Development of a Thermal Energy Storage for the Integrated Solar Energy Project

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Received 6 May 2009, in revised form 13 April 2010 and accepted 31 May 2010

Large percentages of the South African population have no access to grid power and are located at distances that make provision for such facility uneconomical. Also traditional fuels are under pressure. Most areas in South Africa receive 300 days of sunshine per year. The proposed solar system addresses the needs of such communities. The main objective of the paper is the development of a solar thermal energy storage system utilizing phase change material (PCM). The system allows for sensible heat storage as well as latent heat storage using PCM, which melts at sufficiently high temperatures for cooking a variety of food types. The right choice of a suitable PCM to take advantage of the latent heat absorbed during phase changes is important. The system can overcome the time mismatch between solar availability and demand. The developed prototype modules together as a system could provide the essential domestic power requirements of the target groups. This includes power for cooking and hot water provision. The thermal performance of the system was studied by experiments and selected results showed that the heat storage ratio of the cooker is relatively high and increases proportionately with higher heating power levels through the heat transfer pipe. Also during the phase change process, the heat storage cooker can provide a stable heat discharge rate and meet the demand for indoor thermal comfort to an acceptable extent. A mixture of sodium nitrate and potassium nitrate as latent heat storage offers an advantage compared to other materials, particularly when the cycling temperature is close to the phase change temperature and the phase change can be used quite frequently.

Additional Keywords: Solar cooking, molten salt, sodium nitrate, potassium nitrate

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1. Introduction

The most abundance source of energy to be found on the planet is solar energy. In comparison to other energy sources derived from oil, coal and nuclear reaction, solar energy is much cleaner and also far more abundant. Solar energy is usually harnessed and transferred to thermal energy for the purposes of heating homes and water or to generate electricity. Since the availability of solar energy is dependent on various conditions such as time, weather conditions, latitude, and the fluctuating demand for electricity over long periods, the originally harnessed energy needs to be stored. This energy can be stored as thermal energy or electricity, but thermal energy storage is considered the more economical method[1].

There are diverse forms of renewable energy sources including solar, geothermal, wind, tidal, hydro-electric, and ocean thermal energy conversion. Although some of these examples have been applied successfully in practice, many are contingent on climatic conditions, and more importantly, some are cyclic in nature. In addition to this, the demand for energy is also time-based which means that peoples' need for energy varies from season to season and from day to night. It is this cyclic nature of both the supply and demand for energy that has created the need for energy storage.

By using energy storage the supply and demand curves can be shifted with respect to each other in a given time frame, to allow supply and demand peaks to fall in phase. Alternatively, storage can be used to flatten-out the valleys and peaks which occur in the demand and supply curves, making the matching of the two curves an easier task[2, 3].

Solar thermal energy finds its simplest application in the form of solar cooking, which in itself has enormous potential for reducing dependence on conventional fuels in the domestic sector. The different types of solar cookers developed for cooking are a box type, a concentrator type and an indirect type. The detailed design, test procedures, theory and utility of solar cookers are well developed. An indirect solar cooker uses a fluid to transfer heat from a solar collector to the cooking pots, but it has more advantages than a box type or concentrator cookers because it provides high thermal power and temperatures without tracking and allows cooking in the shade or even in a conventional kitchen[4, 5]. One exception is that cooking of food is not possible in the evening. If storage of solar energy can be provided in a solar cooker, then there is the possibility of cooking food during overcast conditions or in the evening and the storage will increase the utility and reliability of the solar cooker. These attractions led us to study the problem of cooking in the evening or during low intensity solar radiation periods.

The aim of this project was to develop prototype modules, which together as a system provide the essential domestic power requirements of a family remote from the national grid. This includes power for cooking and hot

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water. A new latent heat thermal energy storage with a pipe heat exchanger was designed and manufactured. The performance of the unit under various possible operation modes was investigated experimentally.

2. Proposed Investigation

Detailed studies have been conducted on various solar cookers – however, the majority of those are relevant to the day time when the sun is shining which is not our objective.

