Preparing side charging of PCM storage: theoretical and experimental investigation

2015 IOP Conf. Ser.: Mater. Sci. Eng. 100 012021

(http://iopscience.iop.org/1757-899X/100/1/012021)

IOP Conf. Series: Materials Science and Engineering **100** (2015) 012021 doi:10.1088/1757-899X/100/1/012021

Preparing side charging of PCM storage: theoretical and experimental investigation

A H Tesfay[1], F Y Hagos[2], K G Yohannes[3], O J Nydal[1] and M B Kahsay[3]
[1]Department of Energy and Process Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway.
[2]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malysia.
[3]Department of Mechanical Engineering, Ethiopian Institute of Technology-Mekelle, Mekelle University, P. O. Box 231 Mekelle, Ethiopia.

E-mail: kibrom2000@gmail.com

Abstract. In Ethiopia, there is an abundant source of solar energy that is estimated to 5.3 kWh/m^2/day. However, more than 90% of the society uses biomass as a main source of energy for cooking due to lack of technologies to convert this energy. Replacing these cooking activities by using renewable energy resources decreases pollution and reduces deforestation significantly. Using the solar energy in day time has no problem. For night time however, the system needs some kind of back-up system to make the daytime solar energy available. This back-up should have high-density energy storage and constant working temperature to perform a specific application. Latent heat storage using phase change materials (PCM) is one way of storing thermal energy. In the current study, a latent heat storage that uses a PCM material is used to store the solar energy aimed at utilizing solar energy for cooking Injera, main staple bread in Ethiopia. The PCM is a mixture of 60% $NaNO_3$ and 40% KNO_3 that are known as solar salts. The storage has a welded parallel aluminum fins with a gap of 40 mm in between to enhance the thermal conductivity during the charging-discharging process of the storage. The fins are extruded outside of the storage container to enable a side charging technique for the PCM. A prototype was developed with a solar salt of 17.5 kg and is tested for charging-discharging. The numerical simulation done on ANSYS and experimental results show an agreement and the system registered a 41.6% efficiency.

1. Introduction

Energy storage technologies have been in use for different purposes. Although, electro- chemical energy storage technologies are matured; majority of thermal energy technologies are still in their research stage. Since recently, there is a growing interest of solar thermal utilization. As a result, solar thermal storages got global attention. The two widely used heat storages in solar thermal applications are sensible and latent heat storages. These storages are used in different applications such as in drying, space heating, cooking, power generation. The temperature change in sensible heat storage comes as a result of the absorption of solar radiation by the material. On the other hand, latent heat is the energy absorbed and released by a substance during its phase change from solid to liquid, liquid to gas and vice versa.

Even though many developing countries are situated in in the solar belt (between 40° North to 40° South) that is endowed with huge solar energy potential, they are desperately in need of energy. Ethiopia, like other developing countries, is affected by shortage of energy. Consequently, biomass becomes the source of energy as the expense of deforestation and environmental impacts. The northern part of the country for example, has an average solar energy potential of more than 6.5 kWh/m^2/day during the dry season and 4.634 kWh/m^2/day during the rainy season [1, 2]. However, more than 90% of the region's community still depend on biomass for primary energy supply. Biomass took the lead in primary energy supply in most developing countries and majority of this primary energy is used for cooking. Cooking in biomass based energy affects children's' school time, woman and girls health, and contributes to greenhouse gas emission, land degradation and deforestation.

The interventions of solar cookers assure safe and clean energy utilization. However, their acceptance remains limited due to their longer cooking time and dependence to the presence of the sun. The mismatch of the availability and demand for solar energy can be bridged by using thermal batteries. Naturally, cooking requires nearly isothermal heat supply. Therefore, latent heat storage using phase change materials (PCM) are ideal candidate in this regard. Although PCM materials are good solar energy batteries, their charging-discharging process is difficult due to their poor thermal conductivity nature. This paper, deals with charging-discharging of nitrate based thermal storage (mixture of 60% $NaNO_3$ and 40% KNO_3). This mixture has two phase change points, a solid-solid phase change at 110^{o}C and a solid-liquid phase change at 222^{o}C. The material absorbs solar thermal to undergo these phase changes and release the heat in the reverse process during the application. The liquid-solid phase change state gives nearly isothermal heat supply suitable for cooking.

Phase change materials are good potentials to store solar energy, however, their charging-discharging techniques are premature for large-scale usage. Since recently many researches are undergoing on thermal properties of PCMs, heat transfer enhancement and design configurations of the heat storage for various end uses [3]. Cooking is one of the common applications particularly in developing countries, where it took the lion share of households energy share. Although many developing countries are found in the solar belt, there are only few solar cookers introduced in this region. The adoption and extension of solar cookers depends on its affordability, cooking speed, versatility, safety and cooking period. Although PCM materials have the potential to improve the utilization of solar energy, its technological status is at concept development and research level [4]. Some solar cookers with PCM storage enable cooking of family lunch while charging the storage and the stored heat has abled to cook dinner and the next day breakfast [5]. For example, many direct and indirect solar cookers with heat storage are installed in India and some African countries for family and community purpose [6]. Nitrate salts are suitable for high temperature isothermal applications. However, they have low thermal conductivity like other PCMs, which affects their charging-discharging process. For example, DLR test showed its usage for solar thermal power plants and process industry in the range of 2 to 100 kW at a melting temperature of 142°C and 222°C [7].

