DEVELOPMENT OF A THERMAL STORAGE SYSTEM FOR SOLAR PV BASED INJERA BAKING APPLICATION

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Abstract

This study aims to address energy and energy-related issues in urban and rural communities, as well as institutions that still use biomass for Injera baking, in Ethiopia, by developing an efficient and suitable thermal storage that could serve as a base model for the development of solar PV-based injera baking systems. To achieve this, a three-dimensional model of three storage concepts, each using a solar salt mixture of 60% NaNO3 - 40% KNO3, was developed and compared using COMSOL Multiphysics software to investigate their performance during charging and discharging. The first two concepts comprise phase change material (PCM) filled aluminum cylinders with air or oil as heat transfer fluid. The third concept contains packed PCM in between cylindrical fins, which act as both a containing and conducting wall. The temperature, the percentage of PCM that melted, and the energy stored while charging and discharging were all documented. The performance of the packed PCM (conduction-based) system is 58% higher than that of the oil-based system and 62% higher than that of the air-based system. The result obtained from this simulation will be used to develop a prototype of a PV-based injera baking system. The numerical investigation's results were consistent with the findings of experiments documented in previous literature.

Keywords: Injera, charging and discharging, PV, PCM

1. Introduction

Injera is a staple bread consumed daily in Ethiopia and some parts of eastern African countries. It is mainly made from teff and constitutes 70% of the diet of Ethiopians. Mitad is a traditional plate made of clay used for injera baking. It measures 40-60cm in diameter and 20mm thick. The baking process occurs in the temperature range of 180 ℃ to 220 ℃ at an energy consumption of approximately 0.63MJ per Injera and a baking time of up to 3 minutes. Most of the time, biomass is used for injera baking, though sometimes electricity and other energy sources are used in urban and semi-urban areas. According to studies, cooking consumes 90% of the household energy, and 90% of this is for injera baking. The energy efficiency of electric injera baking pans is 56–60%, according to the Ethiopian Energy Agency, and it has not improved over the past 50 years (Getahun, 2017). Deforestation, frequent power outages, voltage drops, and other issues are caused, among other things, by the injera mitads' low efficiency. With an access rate of roughly 45% of the population (58 million) in 2017, Ethiopia is one of the 20 nations with the highest access deficit. In 2017, Ethiopia's total access to clean cooking technologies and fuels was less than 5% in rural areas and 7-29% in urban areas (SDG7, 2019). A large percentage of urban residents can't afford the electricity tariffs for all residential uses, and for those who can, power outages are the main problem, particularly for high-temperature cooking applications like injera baking. In addition to the households, institutions in Ethiopia (universities, schools, refugee camps, restaurants, etc.) use biomass as a source of energy for cooking.

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Fig.1: Injera baking system currently in use at Bahir Dar University

Renewable energy technologies could play a key role in enhancing energy access to rural areas and cities where communities and institutions lack access to energy. However, only lighting and water heating solar energy technologies have been made available in rural areas in contrast to solar cookers. This shows that there hasn't been significant technological progress in using solar energy for high-temperature cooking applications. Various scholars and groups have made efforts to utilize solar energy for injera baking applications (Abdulkadir et al., 2016; Asfafaw et al., 2014a, 2014b; Mesele et al., 2017). The output of these researches and projects shows a promising result on the performance improvement of solar injera baking by employing different techniques, among the efforts, the use of different types of collectors and heat storage media, performance investigation of existing baking systems, and development of new baking pans are some of them. However, the research on the application and feasibility of injera baking with PV and a thermal storage system to solve energy problems in rural and urban communities is limited.

The development of a thermal storage system for solar applications represents a significant advancement in renewable energy technology. Thermal storage systems enable the capture and storage of excess thermal energy generated by solar collectors during periods of peak sunlight. This stored energy can then be utilized during periods of low solar irradiation or at night, allowing for a continuous and reliable energy supply. By integrating thermal storage into solar power systems, we can overcome one of the major limitations of solar energy – its intermittent nature – and enhance its efficiency and reliability.

A numerical investigation is proposed and conducted on a thermal storage system for solar-powered injera baking to address energy availability and sustainability challenges and overcome limitations in existing research. The investigation is conducted on three different concepts for the thermal storage system using a 3D model. Eutectic 40% KNO_3 - 60% $NaNO_3$ is used to store thermal energy due to its demonstrated capability for high-temperature cooking (Asfafaw et al., 2014a, 2014b; Asfafaw et al.,2018; Dejene et al. 2017; Fuente, 2022; Vermachi et al.,2016). The best-performing model from the simulation will be used to develop a PV-based injera baking system.

2. Materials and Methods

In this section, a comprehensive description of the materials used and the methodology followed in conducting the simulation study is presented.

2.1 Physical Model

As the objective is to compare different thermal storage concepts, only a representative physical model is shown, in Fig.2. A PV array is connected with a DC heating element placed on the top of the storage tank. Electric power generated using the PV panels is converted into heat using the heating element. The heat is then transferred to the PCM through different modes of heat transfer depending on the type of the concept. The storage is insulated to minimize heat loss to the surroundings.

