energy stored in the PCM and in the aluminum fins. Hence, the thermal efficiency of the system is computed by:

$$\eta_{th} = \frac{c_{Al} m_{Al}(T_f - T_i) + m\int_{T_i}^{T_f} C_p dT}{A_a I_B} \quad \text{---------------------- (1)}$$

Where, cp is the effective heat capacity of the PCM

Both normal and diffuse radiation enters the aperture area of any solar collectors. However, in concentrating collectors only the direct radiation can be focused on the receiver. The thermal analysis of the system has performed only for its solid phase sensible heat-storing ability as it has not fully charged during the experiment. The systems reached 187°C as maximum temperature of the storage during the experiments of this paper. Therefore, the thermal performance for this test was found 23%. The performance of the systems was affected by non-smooth manual tracking, dust on the reflector and some damages on the collector as shown in figure 3, which affects the focusing of the reflector. In addition, this system was exposed to higher wind speed, which resulted in higher convective heat loss from its receiver and the system as whole.

2.2.4. Tracking Mechanism

The system used a gear mechanism auto tracker to track the sun in the east-west direction. The tracker has 50kg carrying capacity and use 9V DC motor driver. The motor gets its power from a 10W PV source. The gear ratio of the motor is 1:600 and its shaft runs at 9 rpm.

This speed is further reduced in to a 1:10 gear ratio to transfer the required torque to track the collector. This speed of the motor allows the mechanism to catch up the position of the sun in case the sun comes out of clouds after longer time. A light diode and a shading device control the motor. The reflector starts to track the sun automatically until the sensor becomes perpendicular to the sun radiation. Tracking happens when the sun shines and if there is no sun, there is no tracking.

2.2.5. Insulation

Aerogel and Rockwool insulations were used to insulate the storage and the steam pipelines respectively. The insulations maximum working temperature is about 650°C and the maximum working temperature of the system was set to 250°C (by adjusting the pressure relief valve) and the design thickness of the insulation is 25mm for the heat storage and 50mm for the steam pipeline. The insulations thermal conductivity is 0.03W/Km and 0.07 W/Km respectively and they have the same surface emissivity of 0.05.

2.2.6. Pipelines

The steam pipeline is 10mm in diameter and 1mm thickness. This pipe is used as a pipeline of the thermos syphon loop and as a heating element for the frying pan. The pipe has 100bar design pressure and is used for 40bar working pressure. The pipeline used Swagelok connectors and valves. A pressure gage is used to measure the pressure of the steam and regulated with the help of a safety valve that reliefs the pressure when it passed the pre-set value (40bar). The pipeline is used to flash before the beginning of every experiment to avoid air inclusion.

3. RESULTS AND DISCUSSION

The storage integrated solar fryer developed in this research is shown in figures 3 and 7. The polar mounted concept eases the demand of tracking mechanism in the secondary axis. The fixed receiver was found suitable for steam generation. The steam circulates between the evaporator (receiver) and frying pan (condenser) in a closed loop naturally. The steam carries the heat from the receiver and drops it on the frying pan (casted aluminum plate). The fins attached to this plate in return carries this heat to the PCM by conduction. The system has tested for simultaneous charging-discharging, discharging of a fully charged storage and discharging of partially charged storage (cloudy day). The experimental work has studied the phase change and its energy characteristics inside the storage similar to the study of Robynne and Dominic (2014). Accordingly, the system has designed in accordance with single-PCM and multi-PCM thermal energy storage design (Taha and Muhammad, 2014). The principle of test has also assumed indoor experimental investigation of thermal performance (Zhang et al., 2014). The solar radiation used when analyzing the system thermal efficiency has shown in figure 3b.

