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Energy Procedia 57 (2014) 1603 – 1612

Energy Procedia

2013 ISES Solar World Congress

Solar powered heat storage for Injera baking in Ethiopia

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Abstract

Ethiopia with a population of about 85 million meets 96% of its energy needs with bio-mass, charcoal, wood, animal dung and plant residues. More than 50% of this energy goes entirely on baking Injera. Injera the national food of the country demands 180-220 ^{o}C to be well cooked. In this article; Injera baking with solar energy on off-focus system, status of electric powered stove and the potential for solar powered stoves is discussed. The research and development of solar thermal for household energy consumption has not been well developed and adopted. One reason for this is that the system can only be used outdoor and at time of sun shine. In addition to the off-focus solar thermal application this paper discussed the integration of solar thermal with heat storage for a sustainable future use. The prototype for direct steam based baking was developed and tested in Mekelle University (Ethiopia) and Phase change material based heat storage prototype was developed and tested at NTNU. Both experiments showed the possibility of solar energy for Injera baking and its sustainability by including latent heat storage. This research gave hope to break the bottleneck related with on- focus solar cookers.

Keywords: Steam based baking, solar Injera stove; PCM heat storage

1. Introduction

Injera, a processed food of different cereals, teff, millet, sorghum, maize, wheat, rice etc., or combinations of those passed through fermentation and rigorous baking process, is the widely and cultural food of some east African countries particularly Ethiopia, Eritrea and to some extent Somalia. Injera was baked most commonly on a clay plate called Mitad that is placed over a three stone stove or on specialized electric stove. When a fermented dough poured on a hot clay pan and stayed until the boiling

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doi:10.1016/j.egypro.2014.10.152

temperature reached; bubbles from the boiling water escape forming thousands of tiny craters (eyes) that give the peculiar Injera texture. The traditional Mitad consists of a griddle plate of 'black' clay set on a base of stone and clay [1, 2].

Injera baking practice is similar all over the country with a slight difference in pan dimension and stove efficiency. Some researchers indicated the traditional clay stoves, 11-20 mm thickness and 500-600 mm diameter, have an estimated efficiency of 5% [2, 3]. Others show the Tigray state Mitad and Mirt Stove, improved stove, has registered an efficiency of 25 % and 35 % respectively [4, 5]. The people Ethiopia eat Injera two to four times a day. The major energy supply for cooking and hot water supply of the country come from biomass. Injera baking requires over 50 % of the primary energy consumption and over 75 % households' energy consumption. This intensive biomass utilization is accounted for deforestation, expensive fire wood price and poor kitchen environment [6]. This traditional biomass based cooking affected health, energy, school time, and hardship issues of women and children [7]. In Ethiopia, most households have no access to clean energy and most cooking activities are performed in a separated chimneyless confined kitchen and this is worse in rural parts of the country where majorities live. The world energy outlook predicted developing countries dependency on biomass energy supply will increase from what is today. This shows 700 million people in 2030 will be dependent only in Sub-Saharan African [8].

Regardless of the huge solar energy potential of the world, the research and development on solar thermal has not yet matured. Solar PV is a helpful technology to light rural areas and started booming in some African countries, like Kenya and Tanzania, [9]. It is also expected to have a competitive future with grid in Ethiopia [10]; however, its thermal side is in its infant stage to be considered as a reliable clean energy option. The main concern of many researches on high temperature solar cooking to date was dedicated to direct cooking that has safety issues. These cookers were less accepted because of unable: to cook indoor; night cooking, higher system cost, and longer cooking time. Likewise, cooking of energy intensive foods like Injera was difficult. Nevertheless, their introduction in some African countries resulted in considerable fuel and time savings escorted by reliable energy security of households [11]. Solar cooking could be realistic and considered as a clean energy source if its utilization is not limited to the presence of the sun and outdoor cooking, i.e., when solar energy in the form of heat is possible to transport and store. An integrated collector-storage design helps to transport and store thermal energy directly or indirectly using heat transfer fluid (HTF).