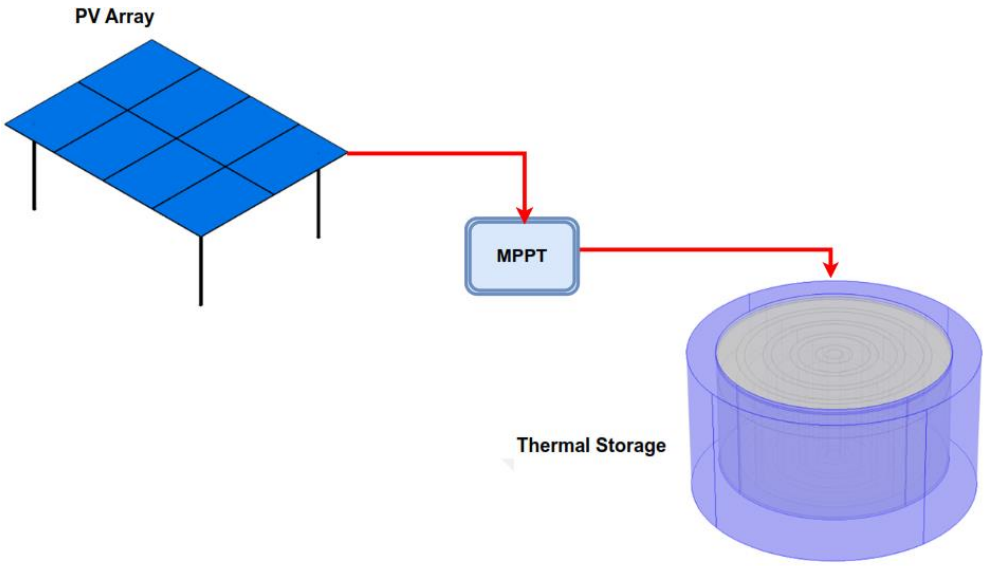


Fig.2: Physical model

2.2 Energy required for baking injera

The first step in designing such a system is determining its energy requirements. The thermal storage and its components can be sized based on knowledge of the required amount of energy. Tab.1 summarizes the energy needed for baking injera including the losses, from previous research.

Tab. 1: Energy required for baking from previous research

No	Reference	Nature of the Study	Energy Consumption
1	Abdulkadir et al., 2016	Experimental	0.630MJ/injera
2	Hiwot et al. 2022	Experimental	0.623MJ/injera
3	Mesele et al., 2017	Experimental	0.454MJ/ injera

According to Tab.1, up to 0.63MJ of energy is required to bake a single injera. For this investigation insulators are used to system can minimize losses on the sides and bottom of the storage. Therefore, assuming 0.6MJ of energy requirement per injera, the system can be sized accordingly.

2.3 Time required for baking injera

The time required for baking is a useful criterion to determine the size of the system. The time required for baking is the sum of the heat-up time (the time to reach baking surface temperature), the total baking time (time to reach boiling temperature of the water in the batter), and the total idle time (time to reach surface baking temperature in between each baking cycle).

$$t_{total} = t_{heatup} + \left(n \times t_{baking}\right) + (n-1) \times t_{idle} \qquad \text{(eq.1)}$$

Where:

t_{total} is the total time for the baking session (s), t_{heatup} is the heat-up time(s), t_{baking} is the baking time for single injera (s), t_{idle} is the idle time (s), n is the number of baking cycle

The heat-up time for the new system is negligible since the baking surface temperature is reached during PCM charging. Tab. 2 shows the total time required for baking a specific number of injeras calculated using eq.1, and taking the average baking and idle time from previous research (Abdulkadir et al., 2011; Asfafaw et al., 2014a).

Tab. 2: Baking time for a specific number of baking cycles

No	No of injeras/baking cycle	Average Baking time(min/injera)	Average Idle time(min/injera)	Total time (min)
1	30	2.5	1.5	118.5
2	40	2.5	1.5	158.5
3	50	2.5	1.5	198.5

2.4 Storage Capacity of the System

Energy storage capacity refers to the ability of a system to store energy for later use. The design and operation of energy systems require careful consideration of storage capacity. The storage capacity of a system depends on several factors, such as the type of storage technology, system size, and energy density of the storage medium. In this case, the system's storage capacity equals the energy needed to bake a specified amount of injera per full charge, including losses. Initially, three storage capacities were proposed, 18MJ, 24MJ, and 30MJ, for baking 30, 40, and 50 injeras, respectively, based on the number of injeras baked in households and institutions in a single baking session. one of the above-proposed systems will be selected after performing the PV power required to charge during the critical month and sizing each system.

2.5 Power required for charging

A detailed sizing of the PV module has been made for charging the proposed storage capacities based on the solar radiation of Addis Ababa. For example, a PV array of 1831W is needed to charge the 18MJ storage during the critical month. This power requirement includes the losses during conversion. The DC heating element converts this power into heat, which is then used to charge the thermal storage. Fig. 3 shows the PV power required for the proposed storage for each month of the year.