Some studies mainly focused on thermo physical properties of potential PCMs for high temperature latent heat storage [8]. Thermal reliability and stability of PCMs are the two most important factors to assure their latent heat storage. Manish and Jyotirmay have identified some of the most reliable PCMs for particular applications [9]. The solar salt PCM has a density of 1800 and 1700 kg/m^3 in its solid and liquid state, respectively. This density difference raises safety concerns and system challenge on how the storage charging-discharging technique was followed. Researchers by the Norwegian Science and Technology University (NTNU) have applied three different techniques to charge and discharge this PCM. While Foong used direct illumination of storage using double reflector collector, Maxim and Asfafaw used indirect charging by immersing the salt container in a hot oil bath and an aluminium block with salt cavities and steam channels, respectively [10-12]. These researches were focused to realize the use of stored solar energy for baking Ethiopia’s Injera. Besides, the later author has able to bake Injera in a steam based solar stove [13]. Although, the literature shows that Injera baking is possible in the temperature range of 180 - 220°C [14], Asfafaw et al. [12] have shown Injera baking is possible in the range of 130 - 150°C. The charging time of PCMs can be improved by the thermal performance enhancement of solar collectors [15]. In addition, when a PCM is charged by using (heat transfer fluid) HTF, the inlet temperature of the HTF has greater influence over its mass flow rate in reducing the charging time [16].

The interest of this paper lies on the design and experimentation of PCM storage capable of storing 4-5 kWh thermal energy when fully charged (up to 250°C) by a side charging and top discharging technique. The outcome of this study will be implemented for solar thermal application using fixed focus offset parabolic dish concentrators. This charging technique will realize and simplify thermal system designs required for high temperature purpose.

.

2. Methodology and materials

Both theoretical and experimental methods are used to investigate the charging-discharging of the PCM Storage. The experiment is conducted in Mekelle University, Ethiopia. The geographical coordinate of the experimental location is 13°28.694' N latitude and 39°29.244' E longitude with 2,208 m above sea level [1, 2, 17]. ANSYS is used for the numerical analysis. In the experiment, about twelve K-type thermocouples are used to record continuous charging-discharging temperature of the storage at different positions as shown in figure 1 and 2.

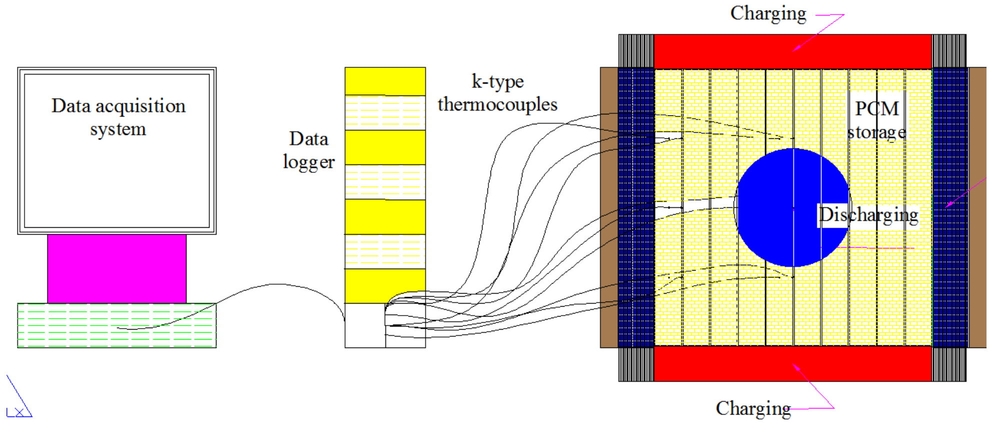

Figure 1. Schematic drawing of the system set up.