Designs of solar thermal energy storage system need to consider three important factors: technical properties, cost effectiveness and environmental impact [12]. Thermal energy researches of latent heat storage with Phase Change Materials (PCM) have drawn attentions of solar power generation and other applications due to their high phase transition enthalpy and high working temperature. Sometimes, it is good to use a combination of latent and sensible thermal storage for optimal utilization of the available energy. Two stage and three stage thermal energy storages are common in solar thermal power plants, where the sensible heat is used to preheat or/and superheat the HTF [13]. A combined thermal storage for cooking purpose was tested in South Africa and suggested PCM latent heat storage need further investigation and design [14]. Another study at Norwegian university of science and technology (NTNU) also indicated PCM storage could have a potential for energy intensive cooking [15] and [16]. Both investigations used a mixture of $NaNO_3$- KNO_3 PCM as latent heat storage and tried to realize if this storage works for cooking. In addition Foong studied the heat capacity of different binary mixtures of the binary salt and concluded the melting point of this mixture did not vary significantly but the specific heat of fusion for the mixture 60% $NaNO_3$ - 40% KNO_3 remains optimal with 108.67 ±1.47 [Jg^{-1}]. A recent study of phase diagram and thermodynamic property of this mixture confirmed varying the mixing values of KNO3 from 0.2 to 0.8 % did not changed the melting point; however, the heat capacity was optimal at 0.6-0.4 % by mol ratio. Its phase diagram developed by different researchers numerically was examined with experimental results of a Differential Scanning Calorimeter (DSC) [15], [16] and [17]. In most literatures this binary mixture is called solar salt; its melting point ranges between 216-222^{0}C and was suggested as a good latent heat storage for high temperature applications. This PCM is found compatible for Injera baking as Injera requires a temperature of 180-220 ^{0}C to be well cooked [18].

Following the latent heat of storage study by Foong, two lines of investigation have been continuing one with parabolic trough –oil HTF and the other parabolic dish-steam HTF (research of the author) and use both used binary nitrate salt PCM. Maxim's nitrate based heat storage coupled to parabolic trough used self-circulating oil HTF and insulated absorber with evacuated tube show the real scenarios with concentrated collectors at higher temperature. However, this colleague has claim the rough top surface of his system as a reason for the poor performance of his system during frying and boiling as he tries to compare it with regular electric stove without considering the difference in heat transfer phenomenon of the two systems [19]. Regardless of its size and performance; this was a good case to the team to consider customizing the three stages, sensible-latent-sensible, thermal storage concept of Thomas B. et al. for power generation [20] if the polar mounted dish concentrator presented in this paper did not show advantages in performance and cost when compared to trough at large scale. The author believed insulating concentrating collectors' receiver can generally improve the overall performance of such systems with particular advantage to dish collectors. The main heat loss of dish concentrator is from its receiver as discussed in, accompanied paper of the author to this conference, Injera baking using solar steam directly. While indirect (indoor) solar cookers integrated to thermal energy storages show high demand, efficient heat discharging process will play vital role for their future expansion. Mawre et al. discharge simulation model was validated experimentally on packed pebbled bed heat storage that use oil as HTF; both results show energy extraction by regulated flow rate of HTF has better efficiency over constant flow rate [21]. The author's work as a continuation of this paper is inline to the later literature in which he is integrating storage to stove and study it's discharging behavior through conduction and steam HTF.

The main objective of the study presented in this paper is to investigate the charging behavior of solar salt and its potential for Injera baking both experimentally and using COMSOL multiphysics simulation.

Nomenclature

a_m	Fraction melted
C_{lp}	Average specific heat between T_m and T_f [J/kg K]
C_p	Specific heat [kJ/kg K]
Csp	Average specific heat between T_i and T_m [kJ/kg K]
DSC	Differential scanning calorimeter
Δh_m	Heat of fusion per unit mass [J/kg]
KNO3	Potassium nitrate
m	Mass of heat storage medium [kg]
MU	Mekelle University

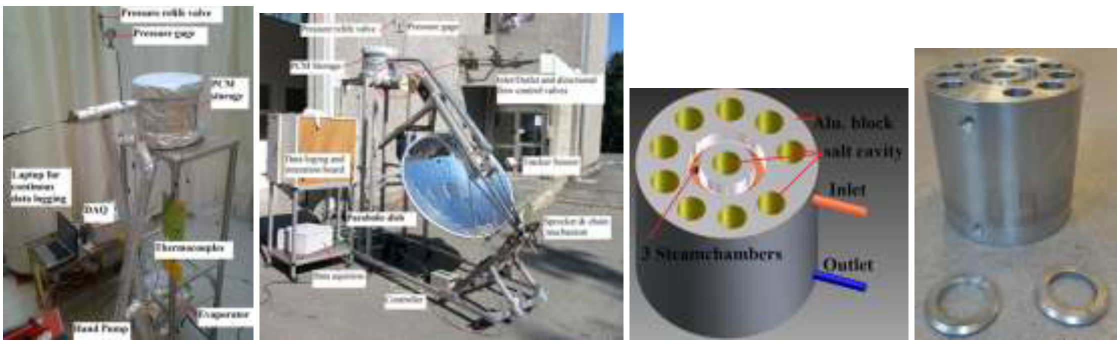
NaNO3	Sodium nitrate
NTNU	Norwegian University of Science and Technology
PCM	Phase change material
Q	Quantity of heat stored [J]
T_f	Final temperature [^{0}C]
T_i	Initial temperature [^{0}C]
T_m	Melting temperature [^{0}C]
ρ	Density of a material [kg/m^3]

