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Research Article

Characterization and Experimental Investigation of $NaNO_3 : KNO_3$ as Solar Thermal Energy Storage for Potential Cooking Application

Elias Wagari Gabisa and Abdulkadir Aman

Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia

Correspondence should be addressed to Elias Wagari Gabisa; eliaswa@bdu.edu.et

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Household cooking is a major energy intensive activity in most of the Ethiopian households. Replacing the existing inefficient cooking stoves and the polluting energy source with a renewable source of energy plays a paramount role in conserving the environment and reducing the indoor pollution. In this study an energy storage phase change material is proposed to store solar thermal energy for a potential household cooking application. The selected phase change material has a melting point range which is well fitted to the operating range of temperatures for most of the household cooking activities. The solar energy source is simulated with electrical heating for experimental investigation of the thermal characteristics. Also it is intended to study the thermal characteristics of the mixture using deferential scanning calorimeter to identify at which mass ratio the mixture shows better thermal characteristics. From the laboratory analysis it is found that the 60% $NaNO_3$ and 40% KNO_3 by mass have shown promising thermal characteristics. For applying the selected salt mixture for cooking application, an experiment was conducted on two Ethiopian local meals, shiro wet and potato meal, to know how much energy is required to cook them and what amount of the PCM is required to store the required energy. The result reveals that 2.38 kWh energy is required for cooking the two meals for five family members for lunch and dinner. To store the energy required 4 kg of the PCM was required. Experiments were conducted to see the charging and discharging time of 60% $NaNO_3$ and 40% KNO_3 by mass. From the experimental result for 1.4 kg of the PCM, charging time of 50 minutes up to 300°C and a discharging time of 4.5 hours (from 300°C to 100°C) are required.

1. Introduction

Energy storage systems have an enormous potential to increase the effectiveness of energy conversion equipment use. Thermal energy storage (TES) deals with the storage of energy by cooling, heating, melting, solidifying, or vaporizing a material; the energy becomes available when the process is reversed. Solar thermal energy can be stored by elevating or lowering the temperature of the substance (sensible heat storage), by changing the phase of the substance (latent heat storage), or through combination of the two. In this study the thermal characteristics of sodium nitrate and potassium nitrate mixture as a phase change material with a different mass ratio are going to be investigated to know at which mass ratio the best thermal characteristics will be found. In order to know the solar thermal energy requirement experiment was conducted on two local meals, shiro wet and potato wet, and experiment was conducted at laboratory level to determine the charging and discharging time of the phase change material.

As it is known worldwide energy demand and supply mismatch are greater problem, especially in developing countries like Ethiopia, which have solar thermal energy for about 13 months. But to fulfill the mismatch between demand supplies in such countries they are using wood energy for cooking and baking, which has an adverse effect on health of the society especially Women.

And this encourages deforestation highly. In order to alleviate such a problem it is important to develop technologies which utilize a renewable energy as source of energy. Solar cook stove which has a storage media in it is one example of such technology. However, solar energy is available during day time and the demand for cooking in those countries is during off shine time [1] during which the sunshine availability is very law.

According to Ethiopian Rural Development and Promotion Center (2006) 77% of total energy consumption is covered by fire wood and charcoal and the other 15% is from agricultural residue, and the other 6% was met by modern electricity and kerosene [2]. Foong et al. (2011) have developed a solar box cooker by using stearic acid and magnesium nitrate hexahydrate as a phase change material for storing Energy. They have conducted an experiment to evaluate the thermal performance of the developed solar cooker for its charging and discharging time. Finally they come up with the fact that the cooker has an efficiency of 82% and maximum temperature within the cooker was ranging from 78 to 84°C [3]. Zhang and Fang (2006) used a mixture of nitrate salts as thermal energy storage material. The nitrate salts are sodium nitrate and potassium nitrate with 60 : 40 mole percent ratio; they have conducted the thermal behavior of the salts by using differential scanning calorimeter (DSC) [4]. Having the above and other related studies, in this study studying the thermal characteristics of $NaNO_3 : KNO_3$ mixture is intended which is not clearly addressed with scholars for different mass ratios, so that different scholars my pick one which is important for their application. The DSC method which is employed here is the world standard to investigate phase transition of phase change materials (PCM) and also to determine their thermal characteristics. The method followed during experimental investigation of thermal energy requirement was designed locally as well as for the charging and discharging time determination.