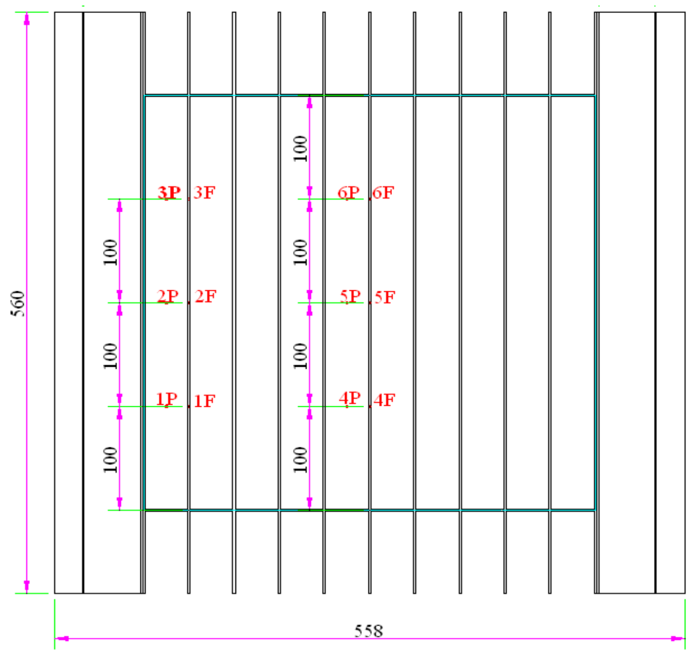

Figure 2. Position of thermocouples.

The storage has symmetric feature on which the thermocouples are connected to twelve points. Six of them were attached to the PCM and the remaining six attached to the fins. Heat was supplied to both sides of the storage and the extruded fins conduct this heat to the PCM. The temperature development inside the storage was sensed by the thermocouples and continuously recorded every second using National Instrument's data logger and Lab view software. Lab view gives continuous digital data and their graphical representation that help to understand how the charging-discharging process is undergoing. The simulated heat used in this study was obtained from charcoal.

3. System modeling

3.1. Theoretical modelling

Generally, heat flows from a high temperature zone towards a lower temperature zone. In the current analysis, only conduction and radiation heat transfers are considered. The conduction and radiation heats can be calculated by using Fourier's law and Stefan–Boltzmann law as given in equation (1) and (2)

$$q=-kA\ dt/ \tag{1}$$

$$q=\varepsilon\sigma A(T_s^4-T^4) \tag{2}$$

where q is the net rate of thermal energy, A is the radiating area, σ is the Stefan-Boltzmann constant (σ = 5.67x10-8 W/m^{2}K^4), ε is the emissivity coefficient, T_s is surface temperature and T is the temperature of the surrounding.

The rule of conservation of energy is used to model the physical problem and analysing the heat transfer problems

$$E_{in} - E_{out} + E_{gen} = E_{stored} \tag{3}$$

where, E_{in} and E_{out} represent the amount of energy crossing into and out of the surfaces of a system, E_{gen}, represents the rate of the conversion of energy from electrical, E_{stored} is the energy stored.

3.2. Fin design

The fins in the current study are made from aluminium sheet of 2 mm thickness with extruded features. Consecutive fins have a gap of 38 mm, which is be filled by the PCM material. Figure 3 shows the arrangement of the fins.

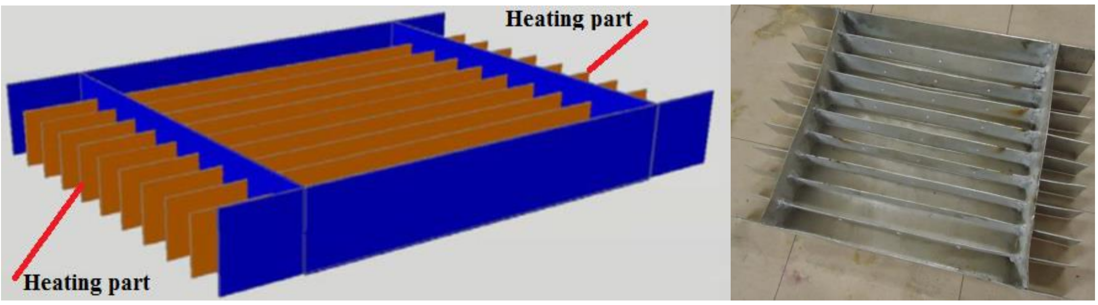

Figure 3. Aluminium fins inserted and welded to the storage.

3.3. Quantifying the amount of PCM

The PCM's melting temperature is 222°C and it has 108 kJ/kg heat of fusion. The amount of PCM is determined based on the average household energy requirement to bake one time Injera need (about 25 Injeras). The heat required to bake a single Injera is 239.5 kJ [18]. Assuming the efficiency of the storage to be 33.8%, then the amount of energy needed is 17,714.5 kJ and then the mass of PCM is found 17.5 kg from equation (4).