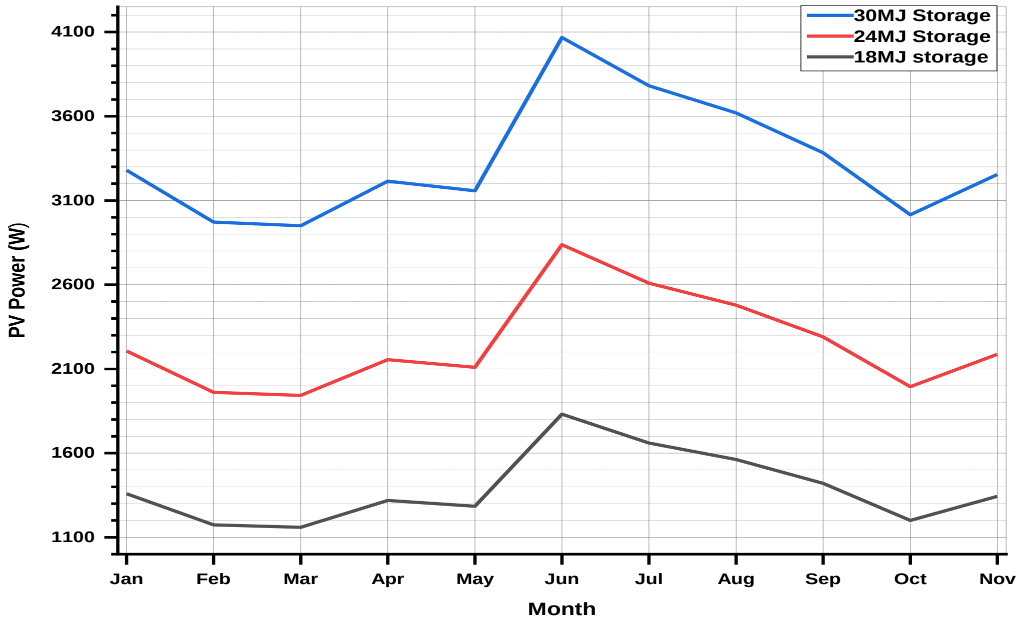


Fig.3: Monthly PV power required for each storage

2.6 Material Selection

2.6.1 PCM Selection

Because of its proven potential for high-temperature cooking (frying), eutectic mixture of 40% KNO_3 and 60% $NaNO_3$ is used as a thermal energy storage system (Asfafaw et al., 2014a, 2014b; Asfafaw et al.,2018; Dejene et al. 2017; Fuente, 2022; Vermachi et al.,2016). Eutectic mixtures are often selected as thermal storage material for cooking applications because they can store large amounts of thermal energy in a compact space and stability. The eutectic mixture of sodium nitrate and potassium nitrate has a melting point of 220°C and can store large amounts of thermal energy at this temperature range. This makes it an ideal storage material for applications such as cooking, where a constant and controlled temperature is required. The mixture is relatively inexpensive and widely available, non-toxic and non-corrosive, making it safe for food-related applications.

2.6.2 Insulation material

The selection of insulation material for cooking applications is an important consideration, as it can affect the efficiency and effectiveness of the cooking process. Different researchers investigate different types of insulation materials for cooking applications. Tab.3 shows some of the insulation materials used for cooking applications.

Tab. 3: List of Insulation materials and their thermal conductivity

No	Material	Thermal conductivity (W/mK)	Max T (^{0}C)	Reference
1	Rock wool	0.033-0.08	750	Ashmore et al., 2013
2	Fiberglass	0.01-0.04	540	Dejene et al., 2017; Watkins et al. 2017
3	Rice hulls	0.05-0.07	440	Watkins et al. 2017
4	Perlite	0.04-0.09	870	Watkins et al. 2017
5	Pyrogel/aerogel	0.015-0.046	650	Musard and O le,2013, Asfafaw et al., 2018

For this application, fiberglass is selected for insulation, because of its availability, lightweight, durability, and excellent insulation properties.

2.6.3 Baking pan material

Replacing the current clay baking pans with metal ones that are better suited for solar application is one of the project's goals. According to prior studies, the main issue with using metal pans to bake injera is that it is difficult to remove the injera after baking (stickiness). The metal pan used needs to have thermal properties to avoid this issue and produce injera of higher quality. A brief simulation was conducted to select the type of metal pan for the concept development. Based on the simulation result, the 6mm aluminum pan was chosen for this investigation.

3. Concept Development and sizing of the system

3.1 Concept Development

The main objective of the concept development is to identify and develop an efficient and suitable thermal storage system for injera baking applications. This process involves evaluating various arrangements and materials for thermal storage that can increase efficiency and improve performance. We initially developed and evaluated six concepts using various criteria, understanding that the selection and organization of the system's components directly impact its performance and size. Subsequently, we discarded three concepts and further analyzed the remaining three using COMSOL multi-physics software. The concept with the best performance will be employed to build a prototype of a solar PV-based injera baking system. The components within each concept include a storage tank, PCM, heating element, base plate, and baking plate. Then, the difference between the concepts lies in the medium of heat transfer and the arrangement of the components.