The obtained result shows that it is possible to use the PCM for high temperature cooking application and it is better to use the 60 : 40 mass ratio since it has promising thermal characteristics. The thermal stability of the PCM with a required range (200–300) of temperature is also very promising.

There are large numbers of phase change materials that melt and solidify at a wide range of temperatures, making them attractive in a number of applications. Paraffin waxes are cheap and have moderate thermal energy storage density but low thermal conductivity and, hence, require large surface area. Hydrated salts have larger energy storage density and higher thermal conductivity but experience super cooling and phase segregation, and, hence, their application requires the use of some nucleating and thickening agents. The main advantages of PCM encapsulation are providing large heat transfer area, reduction of the PCMs reactivity towards the outside environment, and controlling the changes in volume of the storage materials as phase change occurs [4].

TES systems have also been suggested for storing thermal energy at medium (38–304°C) and high temperatures (120–566°C). For instance, systems in an oil-rock system for hot water and heat-recovery applications are examples of medium-temperature applications, while those in molten nitrate salt systems (an excellent storage medium) for steam production for process applications are for high temperatures. Oil-rock TES, in which the energy is stored in a mixture of oil and rock in a tank, is less expensive than molten nitrate salt TES but is limited to low-temperature applications. However, this oil-rock TES has been proven successful for solar thermal applications. The selection of the type of TES depends on various factors such as the storage period (diurnal or seasonal), economic viability, and operating conditions [5].

According to Sulaiman and Inambao [6], based on their studies on development of thermal energy storage and cooker module, they come up with the conclusion that to allow adequate heat flow during rapid cycles of heat charging and discharging the heat transfer coefficient between the thermal medium and PCM needs to be increased.

Tesfay [7] investigates thermal storage wit solar salt experimentally as well as numerically and simulates it in COMSOL. According to Tesfay's study the PCM (solar salt) of 2 kg melts within about 4.5 hours by applying 650 W average power and Tesfay comes up with the possibility of storing thermal energy with solar salt for more than one day since the salt mixture has the melting point in the range of its application, 180–220°C, of Injera baking.

Zhang et al. [8] investigated the thermodynamic evaluation of phase equilibria in $NaNO_3 : KNO_3$ system and came up with the conclusion that the solid solutions in the intermediate phase appeared to be a mixture of the $NaNO_3$ based solid solution and KNO_3 based solid solution depending on the X-ray diffractometry result at 473 K. Finally they understand that solidus behavior indicates that $NaNO_3 : KNO_3$ is better regarded as a system with limited solid solutions rather than as a continuous series of solid solutions.

Greis et al. [9] have conducted a study on phase diagram of the binary system $NaNO_3 : KNO_3$ using DSC. They come up with the result that liquidus curve has its minimum at 494 and 50% mole KNO_3 with a very flat solidus curve.

2. Methods

In this section, the materials used for conducting the characterization of PCM and experimental investigation with the employed methodologies are discussed in detail. For the characterization of the PCM, different standard methods were followed to insure the accuracy of the results. The equipment used to analyze the thermal characteristics of the PCM is differential scanning calorimeter (DSC) which is the method adopted all over the world. Differential scanning calorimeter (DSC) measures the melting point, specific heat capacity, and latent heat of fusion of the PCM. The density of the liquid PCM is determined by the well-known standard method using pycnometer.