The system called 'integrated storage cooker' is shown in figure 1 and figure 2. This system consists of a solar collector and two types of thermal heat storage. The latent heat storage uses phase change materials (PCM) which melts at a sufficiently high temperature for cooking a variety of food types. The proposed heat transfer fluid is either water or Dowtherm A, which is circulated in a hermitically sealed circuit, to transfer the heat to the PCM vessel. By choosing a suitable PCM to take advantage of the latent heat absorbed during the phase change of the material from solid form to liquid form, a large quantity of daytime solar energy can be stored and used later. Heat losses from both the latent heat storage and condenser are captured in the surrounding sensible heat store. The air in this heat store can be used as an economizer for the back-up burner.

The use of a heat storage calorimeter and the physical properties of heat storage materials and the heat transfer characteristics of the design have been examined. Several systems, like an oil heat transfer system, an electric heat storage system and backup liquid petroleum gas burner for the solar cooker have been tested. These systems and units presented demonstrate the methodology for development of our thermal energy storage and cooker model for the solar energy project.

The positioning of thermocouples are designated as Ti, and their radial and longitudinal positions are (r,y) in mm, respectively and in relationship to the heat storage are T1 and T12 (5,55); T2 and T11 (25,140); T3 and T10 (15, 110); T4 and T9 (35,155); T5 and T8 (45,350); T6 and T7 (55,450) as shown in figure 3.