2. Methodology

The main focus of this study was to investigate if heat was transported from receiver to storage without major heat loss and if working with 40 bar steam system to melt a salt mixture is safe and efficient. Two electric based and solar based laboratory models working on the principle of natural circulation boiling-condensation were developed to demonstrate this. Steam as means of HTF has advantages due to its higher heat capacity and the associated high pressure safety issues were addressed through standard component material.

The electric based system shown on Fig 1 (a) was developed by equipping it with 10 mm stainless steel, electric heating element, thermocouples, pressure gage, pressure relief valve, and an aluminum block with salt cavity shown in Fig 1 (c) and (d) as thermal energy storage. A boiling-condensing single-phase steam circulates naturally, between the evaporator and storage to charge it fully. Heat was transported by steam and stored by charging a PCM material.

The real sun system as shown in Fig 1 (b) is a polar mounted system and equipped with parabolic dish of 1.2 m diameter, 0.48 m focus length and a mirror reflector. A similar pipe line, sensors and storage arrangement as the electric system and under the same system principle was used to charge the storage. An automated one axis, east-west, tracking aided by a manual secondary, North south, tracking was studied in this experiment.



(a) (b) (c) (d)

Fig. 1 steam based storage charging a) Polar mounted parabolic dish collector; (b) artificial heating, (C) schematic of aluminum block with salt cavity storage and (d) real storage

3. System design and development

3.1. Collector design

Parabolic dishes of larger aperture area are not commonly fabricated and expensive on special order. Nevertheless, with due attention on precision, design and manufacturing; it is possible to manufacture it from optimized petal shape sheets. Design of layered flexible petals has shown good results [22], especially for low cost solar applications. However, a readymade small scale parabolic dish fabricated from a single sheet of aluminum was used in this experiment. Concentrating parabolic dish collector needs a two axis tracking to follow the sun; however, a polar mount with automated east-west tracker aided by a manual north-south tracker simplifies the design and made it suitable to use a fixed receiver.

3.2. Storage design

The design of PCM based thermal energy storage includes quantifying the total heat storage capacity and fin design. The aluminum block acted as fin and container that contributed substantial sensible heat to the overall storage capacity. The total heat of PCM and aluminum was calculated using eq.1-4 [23] and eq.5 respectively. The specific heat capacity for PCM was modified in to eq. 3 [15] based on the result obtained from differential scanning calorimeter (DSC) and that of aluminum is 883J/kg.K.

$$Q = \int_{T_i}^{T_m} mC_p dT + m a_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \tag{1}$$

$$Q = m\left[C_p (T_m - T_i) + a_m \Delta h_m + C_{lp} (T_f - T_m)\right] \tag{2}$$

$$C_p (kJ/kg) = \begin{cases} 0.75 & T < 110^0 C \\ 4.2 & 110^0 C \le T \le 120^0 C \\ 1.4 & 120^0 C < T < 210^0 C \\ 12 & 210^0 C \le T \le 220^0 C \\ 1.6 & T > 220^0 C \end{cases} \tag{3}$$

$$Q_{PCM} = \int_{23}^{109} mC_p \mathrm{dT} + \int_{110}^{120} mC_p \mathrm{dT} + \int_{121}^{209} mC_p \mathrm{dT} + \int_{210}^{220} mC_p \mathrm{dT} + \int_{221}^{237} mC_p \mathrm{dT} \tag{4}$$