Melting point, specific heat capacity, and latent heat of fusion were analyzed by using standard method of ASTM-D4419-90(2005) by using differential scanning calorimeter. The prepared salt mixtures were 12 g : 8 g ($NaNO_3 : KNO_3$), 10 g : 10 g ($NaNO_3 : KNO_3$), 8 g : 12 g ($NaNO_3 : KNO_3$), 4 g : 16 g ($NaNO_3 : KNO_3$), and 16 g : 4 g ($NaNO_3 : KNO_3$). Differential scanning calorimeter (DSC) analysis was performed using PerkinElmer DSC8000 instrument. Heat flow and temperature were recorded in the instrument with an accuracy of 0.01 mW and 0.05°C, respectively, within temperature ranges of 100–500°C. The measurements were made under purified nitrogen atmosphere with a flow rate of $20\,cm^3$/min and at a heating rate of 5°C/min. The mixtures of the salts are taken from the furnace and kept in oven at 30°C to protect them from moisture and then after a day the samples were taken out from the oven and measured on electrical balance of accuracy of 0.0001 g. The already weighed samples are put in the aluminum pans of DSC and closed with the lid for analysis. The lid is crimped by a sample press. The crimped sample pan was immediately put inside the sample chamber of DSC after preparation. In the experimental procedure, a temperature range from 100°C to 500°C was set with a heating rate of 5°C/min followed by a cooling cycle at the same rate. The density of the liquid $NaNO_3 : KNO_3$ mixture was determined using standard method for density and relative density by using pycnometer (ASTM-148-02(2007)).

The experimental investigation for charging and discharging was conducted in the research grade laboratory of Faculty of Chemical and Food Engineering. The PCM used is a laboratory grade solar salt ($NaNO_3 : KNO_3$) which has a purity of 99.9%.

Thermal energy requirement for cooking the two local meals was conducted electrical stove which has a power meter within it and its rating power is 1000 W. A known amount of shiro wet and potato was cooked by the stove; the power consumption is recorded when the wet becomes matured enough sensibly.

The charging and discharging time were conducted experimentally by selected PCM during DSC analysis and putting it in a known volume stainless steel jar and 600 W power is applied from the bottom of the jar and the increase in temperature of the PCM was recorded within 2-minute interval until the PCM reaches slightly above its melting point.

3. Result and Discussion

In this subsection, the detailed description of the results is discussed thoroughly. The results discussed are the characterization of the PCM, which are the melting point, latent heat of fusion, specific heat capacity and the density, the thermal energy requirement for potential cooking application, and modeling of the heat transfer characteristics during charging.

3.1. Characterization of Storage Material. Differential scanning calorimetry (DSC) was used to determine the melting point. A low scanning rate was chosen to record the heat flow curve as function of temperature in order to improve the sensitivity of detection. It helps to pick up any small endothermic peaks and also avoids the thermal resistance between the internal furnace and sample. All the selected systems are composed of alkaline nitrate; all of them have two basic components which are sodium nitrate and potassium nitrate. DSC plots for each ratio were collected for three runs to ensure the reproducibility. Peak temperatures, enthalpy of fusion for melting peaks, and the solid phase transformation temperatures are shown in Figure 1 for deferent ratios of the sample.

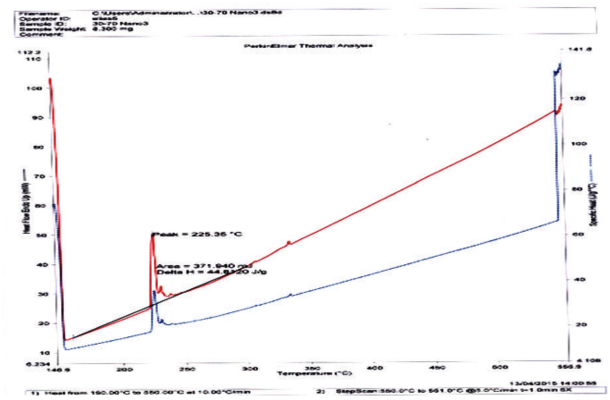

Figure 1: DSC result for sample ratio of 30 : 70.