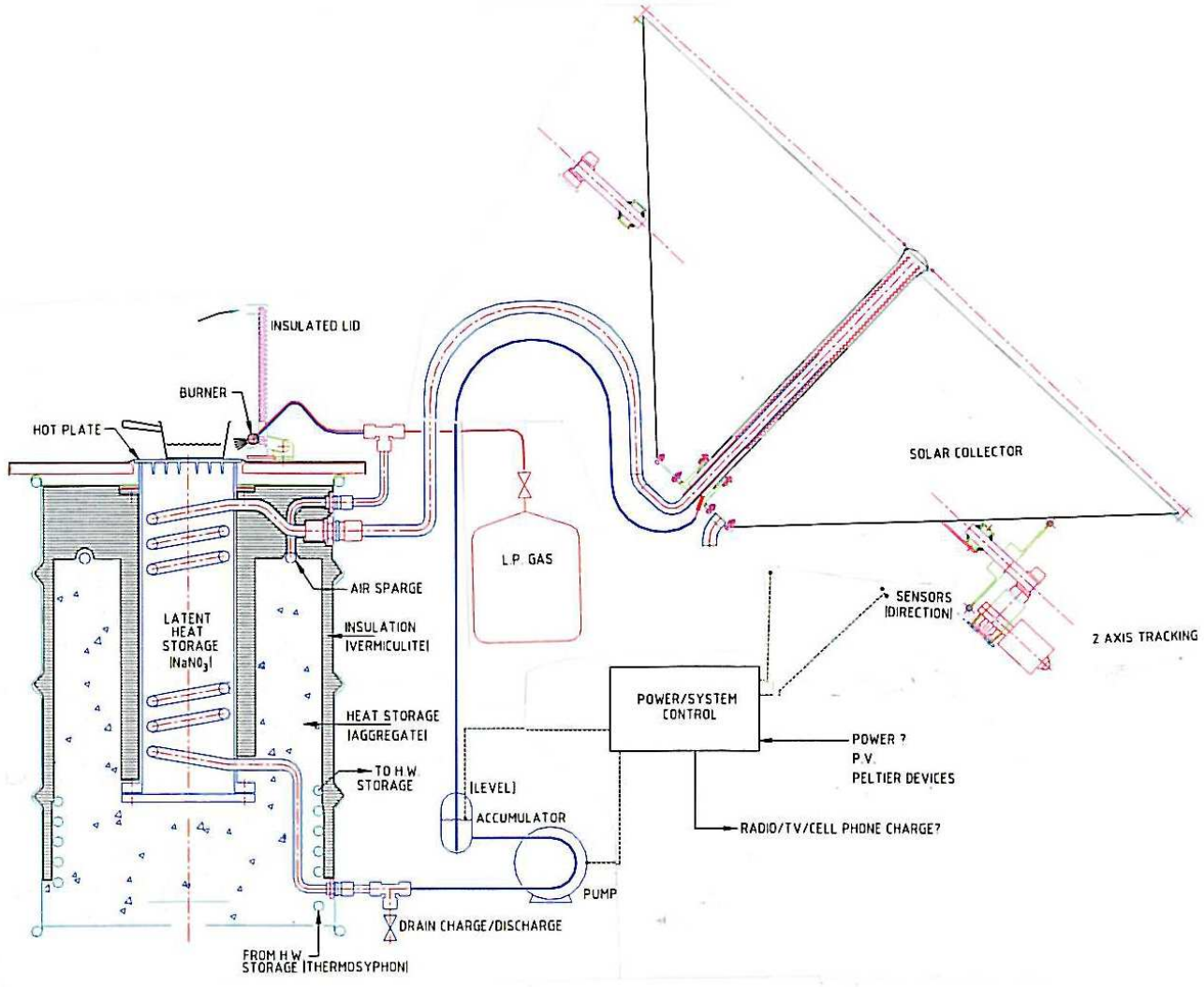

Figure 1: Integrated storage cooker system

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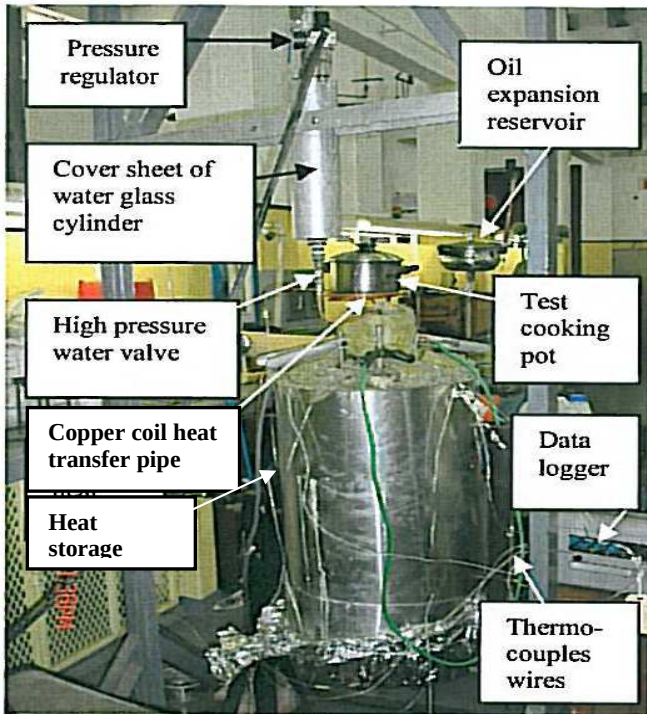


Figure 2: Experimental apparatus

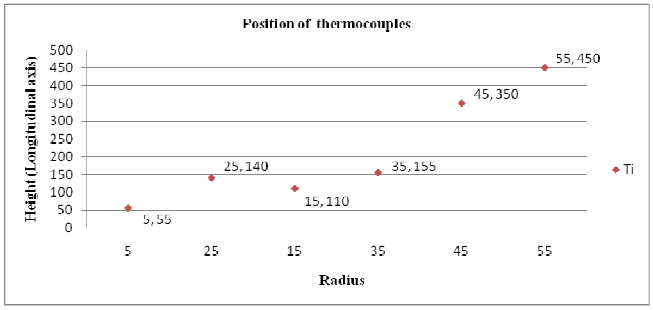


Figure 3: Position of thermocouples

3. Energy Storage Materials Selection

It is essential that the heat store operating temperature be in the region of 200 ºC to 300 ºC in order to provide a suitable heating rate of the food to be cooked. Water is unsuitable as the heat transfer fluid in this range because it vaporizes at 100 ºC at atmospheric pressure, although it has a high specific heat. Pressurizing the system will increase the boiling point but even increasing the pressure to 15 bar will only raise the boiling point to 200 °C. Furthermore, high pressure piping and tanks would be required, which are expensive. Also, the unit could explode showering users with scalding water.