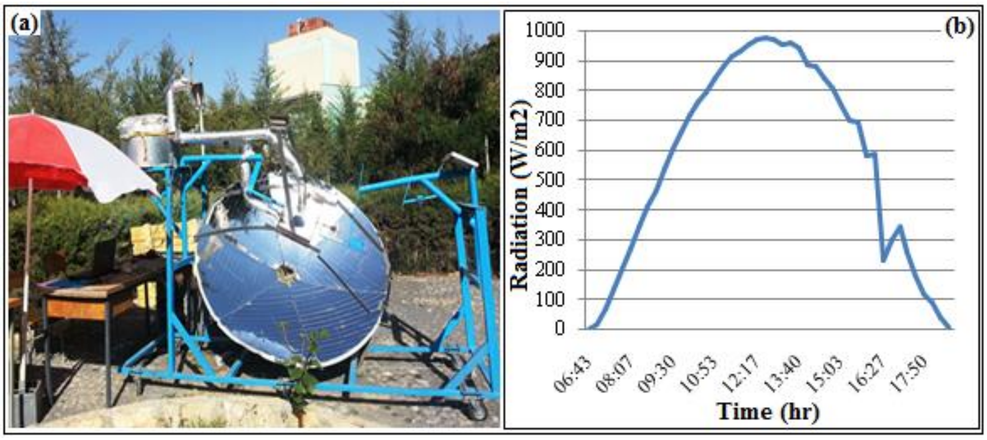

Figure 3. (a) Parabolic dish collector with PCM storage, (b) Global solar radiation of Mekelle on 27-02-2014 during the experiment.

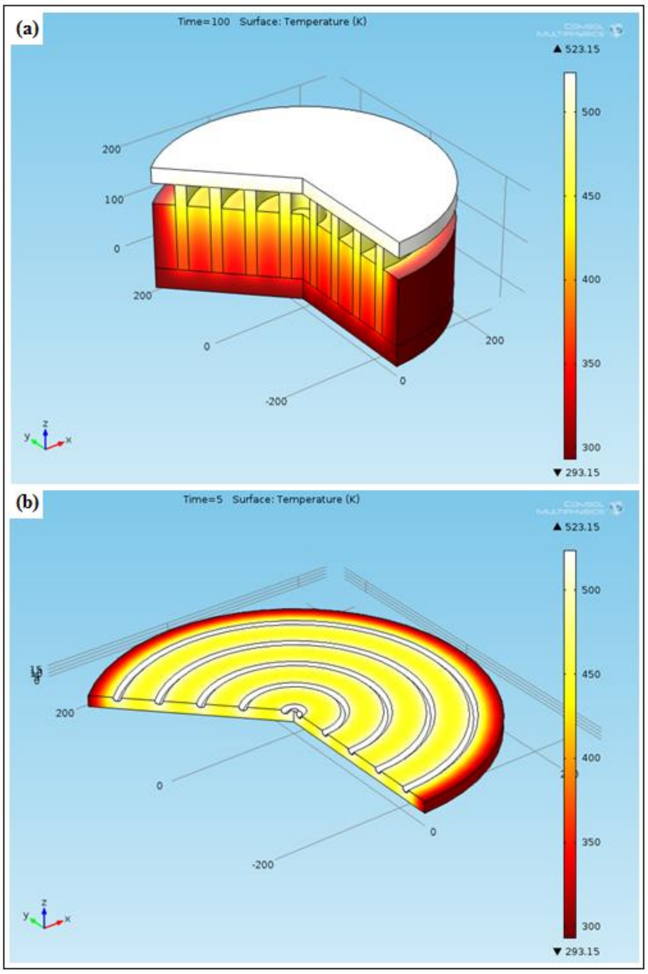

Figure 4. COMSOL simulation of a) PCM charging and heat transfer between SS and aluminum wall, b) frying pan with embedded SS steam pipe.

The storage charging process has simulated using COMSOL Multiphysics 4.3. In this simulation, a 20kg of solar salt with circularly rolled plate fins instead of many cylindrical fins. The 2D and 3D simulation results show the 20kg solar salt storage is fully charged in about seven hours, when a 250°C continuously circulating steam is used to charge. The simulation considers a constant loss of 15°C from the storage. The fins assumption has reduced the overall charging time of the storage. The simulation has shown that the charging of the PCM found between two fins is very quick; however, the PCM adjacent to the storage sidewall and bottom wall changes its phase very slowly. The simulation result suggests, to half the dimension of the gap between the fin and the storage wall (side and bottom). Therefore, the PCM thickness between the fin and the wall should be 20mm. Moreover, it was found rolled plate fins charge the PCM faster than rod fins. In addition to the PCM charging development, the simulation has also run to show the thermal resistance effect of the SS pipe wall on the frying pan as shown in figure 4 (a) and (b).