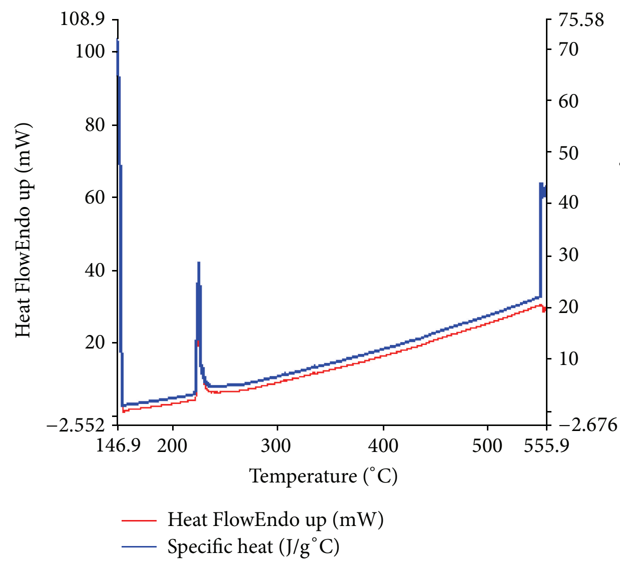

Figure 2: DSC result for sample ratio of 40 : 60.

As indicated in Figure 1, the melting point of 30 : 70 sample ratios by mass is 225.36°C, the enthalpy of fusion is 44.8320 J/g, and specific heat capacity at the solid state (at 200°C) is around 10 J/g°C and above the melting point it increases steeply with temperature. At the melting point the absorbed heat becomes very high and also the specific heat at this point is in order of 40 J/g°C. Even though the melting point of this sample is very promising, the enthalpy of fusion (the latent heat absorbed) is very low. This implies that for storing energy per a given amount of sample it requires larger container.

As indicated in Figure 2, the melting point of 40 : 60 sample ratios by mass is 225.38°C, the enthalpy of fusion is 95.7905 J/g, and specific heat capacity at the solid state (at 200°C) is around 5 J/g°C and above the melting point it increases with temperature. It is about 10 J/g°C in the liquid region at temperature range of 350°C. At the melting point the absorbed heat becomes very high and also the specific heat at this point is in order of 40 J/g°C. Here in this sample the melting point is promising and is in order of required

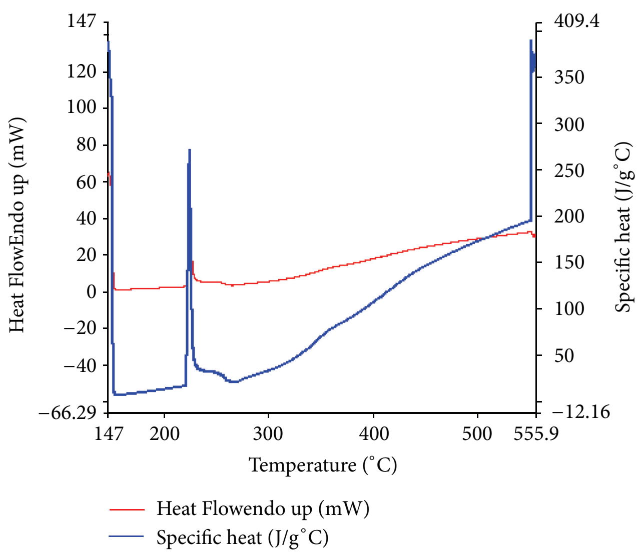

Figure 3: DSC result for sample ratio of 50 : 50.

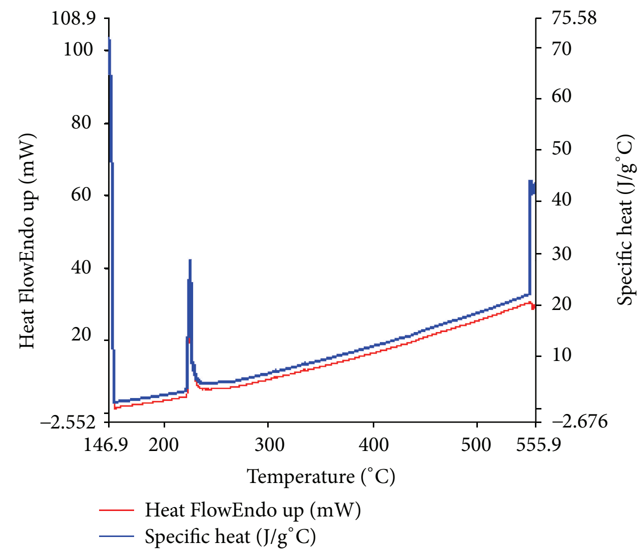

Figure 4: DSC result for sample ratio of 60 : 40.

range. But the absorbed latent heat per a given mass of the sample is not very promising and the additional sensible heat absorbed after the melting point as the temperature increases is relatively low.