$$Q=\int_{T_i}^{T_f} mC_p \mathrm{dT} \tag{4}$$

where m is the mass of PCM, dT is the temperature difference,

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

3.4. Modelling

The thermal behaviour of the system is simulated using ANSYS by formulating the linear thermal conduction problem using an element of plane 55 with temperature as a single degree of freedom variable at each node in the mesh and with the material properties model expressed deeply with temperature change to solve the nonlinear solution. Since transient thermal analysis uses the same elements as of the steady state thermal analysis. The nonlinear transient thermal analysis of the storage is simulated using ANSYS calculating the phase changing properties in two ways; the first one is by assigning the specific heat of the PCM at different temperatures and the second one is by giving enthalpy change through time. The phase changing properties of the solar salt is predicted by assigning specific heat of PCM versus temperature. The energy stored or released during phase change is considered by defining the enthalpy of the material as a function of temperature. Thermal conductivity, specific heat and density must be specified in thermal transient analysis. These inputs can be constant or temperature dependent. The material properties of each component are provided in the data base at different temperatures to make the analysis more accurate and are assigned from the database to the corresponding drawing of materials in the model. This transient analysis is arranged to give output with time steps until the steady state so that it can easily be compared with experimental values. The initial temperature of the PCM was assumed as 288 K for the transient analysis and heat begins to flow into the storage as soon as charging starts and after a period of time the temperature distribution throughout the PCM becomes steady. The element used in this analysis is Plane55 as shown in figure 4, an element description for a 2-D steady state or transient thermal analysis including phase change as shown in figure 4 and figure 5. The element can be used as a plane or ring element with a single degree of freedom, temperature at each node.

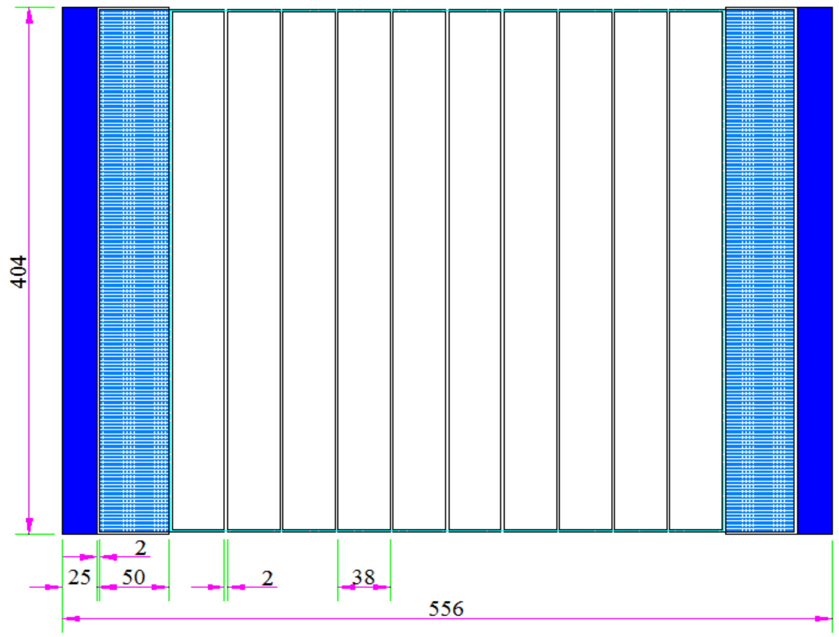

Figure 4. 2-D modeling for ANSYS charging analysis.

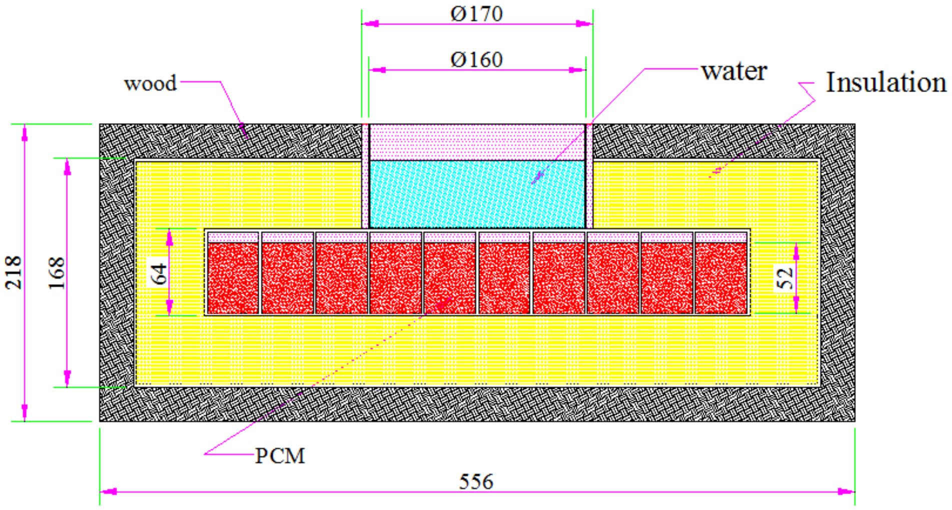

Figure 5. 2-D model for ANSYS discharging analysis.

4. Result and discussions

4.1. ANSYS results

Figure 6 shows the temperature development of the PCM during charging at a constant input temperature of 350°C. An optimized spacing between the fins gives best time in conserving the stored energy and helps to completely melt the PCM by fixing the charging temperature and time.