Concept 1: Air-based system

Fig.4 (a) shows the basic components of the air-based system. This concept consists of PCM-filled cylinders;

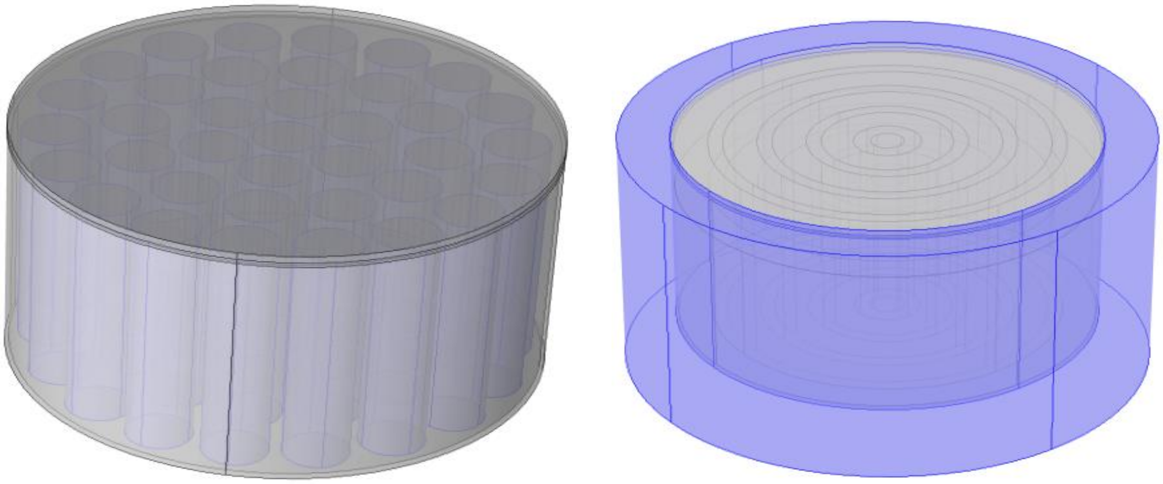
the free space is filled with air.

Concept 2: Oil-based system

Fig.4 (a) shows the oil-based system which is the same as concept 1 except the type of heat transfer fluid used.

Concept 3: PCM-Fins system

Fig.4 (b) shows concept 3 which consists of cylindrical fins integrated with the base plate. The PCM is filled in between the cylindrical fins. In this arrangement, the fins act as a containing wall in addition to conducting heat. Approximately 15% of the storage volume is left for safety.



(a) **(b)**

Fig. 4: Proposed concepts (a) Concepts 1 and 2 (b) Concept 3

Placement of the heater

The placement of the heater has a significant impact on the charging and discharging performance of the system. Placing a heating element at the top or bottom of a thermal storage system can have advantages and disadvantages, depending on the specific application and design. For this case, placing the heating element at the top of the thermal storage between the baking pan and the base plate can allow for more efficient and effective heat transfer. An additional benefit of placing the heating element at the top is baking can be carried out during sunshine hours while charging the PCM.

3.2 Sizing of the different components of the system

3.2.1 Sizing of the Storage

The quantity of injera that needs to be baked will determine how big the storage needs to be. The storage volume for a certain storage capacity can be calculated using eq. (2) by assuming the diameter of the storage to be equal to the diameter of the baking pan:

$$Q_{PCM} = \int_{T_i}^{T_m} m_{PCM} c_{pPCM,S}\, dT + m_{PCM} \Delta h_{fus} + \int_{T_m}^{T_l} m_{PCM} c_{pPCM,L}\, dT \qquad \text{(eq.2)}$$

Where Q_{PCM} is the energy stored in the PCM, T_i is the initial temperature, T_m is the melting temperature,T_l is the liquid PCM temperature, $c_{pPCM,S}$ is the specific heat of solid PCM,$c_{pPCM,L}$ is the specific heat of liquid PCM, and m_{PCM} is mass of PCM.

The mass of PCM is given as

$$m_{PCM} = \rho_{PCM} V_{st} (1 - \xi) \qquad \text{(eq.3)}$$

Where V_{st} is the volume of the storage.

ξ is the fraction of the total volume occupied by fins (ξ_f) or the heat transfer fluid depending on the concept type (ξ_{air} *or* ξ_{oil}). The porosity value is taken as 0.4 (Dejene et al. 2017).

Table 4 shows the volume of storage for the proposed storage capacities.

Table 4: Mass and Volume of PCM

No	Storage capacity (MJ)	Volume of storage(m^3)	Volume of PCM (m^3)
1	18	0.0256	0.0154
2	24	0.0342	0.0205
3	30	0.0427	0.0256

The height of the storage is calculated using

$$V_{st} = \frac{1}{4}\pi h_{st} d_{st}^2 \quad \text{(eq.4)}$$

The diameter of the storage (diameter of injera pan) is set to be 40cm for the reasons listed below:

- Most institutions are using the 40cm pan.
- The storage system is made of casted aluminum; therefore, it will be easier for machining if the 40cm storage diameter is used.

Now it is time to decide the storage capacity among the proposed storages. Having considered all proposed storage options, the 18MJ (30 injera) capacity emerges as the most suitable solution. Further justification is provided below:

- The cost of the overall system increases as we increase the storage capacity (cost of PV, PCM, etc…).
- 30 injera is commonly the amount of injera baked in most households in a baking session.

Sizing the concepts for 18MJ capacity

In concepts 1 and 2, we calculate the volume of the storage occupied by the fluid by assuming that the void fraction accounts for 40% of the total storage volume. In concept 3, we use the same fraction. However, for safety reasons, only 15% of the total volume is occupied by the air, while the remaining portion is occupied by the fins. The thickness of the fins is then calculated based on this volume. Fig. 5 shows the 2D and 3D views of one of the concepts.