$$Q = \int_{T_i}^{T_f} mC_p \mathrm{dT} \tag{5}$$

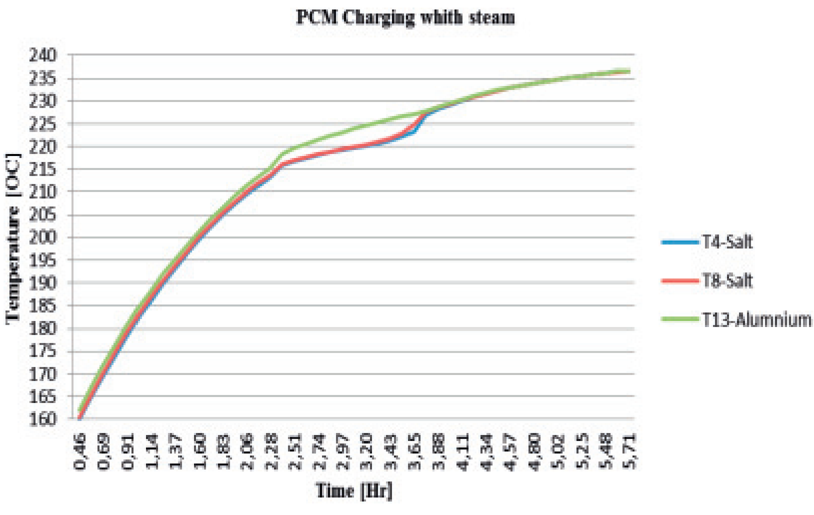
The quantity of PCM depends on the available cavity size; in this storage 10 salt cavities of same size, 0.032 m diameter and 0.15 m height were provided. A ten percent volume was left vacant for expansion during melting. The density of the PCM varies from 1800 to 1700 [kg/m3] in the course of phase change from solid to liquid. The conductivity of solar salt is very poor (0.8 W/m2) and it demands a fin with good thermal conductivity to improve heat transfer rate with in the salt.

4. Results and discussions

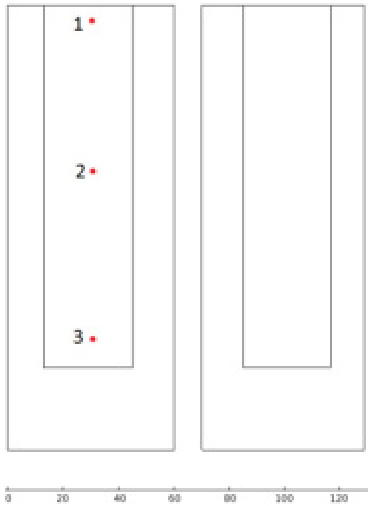
Injera is commonly baked on electric/wood stoves in cities and wood/animal dung in rural areas of Ethiopia. The hardly published energy consumption behavior of Injera blocked its research for alternative energy options. The literature value of Injera baking lacks depth; an accompanied paper of the author discussed the impact of working within and outside of the literature values, and investigated 135-160 oC is sufficient.

The thermal storage loaded with two kilos of solar salt was experimented and simulated in COMSOL. The PCM was completely melted after it was charged by an average power of 650W for 4.5 hours; the storage showed a slow increment up on charging near the saturated temperature of the steam. A useful heat was stored for more than one day in this experiment.

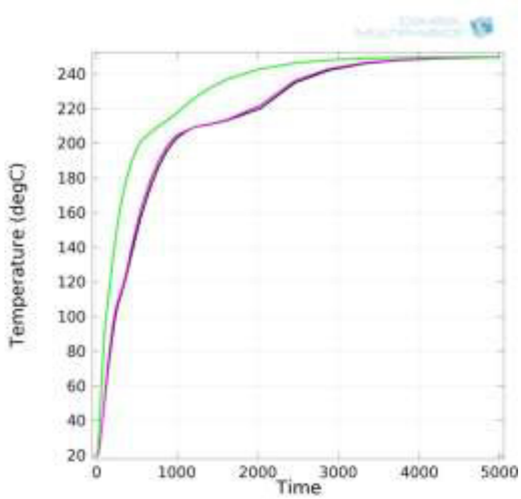
The experimental and COMSOL simulation results for charging of the storage gave a similar result. However, Fig 2 (c) shows the PCM temperature at point 3 is very similar to T13-Aluminum of Fig 2 (a). This indicates the aluminum block near the bottom is an excess fin and the PCM behavior was dominated by the sensible heat behavior of the aluminum block. The useful heat stored was 374.4kJ latent and 853kJ sensible, that is equivalent to the heat required to bake two Injeras including heating up power.



a.



b.



c.