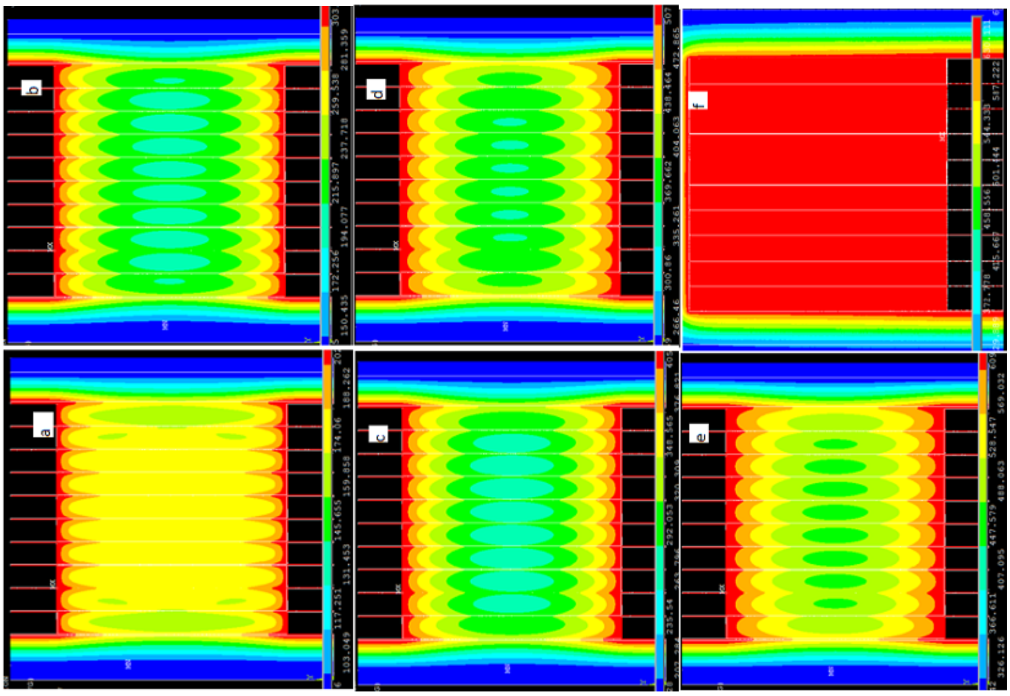

Figure 6. Results of ANSYS temperature contour during fin spacing design, (a) temperature contours at 2 hours of charging, (b) at 3 hours, (c) at 4 hours, (d) at 5 hours, (e) at 6 hours and (f) at steady state position.

The ANSYS result shows side charging is possible for solar collectors that can give an average temperature of 350°C at their receiver or charging sides of the storage for a consecutive eight hours. For less than 350°C input temperature to the storage charging side either it should get for more than 8 hours or there will not happen complete melting of the PCM. Optimizing the gap among the heat exchanger fins give the storage maximum efficiency by charging fully at the available time of solar energy and store for the whole night. If the gap is reduced to less than 40 mm the storage will be able to fully charged soon but the heat loss from the storage will increase due to high thermal conductivity of aluminium fins. During charging, it is expected to gain slightly higher temperature in the fins than the PCM. The PCM has zero slopes at about 110°C and 222°C where a solid-solid and solid-liquid phase change happens. Figure 7 shows results of ANSYS simulations while the storage is charging.

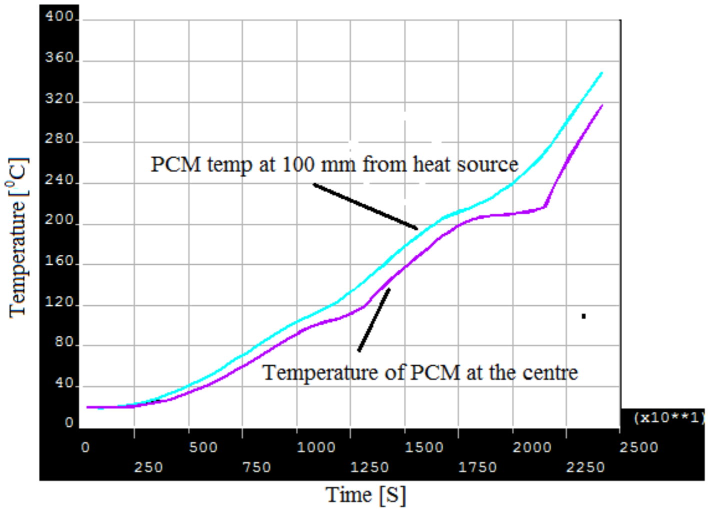

Figure 7. Temperature trend of PCM at the centre of the storage and 100 mm from the heat source.

Discharging of the stored heat is made using two cooking pots, which are aluminium and stainless steel pots. When the aluminium pot took 3,381 seconds to boil water to the temperature of 82.6°C, the stainless steel pot took 40,891 seconds to reach water temperature of 81.3°C. This difference happened due to the thermal conductivity of aluminium which is approximately 20 times greater than stainless steel. Figures 8 and 9 show the ANSYS simulation of water boiling on the two pots.