3.1. Simultaneous Charging-Discharging

In this system, when the collector starts focusing the radiation on the receiver, the regulated water inside the receiver starts boiling and a vapor at low temperature starts circulating in the closed loop of the thermos syphon loop. On the first day of the test, the stagnation temperature of the system was not reached the melting point of the PCM. It has tried to charge the storage in successive days using the advantage of the PCM's heat retention ability; however, this did not help to charge the storage fully, this might be due to heat losses at the receiver.

The test was then preceded to a simultaneous charging-discharging during the peak hours of solar radiation. When simultaneous charging-discharging test has started, the circulating inlet/outlet steam temperature reached 160°C and 150°C respectively. During this test Injera and bread baking was performed perfectly. When baking has started, the circulating steam and the storage have experienced a sudden drop of temperature. However, the temperature has slowly recouped during baking period, and baking and charging behavior of the system during simultaneous charging-discharging (Fig 5).

In the first cycles, the progress of the storage temperature was very slow, because it took extended time to cook the food from the frying plate. And this was accompanied by large losses from the baking surface. However, reducing this time by improving the baking surface interaction as shown in the last two cycles of figure 5, the baking speed and storage temperatures have reacted fast.

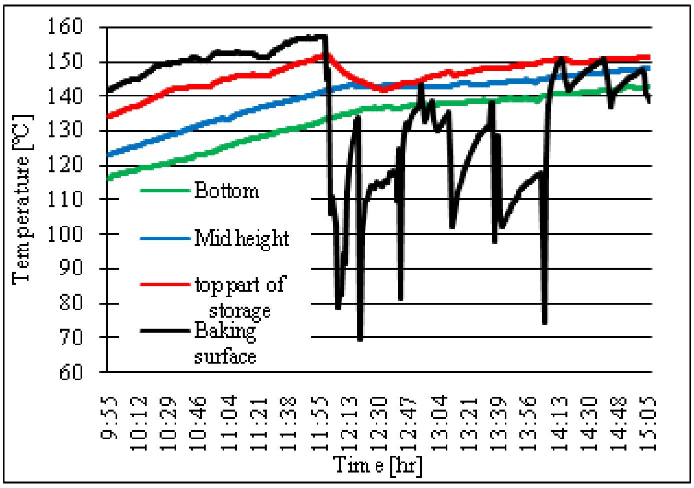

Figure 5. PCM charging and baking practice simultaneously from the sun.

In the beginning of Injera baking on this stove, the surface texture of the frying pan was rough and Injera was sticking to the frying pan. Taking out the baked Injera from the pan was a big challenge. Also, the quality of the Injera was not attractive. To avoid sticking, borosilicate glass was placed on top of the aluminum-baking surface. But Injera quality still remained unattractive. However, the frying pan was suitable for bread baking. Simultaneous changing-discharging process helps to utilize more energy during the day. However, the storage charging process took more time as the inlet heat splits in to charging and baking.

3.1.1. Discharging of a fully Charged PCM Storage

In this study, an artificial resistor heating element was coiled around the receiver in order to melt the salt fully. The heating element has been delivering a uniform and regulated heat. The heating element is set to maximum temperature, 450°C, at which it was delivering an average power of about 700W to the receiver. This power is equivalent to the solar power supply obtained from a 1.2m parabolic dish concentrator with 80% optical efficiency and $800w/m^2$ average beam radiation. The storage took about eight hours of phase change duration (Fig 6).

The stored heat is tested to bake 19 Injeras and six breads, need of an average household. The stored heat was run for about 4hrs of intensive baking and the remaining heat was left to discharge naturally while it was still capable of performing another cooking. The Injera baking speed of this stove is faster than ordinary electric and biomass stove baking speed. In the baking process, Injera consumes the phase transition heat and in bread baking process, consumes sensible heat of the solid PCM. The uniform temperature drop with short baking cycle during Injera baking cycles shows the role of the heat buffer/storage to perform isothermal practice. The sticking problem of the baking surface has been improved with continuous heating and polishing with oil. Consequently, the baking process and the quality of the Injera are improved.