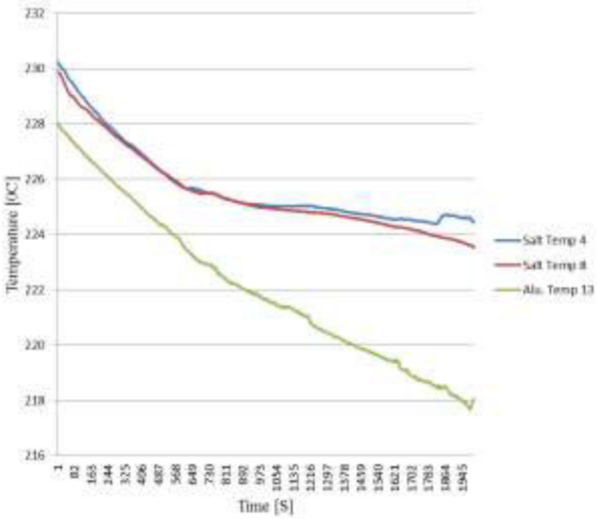
Fig. 2 PCM and aluminum temperature profile a) experimental results, b) Locations of temperature measurement points in COMSOL and c) Simulation of temperature development PCM (1-Black, 2-Magenta, 3-Green and time [S])

Fig 3 (b) shows the PCM temperature was getting constant when discharging was approached to the phase change zone, where a massive near isothermal heat supply is expected. The other interesting result is the temperature of the aluminum container which decreased rapidly indicating Aluminum is not an appropriate container material. The aluminum block improves thermal conductivity during charging when it acts as a fin and very fast deterioration of the stored heat when used as storage container. Considering the mass of the PCM the storage was tested for night cooking by frying egg. The egg frying took about 32 minutes and it only utilized the sensible heat part of the stored heat. The longer frying time was occurred because the frying pan was not fully griped the aluminum surface due to the presence of thermocouples. The thermocouples shown on Fig 3(a) hindered a firm grip between the pan and the top surface of the storage that caused poor conduction-convection heat transfer. A major radiation and convection heat loss in the air gap was estimated using eq. 6 as it was given by [24].

$$Q = Ah_c(T_s - T_{am}) + \sigma A\varepsilon(T_s^4 - T_{am}^4) \qquad (6)$$

Where: A is the area of the top surface of the storage (≅ 0.0314m2), hc is the convective heat transfer coefficient (W/m2K), Ts is the surface temperature, Tam is ambient temperature, σ is the Stefan-Boltzmann constant (5.67*10-8W/m2K4) and ε is the surface emissivity for aluminum (0.035).

Storage charging using electric and real sun showed a substantial time difference. The electric heating element, coiled on a stainless steel was set at a temperature of 350OC, took longer time to fully charge the storage. The polar mounted parabolic dish concentrator, having a concentration ratio of 144, has fully charged the storage which was faster by an hour or more depending on the solar radiation of the day.



(a)

(b)

Fig. 3: cooking when there is no sun (a) egg frying, (b) heat discharge during frying

5. Conclusion

Solar concentrating collectors known for their higher energy capacity were inapplicable for decades because it was difficult to demonstrate a fixed receiver with efficient heat transport and heat storage. The research and development researched in this article proved heat was transported, stored and utilized by indoor cooking during the night. The successful night cooking and lower Injera baking temperature has begun a new chapter in the research of solar energy for intensive high temperature cooking. The natural circulation principle made this design very handy and economically feasible in the sense of developing countries, where system sophistication, deep operating skill and maintenance were not well developed.

The ever increasing price for primary energy supply in Ethiopia will give an opportunity to emerge new solution designs. The rural societies of the country were introduced different energy options, solar box cooker, Hk14 concentrating cookers and bio-gas stoves; however, the acceptance was not large as all the introduced technologies were unable to bake Injera. PCM storage designed for household Injera baking consumption will help to break the attitude of the society towards alternative baking energy. The fast thermal decay time observed in this experiment can be improved by replacing aluminum with a poor thermal conductivity material of the storage.

Acknowledgements

The Author forwards his heart felt gratitude to the government of Norway for supporting Ethiopian institute of Technology-Mekelle (Mekelle University) to run the EnPe program under mechanical engineering department; under which he was granted the fund of capacity building, to persuade his PhD study, as part of the program. He also wants to forward his special thankfulness to professor Ole J. N and Dr. Mulu B. K for their endless support and supervision. Lastly his appreciation and profound thanks goes to the technical staffs of NTNU and Mekelle University for their technical help.

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