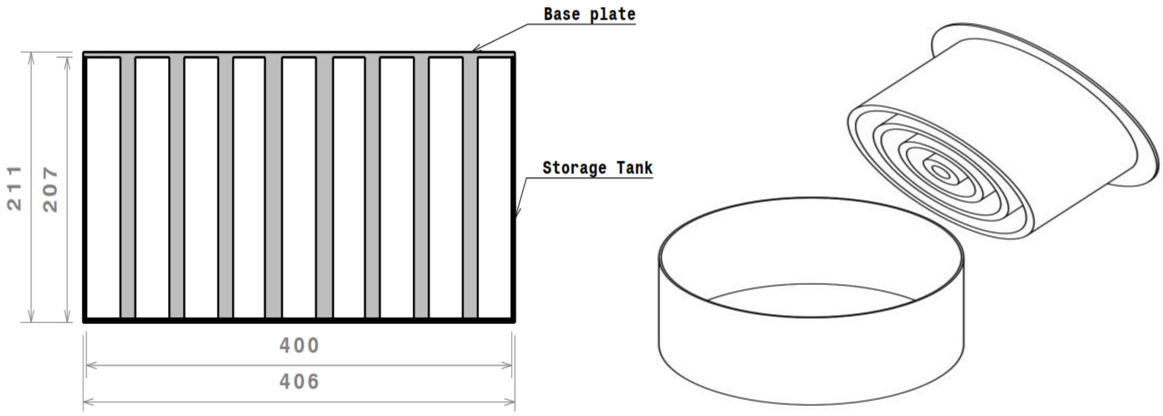


Fig.5: A 2D and 3D view of one of concept 3

Cylindrical encapsulation of the PCM

The PCM is encapsulated in cylindrical tubes made of aluminum to ensure efficient heat exchange between the heat transfer medium and the PCM. The encapsulating cylinders are attached to the bottom of the storage to avoid overheating of the PCM due to the high thermal conductivity of the base plate. A 10% clearance volume is required within each cylinder for safety purposes. The outer and inner diameters of the encapsulating cylinders are 50 mm and 48mm, respectively.

The total volume of the encapsulating cylinder is calculated using:

$$V_{cylinder,total} = V_{PCM} \times 0.10 + V_{PCM} \quad \text{(eq.5)}$$

The number of encapsulating cylinders is calculated from

$$V_{cylinder,total} = n \times V_{cylinder} \quad \text{(eq.6)}$$

Where n is the number of cylinders; $V_{cylinder}$ is the volume of a single cylinder.

4. Mathematical Modeling

The mathematical and numerical models are based on COMSOL multi-physics models for heat transfer in solids, liquids, and phase change materials. The following input boundary conditions are also used in addition to the governing equations:

Boundary conditions during charging:

- Boundary heat source between the baking plate and base plate.
- Natural Convection and radiation boundary conditions on the surface of the insulation.

Boundary conditions during discharging:

- Natural convection and radiation on the surface of the baking plate.
- Natural Convection and radiation boundary conditions on the surface of the insulation.

A 5cm fiber glass insulation is used to minimize loss during charging and discharging. The losses in the system are mainly radiation and convection losses over the surface of the insulation. Other boundary conditions are treated based on COMSOL Multiphysics, depending on the interaction of the mediums. Fig.6 shows the different boundary conditions during charging and discharing.