Figure 3 shows the DSC results of the 50 : 50 mass ratio samples. This shows that the melting point is still promising and is in the required range for potential cooking application. The melting point is 225.10°C; enthalpy of fusion is 54.9971 J/g and the specific heat capacity in the solid region seems uniform at about 3 J/g°C. In the liquid region it is around 25 J/g°C in the required temperature range of cooking application which is required actually in the liquid region. Having good melting point and specific heat in the liquid region did not guarantee the use of this sample for utilization for the required application. The absorbed energy per a given amount of sample should be in order of 100 J/g and above for consideration as good thermal energy storage.

In Figure 4 it is indicated that the melting point of the sample 60 : 40 ratio is 225.38°C, the heat absorbed per gram of the sample as a latent heat is 120.9100 J/g, and specific heat capacity of the sample in the solid region is around 6 J/g°C. The specific heat increases with the temperature in the liquid region and it is around 10 J/g°C in the required temperature range (200–300°C) for cooking application; it absorbs large amount of energy as the peak value which makes it more preferable and highly promising for thermal energy storage. The area under the peak is the amount of energy absorbed per a given mass of the sample, and it shows that the melting process requires a large amount of energy.

From Figure 5 the DSC result of the 70 : 30 mass ratio samples is shown with two peeks. The first peak indicates the melting point of the mixture, while the second peak shows when the DSC scans the sample and found some pure $NaNO_3$ salt alone. The melting point of the mixture is 224.30°C, enthalpy of fusion is 29.3720 J/g which is lower. The specific

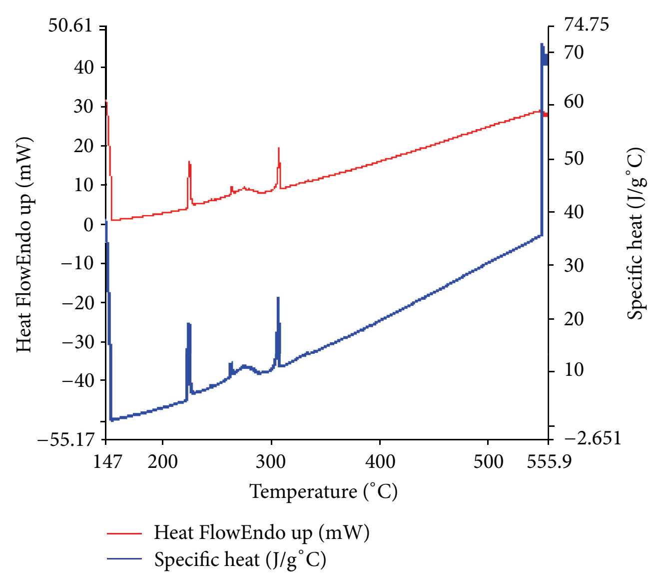

Figure 5: DSC result for sample ratio of 70 : 30.

heat capacity, C_p, in the solid region looks lower, 3 J/g°C, as compared to other samples and it is still lower in the liquid region, 8 J/g°C.

3.2. Charging and Discharging Time Determination. The temperature distribution in the stainless steel PCM container jar is recorded during charging and discharging process. The increase in the temperature of PCM during charging process and the decrease in temperature of the PCM during discharging process are recorded.