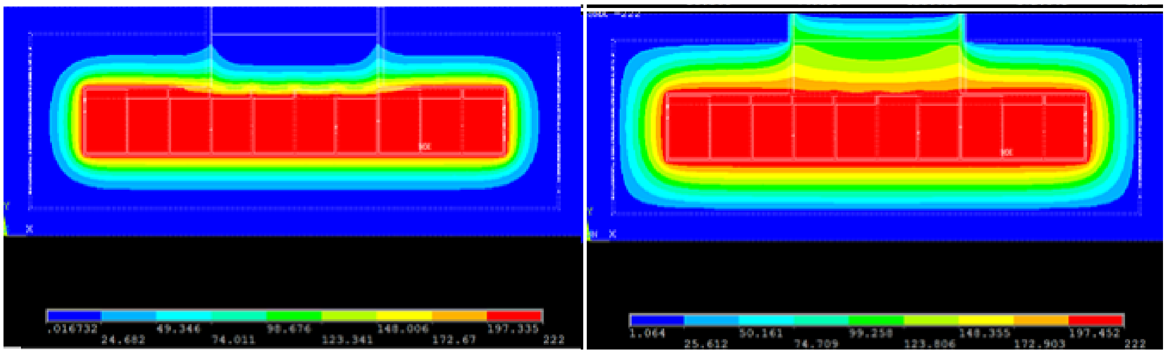

Figure 8. Temperature contour of water boiling using stainless steel pot, (a) at 300 seconds and (b) at 7200 seconds.

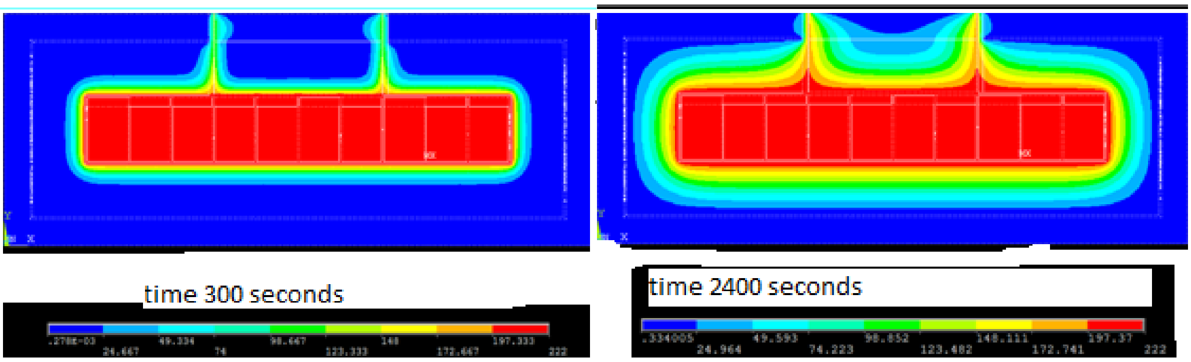

Figure 9. Temperature contour of water boiling using Aluminium pot, (a) at 300 seconds and (b) at 2400 seconds.

4.2. Experimental results

The experiment is carried out having 7 and 10.5 kg of KNO_3 and $NaNO_3$, respectively. The storage is a rectangular box with 400 mm length, 400 mm width and 60 mm height. The box has an allowance for expanding the PCM during melting. The storage can be considered as symmetric and representative temperature distribution can be taken from the first from left or right side and fifth fins at a distance of 100 mm from the charging side and 100 mm among the thermocouples. The thermocouples read temperatures of the fin and PCM. In order to prime a complete mixing of the two salt mixtures, the melting was performed using a digital electric furnace. After melting and mixing of the two salts pouring to the storage container is performed as shown in figure 10.

The temperature variation of the storage during charging is given in figure 11 and 12. The readings of 1F and 3F, 1P and 3P, 6P and 4P, and 4F and 6F, as given in figure 2, are expected to show the same temperature profile. In the ANSYS analysis, the same temperature contour is observed for these pairs. However, the temperature distribution of the heat source in the experimental investigation is not uniform. During ANSYS analysis a very small amount of temperature deviation is plotted between 1F and 4F, 1P and 4P, 3P and 6P, and 3F and 6F; even though these pairs are at the same distance from the heat source and are reading of the same material the slight difference comes due to the effect of insulation material.

Figure 10. PCMs melted and pouring.