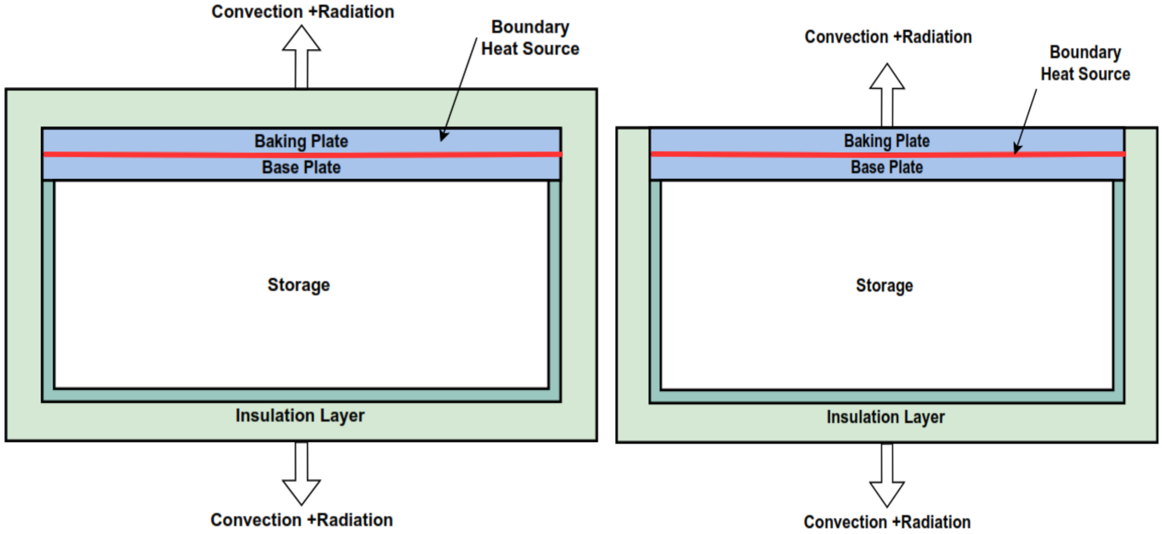


Fig.6: Boundary conditions during charging and discharging

5. Results and Discussion

In this study, three different thermal storage concepts for solar PV-based injera baking applications were developed and compared. The best performing one is selected by conducting a simulation using COMSOL multi-physics software. The three concepts include air-based, oil-based, and PCM-filled storage systems. The concepts were compared in terms of charging efficiency and temperature stability by simulating for a specific charging period (sunshine hours for the critical month) and a constant Power input of 1250W from a PV source during the critical month. The simulation provided results for various parameters, including PCM temperature, melt fraction, pan surface temperature, and energy stored during the charging period. Fig. 7 shows the PCM temperature profile during charging and discharging at three different locations, melt fraction, and insulation surface temperature for concept 1.

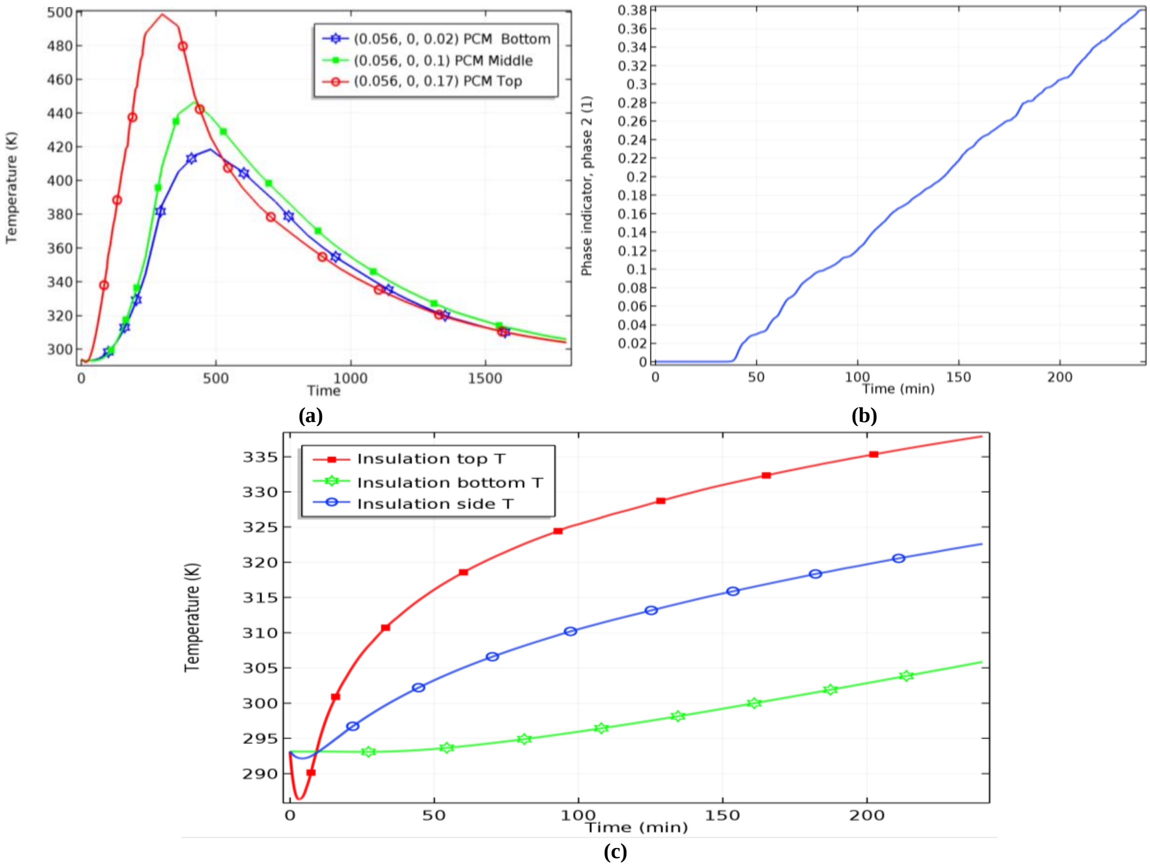


Fig.7: Plots of (a) PCM Temperature profile, (b) melt fraction, and (c) insulation surface T of concept 1

Fig. 8 shows the PCM temperature profile during charging and discharging, melt fraction, and insulation surface temperature for concept 2.