Figure 6 shows the charging process of the PCM. Initially the temperature of the PCM was at 25°C and the thermostat of the stove on which the jar is put is set to 300°C, which is

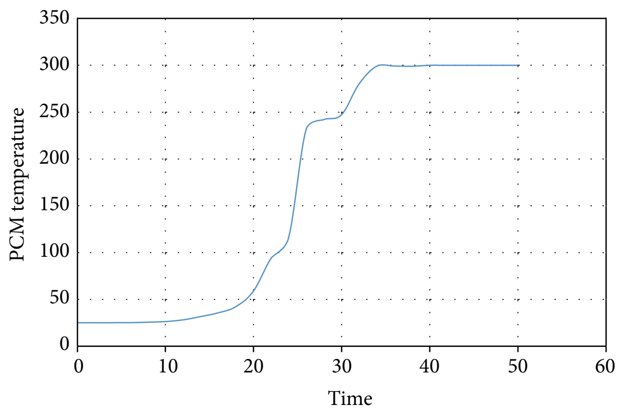

Figure 6: PCM charging process for experimental setup.

the maximum temperature required for cooking application. The charging process is continued until the PCM temperature becomes in order of 300°C, which is about 70°C greater than that of the PCM melting point. The temperature of the PCM at the top of the jar was recorded at interval of two minutes. From Figure 6 it is observed that PCM temperature increases gradually until it reaches its melting point and it increases steeply until it reaches the melting point within 25 minutes and stays there at almost constant temperature for some time since it is a phase change process.

The discharging process was conducted with load application and without load application. 500 mL of tap water was put on the jar containing charged PCM and the decrease in temperature of PCM and the increase in water temperature were recorded with an interval of two minutes when load is applied. Meanwhile for the case with no load application the PCM is taken from the heat source and the bottom part is put on insulator prepared by the size and then the decrease in temperature is recorded by interval of 2 minutes.

The discharging process is continued until the PCM temperature reduces to be in order of 100°C, though it contains high amount of usable energy. Figure 7 shows the variation of load temperature and PCM temperature during discharging process. The load temperature increases gradually, while the PCM temperature decreases. As it is clearly seen in the figure the load starts to absorb the heat rapidly until it becomes above 50°C and starts to decline; this is because there was a gap between the PCM and the load and the heat transfer was by convection in the gap and conducted to the load through the air in the gap rather than pure conduction between the PCM and the load.

Figure 8 shows the variation of PCM temperature without load and with load during discharging process. The PCM temperature decreases gradually and reaches 100°C within 4.53 hrs, while it takes about 4.9 hrs with the case of no load. When the load is applied the PCM temperature starts to decrease to its phase change temperature at about 25 minutes, while in the no load case it starts to decrease to its phase change temperature after 60 minutes. The PCM stays at its phase change temperature for about 100 minutes when there is no load application. Both become decreasing slowly beyond the phase change process to 100°C.

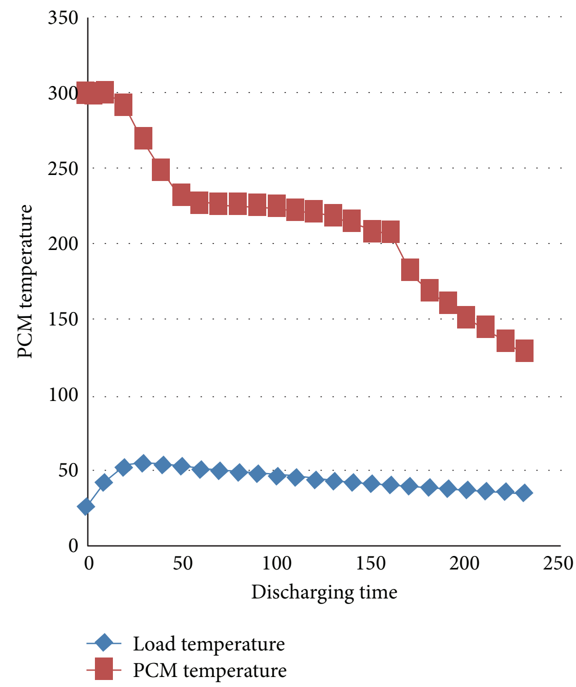

Figure 7: Discharging processes with load.