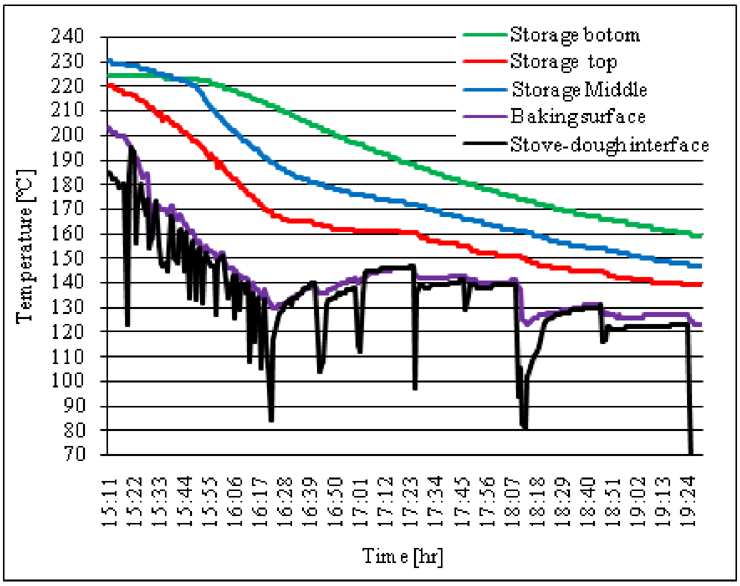

Figure 6. Fully charged PCM discharging through backing.

3.1.2. Discharging of Partially Charged Storage

The third practical test for this system was to prove if it works for cloudy seasons; when the available radiation is not capable to melt the salt. Successive Injera baking tests were performed from a partially charged storage. All baking tests have shown smooth baking process with very good Injera quality, which is the same as the quality of Injera baked on customary Injera stoves as shown in figure 7. This system has smooth baking surface texture similar to the ordinary stove and it used oilseeds to polish it. Unlike oil, oilseed shave the ability to give smooth baking surfaces by filling its irregularities.

This system has been giving demonstration of solar Injera baking to local media, Mekelle University communities, and external guests. The demonstration has impressed many students, internal and invited professors from six universities, media and to the university community at large. In addition to the routine solar Injera baking demonstration during experiment, one planned demonstration has arranged. The aim of this planed demonstration was to create awareness how solar energy can bake Injera and also cook different common Ethiopian dishes. The University community appreciated the innovation and the role of research in mitigating climatic and health problems caused from extensive use of biomass fuel during Injera baking and cooking processes. Figure 7 shows the Injera baking process, which includes polishing, pouring, and taking off the baked Injera.

Figure 7. Injera baking process and the final Injera quality (a-d).

The Injera baking cycles plotted in figure 8 shows the Injera baking process has took on average three minutes per cycle. This graph indicates another important point, i.e. during Injera baking; it is not the surface temperature that matters most but also the heat transfer. In the present case, the baking surface temperature was unbelievably able to bake Injera as low as at 60ºC and 80ºC. For instance, nearly all the Injera baking cycles shown in figure 8 are below 110°C. This result is very attractive compared to the published values (180-220°C) and can possibility revolutionize the present stove technology (Fig 9).