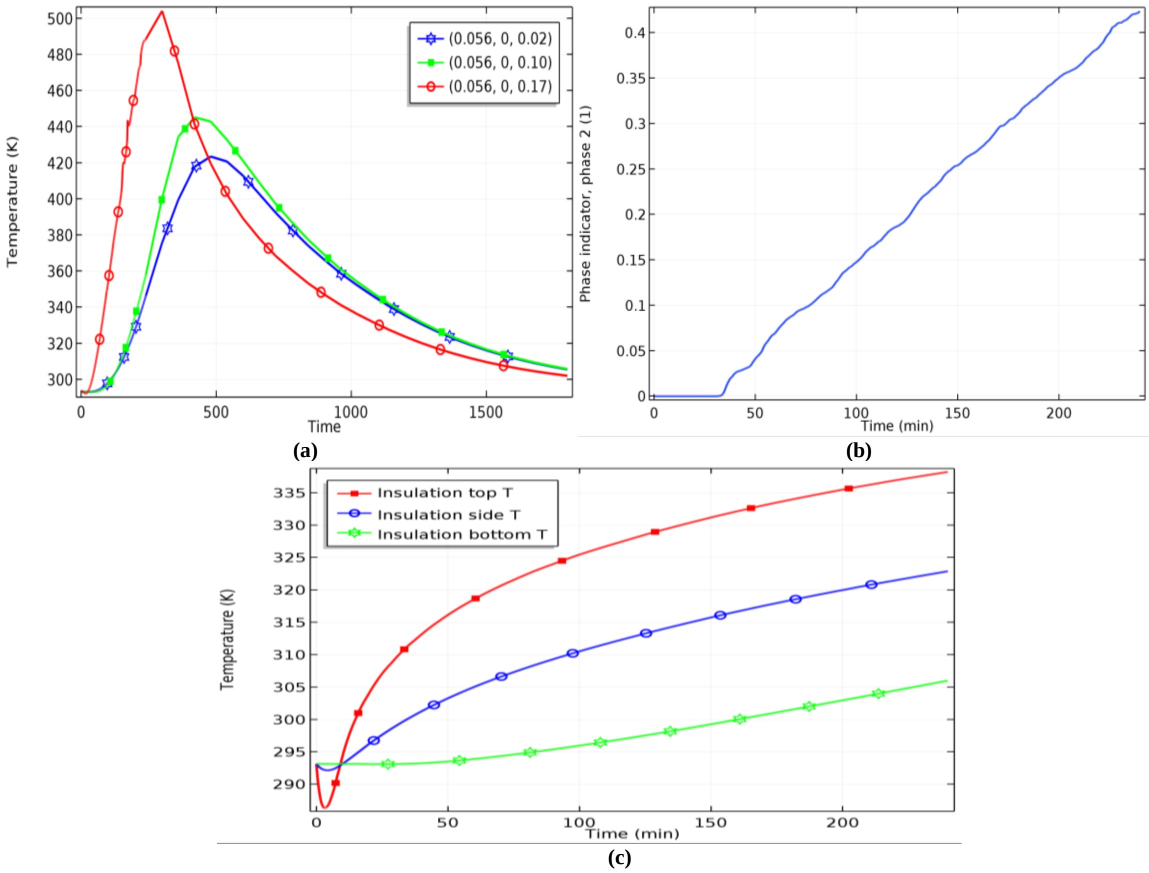


Fig.8: Plots of (a) PCM Temperature profile, (b) melt fraction, and (c) insulation surface T of concept 2

Fig. 9 shows the PCM temperature profile during charging and discharging, melt fraction, insulation surface temperature, and pan surface temperature during charging for concept 3.