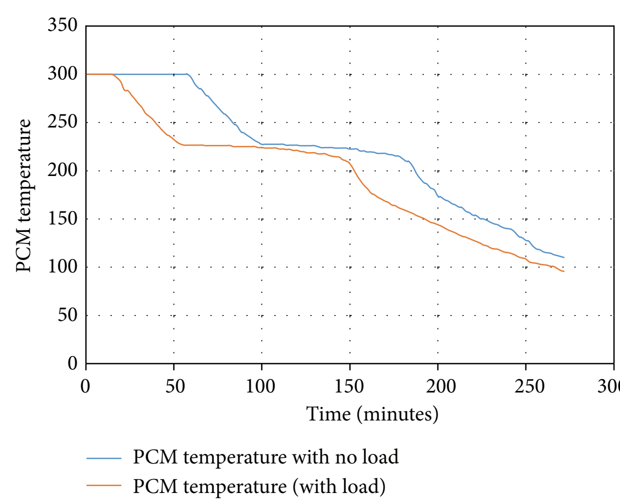

Figure 8: Discharging of the PCM with no load and with load.

4. Conclusion

This paper presents the characteristics of different ratio by mass of the PCM ($NaNO_3 : KNO_3$) mixture and the numerical modeling of the PCM was simulated using ANSYS mechanical APDL 15.0 to see the temperature distribution in the PCM. And the potential energy requirement for potential local cooking application was conducted. Finally experimental investigation was conducted to see the validity of the model. Generally from the whole study we have the following conclusions.

After characterizing the different ratios of the PCM the one which is 60% m/m of $NaNO_3$ and 40% of KNO_3 m/m ratio was selected as promising one which has the thermal characteristics of melting point of 225.38°C, latent heat of fusion of 120.91 J/g, and specific heat capacity of <6 J/g°C in the solid region and >10 J/g°C in liquid region. The thermal characteristic of the PCM shows that there is possibility of using the PCM for a wider high thermal application.

From the experimental analysis of the energy requirement for cooking of two local meals it was found that 2.38 kWh of power is required to cook "shiro wet" and "potato meal" for five family members for lunch and dinner. To store 2.38 kWh of energy 4 kg of PCM and 2.19 liters of PCM container are needed. Having PCM in small volume container will provide a large amount of energy and therefore it is possible to use the PCM for cooking application.

On evaluating the model by experimental work to fully charge the PCM of 1.4 kg consumes about 50 minutes to bring it to 300°C, while it needs about 4.9 hours for discharging to 100°C without any load application and 4.53 hour when 500 liters of water is used as a load. From this experimental result it is concluded that it is possible to use this PCM by charging it with a short period of time as it is also seen in the numerical modeling, and it can be used for a longer time; therefore the model and the experiment reveal the same conclusion of short charging time.

Generally, standing on all conclusions above, the PCM ($NaNO_3 : KNO_3$ 60% m/m : 40% m/m) is the appropriate choice for potential cooking application by storing a cheapest solar thermal energy.

5. Recommendation

Even though different parameters are investigated and analyzed during the study still there are other remaining works to be investigated by different scholars in the area. The observations for further investigation are summarized as follows. Since solar energy is the most available and promising source of thermal energy, it is better to design a system comprising the PCM for solar thermal energy storage system, so that the energy will be available at any time required storing it in such materials.

Industries are using thermal energy for different application in the process. During the time of utilization there is waste thermal energy which can be used for the same process or other processes by storing the energy that is going to be wasted. Here, for industries that are using high temperature thermal energy, recovering the thermal energy waste using $NaNO_3 : KNO_3$ (60 : 40% m/m) is recommended allowing further study for the mechanism of utilization and recovery options in their waste recovery strategy.

The effect of insulation on heat transfer is a very critical thing in order to minimize loss of thermal energy. In the case of such a PCM material it is the case which is very critical and has a very large effect on the efficiency of the designed system. For such matter it is highly recommended to investigate how it affects a storage process and efficiency of a certain designed system during charging and discharging of the PCM.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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