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Solar cookers with latent heat storage for intensive cooking application

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Abstract

Many developing countries use biomass as their primary energy supply. Unwise utilization of biomass affects the environment, health and safety of women and children in particular. In addition, it causes indoor air pollution, which is a reason to the deaths of millions. This paper demonstrates solar cooker with an integrated PCM thermal storage and heat transportation loop suitable for high temperature applications. The system is designed to particularly suite *Injera* baking application. *Injera*, a yeast-risen flat bread type is the most common staple food type served three to four times a day in Ethiopia. A similar food type is also eaten in, Eritrea, Somalia, Sudan and Yemen. The system storage has a capacity of about 250ºC and retains the heat for about two days. The storage is coupled polar mounted concentrator with fixed receiver and steam heat transfer fluid. The steam circulates naturally between the evaporator and condenser in a closed loop. The study has demonstrated indirect charging, simultaneous charging-discharging and discharging of the stored heat. 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 are 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 on top of a heat storage charged by a solar energy. This baked Injera able to cover three to four days food consumption of the family.

Keywords: *solar energy, solar cooker, solar Injera baking, parabolic dish cooker,*

1. Introduction

1.1. Background on solar cooker and thermal storage

Many developing countries use biomass as primary energy supply for their household's energy consumption. This energy in return affects the environment, health and the livelihood development of the people. In these countries women and children are often in charge of fetching firewood and cooking, in which they spent most of their valuable energy and time traveling long distance in search of this fuel. In addition, they are also the most affected from indoor air pollution from this energy and traditional cookstoves.

On the other hand, the progress of solar cookers technology is very slow in spite of their benefits. One reason for this can be lack of integration between social and technology 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

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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. Thermal energy storage helps to store the surplus energy during the day and keep it for late evening use. 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, A. Lecuona et al.'s solar cooker could cook family lunch while charging the storage simultaneously [1]. 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 used heat pipes, flat-plate collector and integrated indoor phase change material (PCM) storage, was able to cook food at noon, evening and keep the food warm at night and the following morning [2]. The solar fryer in this paper will solve these barriers 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, H.M.S. Hussein et al. [2] have tested a PCM storage coupled to flat plate collectors for indoor cooking and heating of food during the evening. In addition, A. Lecuona et al.'s [1] portable solar cooker with PCM storage enables day and nighttime cooking.The purpose of this paper is therefore to design an indirect solar cooker with latent heat storage, which is dedicated for baking the Ethiopian food called Injera.

Injera is yeast-risen flat bread with slightly spongy texture. It is the most common food type, which is served three to four times a day. Similar food type is also eaten in, Eritrea (Injera), Somalia (Canjeero), Sudan and Yemen (Lahoh) [3]. Injera is used to bake on a clay stove called "Mitad". The baking process demands a significant amount of energy, which mainly comes from biomass as most of the populations live without access to electricity. The biomass based Injera kitchen is full of smoke and soot that affects the health of millions. The solar stove designed in this study has tried to give a solution for this acute problem.

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 halts any direct contact of the steam and the PCM. More over the storage has a 10% vacant space to avoid any pressure development and volume variation during phase transition of the PCM. The schematic of the whole system is given in Fig.1. The thermosyphon loop is designed to simplify the heat transfer mechanisms over long distances.

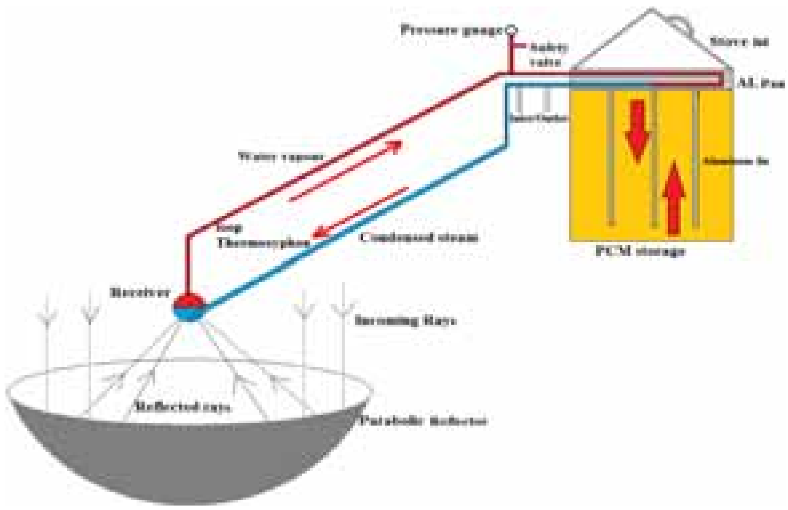

Fig.1: Schematic of the developed system

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 used polar mounted reflectors with fixed receiver philosophy. The list of sensors and equipments 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, its use for small-scale application such as cooking is rare. 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.