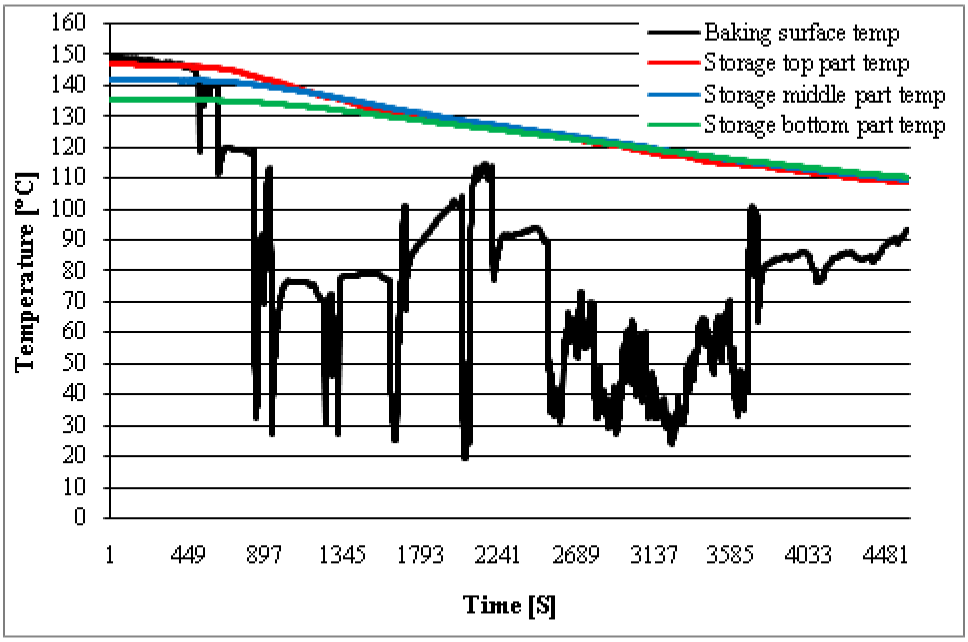

Figure 8. Injera baking from a partially charged PCM storage.

Figure 9. Serving Injera during a function prepared by solar cooker.

4. CONCLUSION

This research has proved the concept of Injera baking (Ethiopian bread) on top of a heat storage, which has charged from a solar concentrator. Heat transfer by a thermosiphon principle, with water as the working fluid at about 40-bar pressure has employed to charge the storage. The steam generated at the absorber of the parabolic concentrator has condensed in the coiled tube of SS, which has embedded by casting in the aluminium baking plate. The baking plate has heat-conducting fins extending into the latent heat storage. These fins facilitate the charging–discharging process of the storage during heat collection and baking respectively.

The study shows Injera baking on a smooth aluminium surface without any problem in the baking process and quality. In addition, it revealed that Injera can be baked at lower temperatures (110-150°C) than previously assumed (180-220°C), as long as there is sufficient and fast heat transfer during the baking process. Furthermore, the boiling-condensing natural circulation loop (thermosiphon) has demonstrated feasible heat transportation. The water volume of the thermosiphon being small it helps to manage the high-pressure steam easily by using high quality pipe and valve components.

The system can further be optimized with respect to heat losses in the heat transfer loop, also at the absorber for better performance, in this view, the authors recommend for further improvement in the robustness of the tracking mechanism and heat loss control at the receiver.

5. ACKNOWLEDGEMENTS

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6. REFERENCE

Abduljalil A. Al-Abidi., Sohif Mat, K., Sopian, M. Y., Sulaiman, & Abdulrahman, Th Mohammad. 2014. Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins. *Energy and Buildings*, **68**: 33-41.

Antonio Lecuona, José-Ignacio Nogueira, Rubén Ventas, Rubén Ventas & Mathieu Legrand. 2013. Solar cooker of the portable parabolic type incorporating heat storage based on PCM. *Applied Energy*, **111**:1136-1146.

http://en.wikipedia.org/wiki/Injera, [last retrieved on 10.09.2014]

Hussein, H.M.S., El-Ghetany, H.H & Nada, S.A. 2008. Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit. *Energy Conversion and Management*, **49**: 2237-2246.

Dobson, R. T & Ruppersberg, J. C. 2007. Flow and heat transfer in a closed loop thermosiphon: part I- theoretical simulation. *J. Energy in South Africa*, **18**: 32-80.

Lifang, Li & Steven, D. 2011. A new design approach for solar concentrating parabolic dish based on optimized flexible petals. *Mechanism and Machine Theory*, **46**: 1536-1548.

Robynne, E. M & Dominic, G. 2014. Experimental study of the phase change and energy characteristics inside a cylindrical latent heat energy storage system: Part 1, Consecutive Charging and Discharging, *Renewable Energy*, **62**; 571-581.

Taha, K. A & Muhammad, M. R. 2014. Comparison between the single-PCM and multi-PCM thermal energy storage design. *Energy Conversion and Management*, **83**: 79-87.

Zhang, L., Fan, L., Hua, M., Zhu, Z., Wu, Y & Yu, Z. 2014. An indoor experimental investigation of the thermal performance of a TPLT-based natural circulation steam generator as applied to PTC systems. *Applied Thermal Engg.*, **62**: 330-340, 2014.