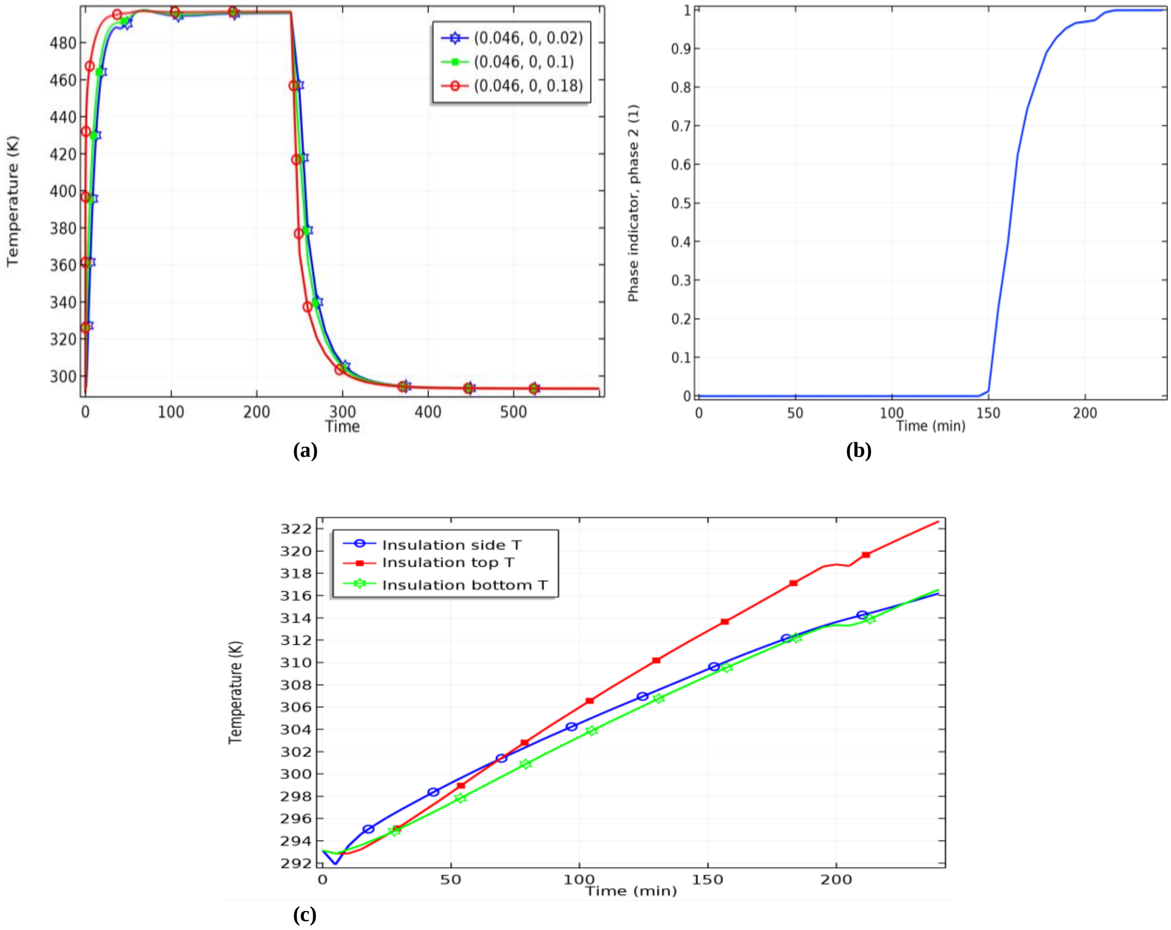


Fig.9: Plots of (a) PCM Temperature profile, (b) melt fraction, and (c) insulation surface T of concept 3

The air-based concept typically exhibits slower charging and discharging rates compared to the oil-based and PCM with fins concept due to the lower thermal conductivity of air (Fig.7a). The oil-based concept allows for efficient heat transfer due to the high thermal conductivity of the fluid, resulting in relatively fast charging and discharging rates compared to the air-based system (Fig. 8a). In the PCM with fins concept, the PCM is combined with fins that enhance heat transfer. During charging, heat is transferred from the base plate to the PCM through the fins, resulting in a relatively fast increase in temperature. The fins increase the surface area available for heat transfer, thereby improving the charging and discharging rate (Fig. 9a).

The air-based storage system exhibited the lowest thermal performance of the three concepts, with a 38% melt fraction, as the air acts as an insulator because of its lower thermal conductivity (Fig.7b). The oil-based storage system displayed a slightly higher melt fraction of 42%. However, there is still a significant portion of the substance that remains in a solid state (Fig. 8b). The PCM-filled storage system showed the highest charging performance, with a melt fraction of 100%, due to the direct contact between the high thermal conductivity aluminum fins and the PCM (Fig. 9b).

Based on the simulation data for insulation top surface temperature (Fig. 7c, 8c, and 9c), Concept 2 has the highest temperature at 338K, followed by Concept 1 at 337K, and Concept 3 has the lowest temperature at 323K. Concept 2 also has the highest temperature at 323 degrees for the side surface, followed by Concept 1 at 322.5K, and Concept 3 has the lowest temperature at 316K. Once again, Concept 3 performs better in maintaining a lower temperature on the side surface. The bottom surface temperature for Concepts 1 and 2 is 306 K, while Concept 3 has a slightly higher temperature of 316 K. In summary, the temperature at the top surface of the insulation in all cases is higher as a result of the placement of the heating element. Concept 3 consistently performs the best among the three concepts in terms of maintaining nearly uniform temperatures on the surfaces of the insulation layer.

In the case of concepts 1 and 2, more heat is transferred through the baking pan instead of charging the PCM, due to the insulating effect of the heat transfer fluid in the storage, resulting in a higher temperature on the surface of the pan. Concept 3 has a relatively lower pan surface temperature since it is in contact with the aluminum base plate and fins at the bottom. Aluminum is known for its high thermal conductivity. As a result, the aluminum absorbs and conducts heat to the PCM away from the pan, leading to a lower temperature for the pan surface.

6 Conclusion

Injera baking is a highly energy-consuming process. To design an efficient injera baking system for solar applications, we should first develop an appropriate storage system suitable for that particular application. The development of a thermal storage system for solar injera baking will play a significant role in the advancement of renewable energy technology. By integrating thermal storage into solar power systems, we can overcome one of the major limitations of solar energy – its intermittent nature – and enhance its efficiency and reliability. In this investigation, three different storage systems (air-based, oil-based, and packed PCM) are proposed and compared numerically by charging them for a specific period and power input. The result of the simulation clearly shows which model has a faster charging period and suitable discharging for injera baking application. The conduction-based model performs best among the three proposed concepts, with a performance of 58% higher than that of the oil-based and 62% higher than the air-based model. All three models demonstrate enough baking surface temperature during discharging, which is more suitable for injera baking. The concepts are also compared based on their pros and cons from different points of view (flexibility, weight, cost, etc.). The result obtained from this investigation will serve as the base model to develop a prototype that incorporates a PV system, thermal storage system, and a metal baking pan.

Further experimental investigation is needed to assess its long-term performance and economic feasibility of implementing these systems at scale. Nonetheless, the results provide a promising starting point for the future development of injera baking systems with thermal storage and demonstrate the potential of these systems to contribute to a more sustainable and energy-efficient injera baking system in rural and urban communities of Ethiopia.

7. Acknowledgment

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