a) Collector design

The fixed receiver of this concentrator was 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 [4]. The other and easier way to get parabolic dish for solar concentration purpose is to customize existing satellite dishes by filming them with appropriate reflector materials. The parabolic dish used in this paper is a six petal satellite dishes. The dish is filmed with a self-adhesive aluminum reflector, Miro high reflective 95 and thicknesses of 0.5mm.

b) Receiver design

The receiver used in this research is developed by welding of two cylindrical cups of black steel. The cups have 100mm diameter, 5mm thickness and 40mm height. Figure 2 shows the actual pictures of the receiver during experiment. Random temperature measurements in the illuminated area of the receiver lie between 300 to 1150°C. However, larger part of the receiver is exposed to radiation loss.

Figure 2 Receiver of a parabolic dish collector

c) Thermal performance

The thermal efficiency of the system is given by the ratio of the useful energy stored to 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:

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

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 was performed only for its solid phase sensible heat-storing ability as it was not fully charged. 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 Fig. 3, which affect its focusing. 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.

d) 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 longer time stay in clouds. 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.

e) 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.

f) Pipe lines

The steam pipeline is 10mm in diameter and 1mm thickness. This pipe is used as a pipeline of the thermosyphon 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 was 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 Fig. 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 unit was tested for simultaneous charging-discharging, discharging of a fully charged storage and discharging of partially charged storage (cloudy day). The solar radiation used when analyzing the system thermal efficiency is shown in Fig. 3(b).

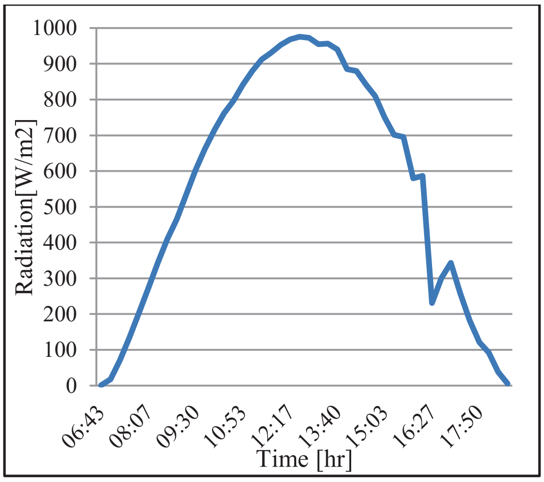

Figure 3: 1.8m parabolic dish collector with PCM storage (Mekelle Unit) Figure 1: Global solar radiation of Mekelle on 27-02-2014, when the stove reach 187°C

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 the charging of the PCM found between two fins is very quick; however, the PCM adjacent to the storage wall and bottom changes its phase very slowly. This 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 Fig. 4(b).

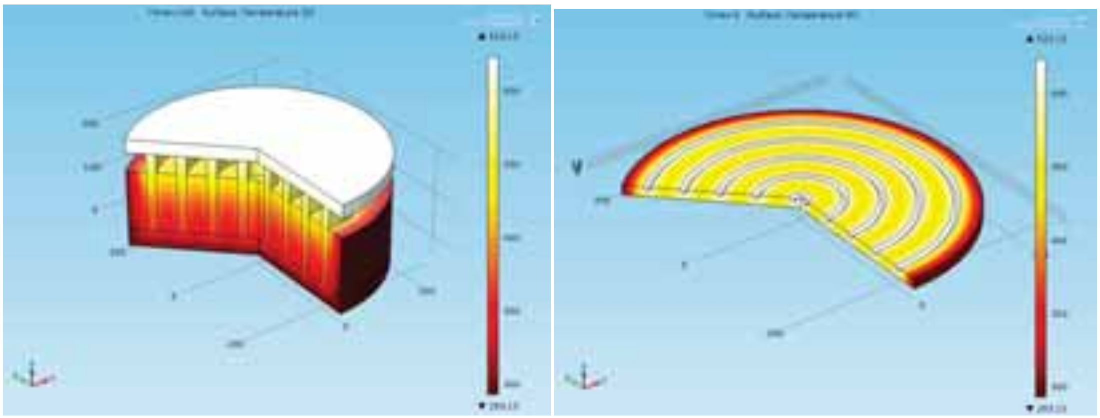

Figure 4: COMSOL simulation of a) PCM charging and heat transfer between SS and aluminum wall, b) frying pan with embedded SS steam pipe

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 thermosyphon loop. In the first day of the test, the stagnation temperature of the system was not reached the melting point of the PCM. Though, the storage was tried to be charged in successive days using the advantage of the PCM's heat retention ability this did not help to charge the storage fully, this was probably mainly due to the huge heat losses from the receiver.