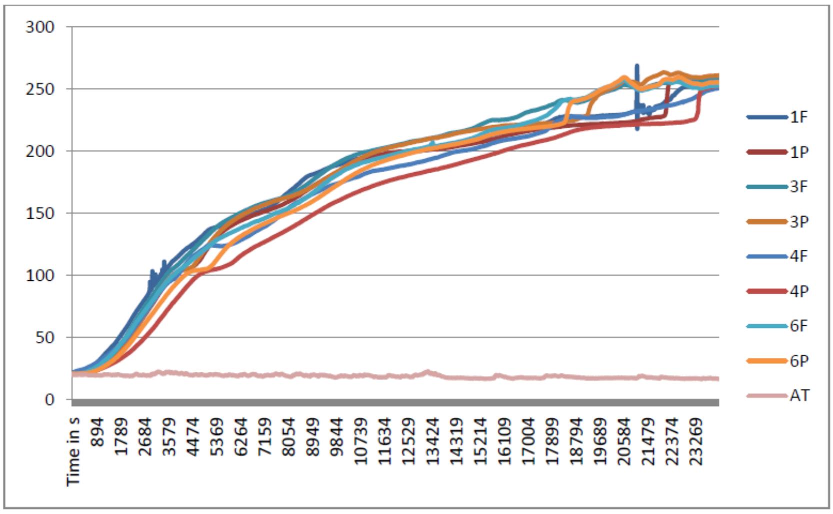

Figure 11. Charging temperature distribution 100 mm from the heat source.

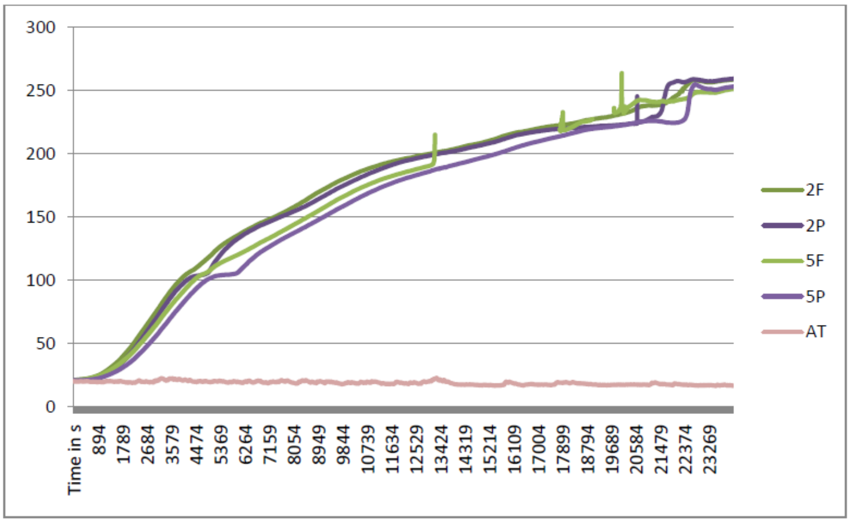

Figure 12. Temperature distributions at the centre of the storage during charging at a heat source of 490°C.

In the experimental study, the solid-solid phase transition temperature has happened in the range of 104 to 109°C and solid-liquid phase transition in the range of 217 to 228°C. The temperature variation from 228°C onward shows a sharp increase in its temperature. The maximum difference in temperature reading between the average readings of fins and PCM at 100 mm from heat source is 15°C and the average difference is calculated to be 7°C. Similarly, the maximum difference in average temperature reading between the fins and PCM at the centre or 200 mm away from charging side is 14°C and the average difference is calculated to be 5°C. The difference between average readings registered at PCM 100 mm away from heat source, PCM at the centre is 6°C, and the maximum temperature difference recorded is 11°C. On the other hand, the difference in the average reading between fins at 100 mm away from heat source and fins at the centre registered a maximum temperature of 17°C and the average difference is calculated to be 7°C. In all charging process the temperature of fins is greater than the PCM at the same position from the charging side.

4.3. Discharging tests

During charging, there is a considerable temperature variation throughout the storage until the phase transition is completed. After this state, the temperature increases almost at the same rate in all nodes. During discharging the storage temperature decreases at constant rate and at very small difference between fin and PCM temperature. Figure 13 shows a uniform declination of the storage temperature. The temperature of water initially has increased but at about 32,123 seconds and 32,905 seconds, the cover of the pot is opened twice and it started to maintain a constant temperature. At 39,730 seconds, the water is replaced by cold tab water and at 45,665 seconds, the temperature raised to 82.94°C. The thermal degradation of the container is less than 10°C per hour. The storage is tested for thermal degradation without load and a temperature of 85-95°C is recorded after 12 hours of disconnection from heat source. Heat loss is directly proportional to the external surface area of the storage. Better heat conservation is expected if it is made in full size as the surface area to volume ratio decreases. If the storage is fully charged during day time, its temperature in the next early morning will be about 90°C which makes the storage applicable for the whole night. The thermal efficiency of the system from the experimental work is also calculated to be 41.62%.