The test was then preceded to a simultaneous charging-discharging during the peak hours of solar radiation. When simultaneous charging-discharging test was started, the circulating steam and temperature was 160°C and 150°C respectively. During this test the intended application, Injera and bread baking, was perfect regardless of literature values. When baking was started, the circulating steam and the storage have experienced a sudden drop of temperature. However, the temperature has slowly recouped during the baking period. Figure 5 shows the baking and charging behavior of the system during simultaneous charging-discharging.

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

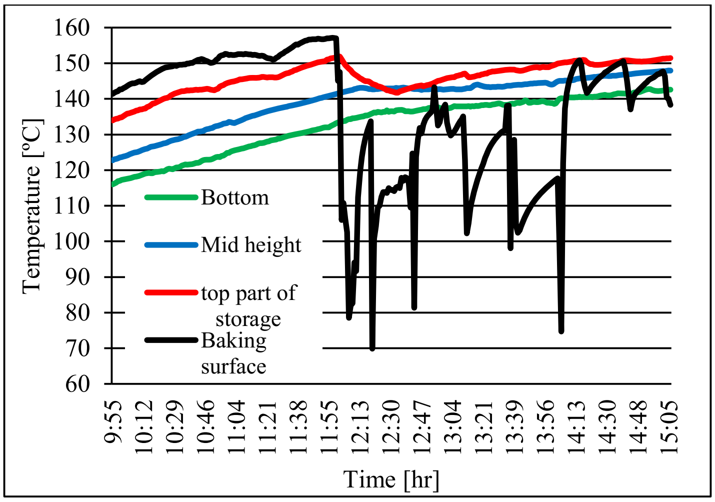

Figure 5: PCM charging and baking practice simultaneously from the sun

In the beginning of Injera baking on this stove, the surface texture of the frying pan was rough and it stacked the Injeras. Taking out the baked Injera from the surface of the frying pan was a big challenge. In addition, the quality of the Injera was not attractive. To avoid the sticking impact of the aluminum-baking surface, a borosilicate glass has been placed on top of it, but the Injera quality 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.

a. 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 was set to a maximum temperature of 450°C, at which it was delivering an average power of about 700W to the receiver. This power was 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.

The stored heat was tested to bake Injera and bread needs of average household size, i.e. 19 Injeras and six breads. The stored heat was run for about four hours 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 test was faster compared to ordinary electric and biomass stove baking speed. In the baking process, the Injera consumes the phase transition heat. And the bread baking process consumes sensible heat of the solid PCM. The nearly 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's were improved.

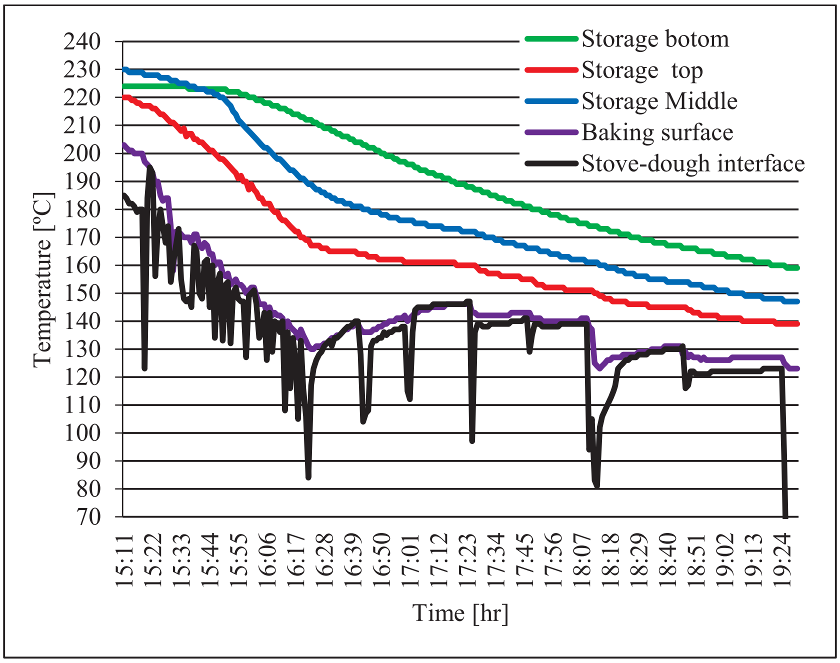

Figure.6: PCM discharging through backing

b. Discharging of partially charged storage

The third practical test for this system is 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. The baking tests show smooth baking process with very good Injera quality, which is the same as the quality of Injera baked on customary Injera stove as shown in Fig. 7. This system has smooth baking surface texture similar to the ordinary stove and it used oil seeds to polish it. Unlike oil, oil seeds have the ability to give smooth baking surfaces by filling its irregularities.

Figure 7: Injera baking process and the final Injera quality

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 on test demonstration, one planed demonstration was arranged. The aim of this demonstration was to create awareness how solar energy was able to bake Injera and cook the different common Ethiopian dishes. The university community has appreciated the innovation of the research's role in mitigating climatic and health problems caused from extensive use of biomass fuel during Injera baking and cooking processes. Figure 17 shows the Injera baking process, which includes polishing, pouring, and taking off and the final Injera.

The Injera baking cycles plotted in Fig. 8 shows the Injera baking process was taking 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 many of the experiments, the baking surface temperature was unbelievably abled to bake Injera as low as at 60 and 80ºC. For instance, nearly all of the Injera baking cycles shown in Fig. 18 are below 110°C. This result is very attractive compared to literature values (180-220°C), which can possibility revolutionized the stove technology.

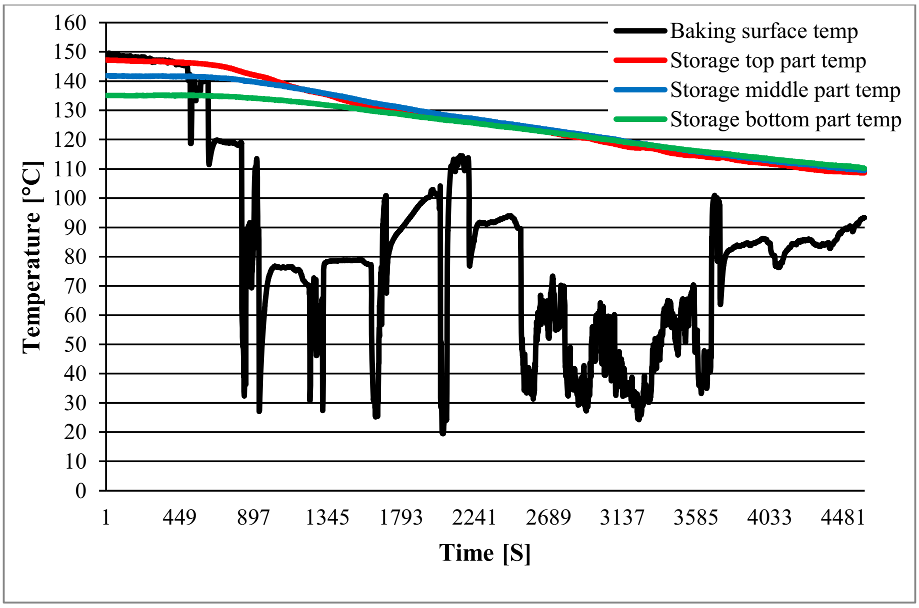

Figure 8: Injera baking from a partially charged PCM storage

Figure 9: serving solar prepared meal

Conclusion

A concept for Injera baking (Ethiopian bread) on top of a heat storage charged from a solar concentrator has been developed and demonstrated. Heat transfer by a thermosyphon principle, with water as the working fluid at about 40-bar pressure. Vapor is generated at the heat absorber in the focus point of the parabolic concentrator and condenses in coiled tube, which is casted into an aluminum baking plate. The baking plate has heat-conducting rods extending into a latent heat storage ("solar salt", Nitrate mixture). The following conclusions can be noted: Injera can be baked on an aluminum surface, provided the surface is sufficiently smooth and otherwise prepared similarly as for the traditional clay based pan during the frying process. Injera can be baked at lower temperatures (110-150°C) than previously assumed (180-220°C), as long as sufficient heat transfer can be maintained during the baking process. The required temperature will then depend on the material of the baking plate. A boiling/condensing natural circulation loop (thermosyphon) is feasible with water as the heat transfer fluid. As the water volume is small, the high pressure is manageable but requires high quality pipe and valve components. A boil-off startup procedure is operationally easy. The system can be optimized with respect to losses in the heat transfer loop, in particular at the absorber. The absorber is a spherical boiler in a fixed position, with the solar illuminated area moving from one side to the other during the daily sun tracking.

4. References

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