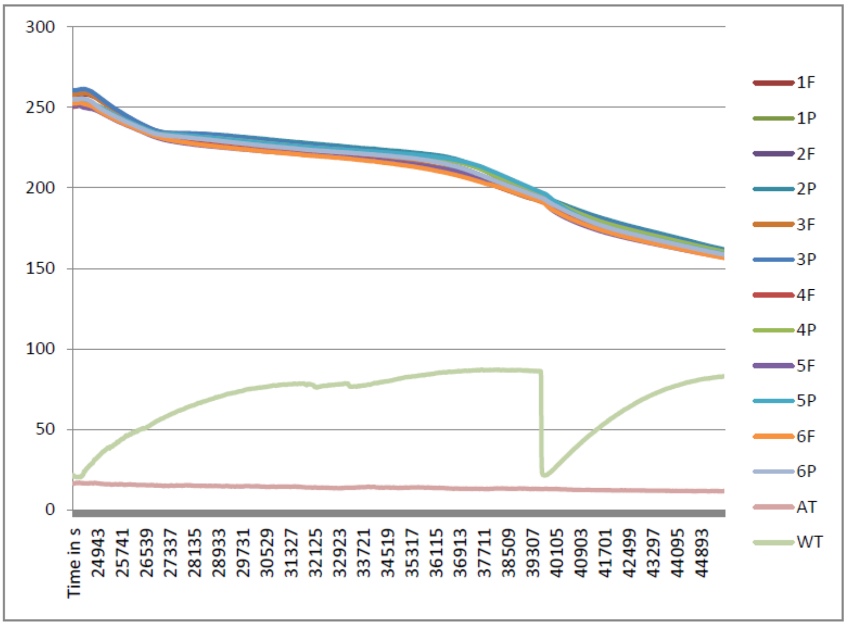

Figure 13. Discharge temperature distributions of the storage during water boiling.

5. Conclusions

In the current study, a solar-salt with a chemical composition of 60% $NaNO_3$ and 40% KNO_3 is used to store solar thermal energy. The PCM melts at 222°C, which is suitable for cooking and baking applications. The charging and discharging process is investigated experimentally and numerically. Twelve K-type thermocouples were used to record continuous charging-discharging temperature of the storage at different positions. Six of them were attached to the PCM and the remaining six attached to the fins as the storage has symmetric features. The PCM charging time depends on the level of input steady heat supply (input temperature), when the input temperature changes from 350 to 490ºC the charging time has reduced dramatically. The charging time difference observed in this study comes from the different natures of heat supply. The heat supply in the numerical work considers an ideal steady heat input, however, the charcoal heat was difficult to regulate. The practicality of side charging has many advantages to utilize solar energy efficiently. Hence, combination of this design concept with offset parabola will give side charging and top discharging simultaneously, which is an ideal feature for cooking and baking applications.

Acknowledgments

The authors would like to acknowledge the support from Mekelle University, Department of Energy and Process Engineering and Norwegian University of Science and Technology (NTNU).

References

[1] Mahmud A M, Kahsay M B, Hailesilasie A, Hagos F Y, Gebray P, Kelele H K, et al. 2014 *Energy Procedia* **57** 1266-74
[2] Mahmud A M, Kahsay M B, Hailesilasie A, Hagos F Y, Gebray P, Kelele H K, et al. Solar Potential in Geba Catchment. International Congress: Livelihood 2013; Mekelle, Ethiopia2013.
[3] Kenisarin M, Mahkamov K 2007 *Renewable and Sustainable Energy Reviews* **11** 1913-65
[4] Muthusivagami R, Velraj R, Sethumadhavan R 2010 *Renewable and Sustainable Energy Reviews* **14** 691-701

[5] Lecuona A, Nogueira J-I, Ventas R, Legrand M 2013 *Applied Energy* **111** 1136-46
[6] Schwarzer K, Da Silva M E V 2003 *Solar Energy* **75** 35-41
[7] Laing D, Bauer T, Steinmann W, Lehmann D, Advanced High Temperature Latent Heat Storage System—Design and Test Results. Proceedings of the 11th International Conference on Thermal Energy Storage—Effstock; 2009.
[8] Cárdenas B, León N 2013 *Renewable and Sustainable Energy Reviews* **27** 724-37
[9] Rathod M K, Banerjee J 2013 *Renewable and Sustainable Energy Reviews* **18** 246-58
[10] Foong C W, Nydal O J, Løvseth J 2011 *Applied Thermal Engineering* **31** 1807-15
[11] Mussard M, Nydal O J 2013 *Solar Energy* **95** 144-54
[12] Tesfay A H, Kahsay M B, Nydal O J 2014 *Energy Procedia* **57** 1603-12
[13] Tesfay A H, Kahsay M B, Nydal O J 2014 *Energy Procedia* **57** 2946-55
[14] Hassen A A, Amibe D A
[15] Sharma S, Iwata T, Kitano H, Sagara K 2005 *Solar Energy* **78** 416-26
[16] Al-Abidi A A, Mat S, Sopian K, Sulaiman M, Mohammad A T 2014 *Energy and Buildings* **68** 33-41
[17] Kahsay M B, Mahmud A M, Hagos F Y, Kiros H, Tesfay A H, Gebray P, et al. 2013 *Wind Engineering* **37** 333-46
[18] Gebregziabher A. Gasification based Injera baking stove. Mekelle University: Mekelle University; 2012.