The sensible heat Q gained or lost by a material in changing temperature from T_1 to T_2 is given by:

$$Q = \int_{T_1}^{T_2} mc_p dT = v\int_{T_1}^{T_2} \rho c_p dT \qquad (1)$$

where Q = quantity of heat stored (J); m = mass of heat storage medium (kg); T = temperature (°C); T_1 = initial temperature (°C); T_2 = final temperature (°C); ρ = density of heat storage medium (kg/m^3); c_p = specific heat (J/kg °C); v = volume of heat storage medium (m^3).

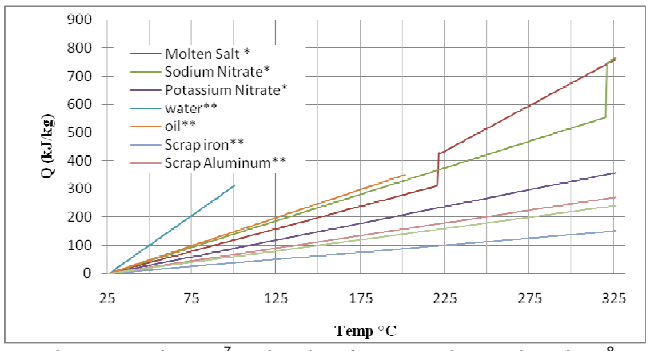
The quantity of heat stored Q in the PCM system is given by:

$$Q = ma_m\Delta h_m + \int_{T}^{T_m} mc_p dT + \int_{T_m}^{T_2} mc_p dT$$

$$= m\left[a_m\Delta h_m + \bar{c}_{pi}(T_m - T_i) + \bar{c}_{pi}(T_2 - T_m)\right] \qquad (2)$$

where Q = quantity of heat stored (J); m = mass of heat storage medium (kg); a_m = fraction melted; Δh_m = heat of fusion per unit mass; T = temperature (°C); T_i = initial temperature (°C); T_m = melting temperature (°C); T_2 = final temperature; c_p= specific heat (isobaric) (J/kg °C); $\bar{c}_{ps}$ = average specific heat between T_i and T_m (J/kg °C); and $\bar{c}_{pi}$ = Average specific heat between T_m and T_2 (J/kg °C).[6]

To draw figure 4, equation 1 was used to calculate the sensible heat storage, and equation 2 to calculate the latent heat storage per unit mass. The heat storage capacity per unit mass and per unit volume for water (20 – 99.9 °C), molten salt (60 % sodium nitrate, 40 % potassium nitrate), sodium nitrate and potassium nitrate, oil, scrap iron, scrap aluminium and rock at temperature from 25 to 325 °C are shown in figure 4. The reference temperature is 25 °C. Because water evaporates over 100 °C at 1 atm pressure, the upper limit for the water temperature is usually less than 100 °C. From the graphs, it is evident that molten salt has the highest heat storage capacity. For the temperature range from 20 °C to 320 °C, the heat storage capacities per unit mass of molten salt is 3.15 that of rock. The types of oil and rocks used were cooking oil and pebbles of 1.5 – 3.5 cm size, respectively.



* Authors' experiments[7] and ** data from experiments by others[8]

Figure 4: Heat storage capacity per unit mass

Although the heat storage capacity of water is significantly higher than molten salt in the range of 0 – 100 °C, water storage at atmospheric pressure is only possible up to 100 °C, and therefore not suitable for temperatures above 100 °C. The heat storage capacity per unit mass of molten salt (20 – 320 °C) is 2.36 times that of water (20 – 99.9 °C). Figure 4 shows until 290 °C there are no changes in phase of sodium nitrate and potassium nitrate.

In order to observe the behaviour of sodium nitrate and potassium nitrate, a sample of 200 g of sodium nitrate and 200 g of potassium nitrate were heated in a kiln. The temperature was increased from 0 °C to a maximum of 290 °C in increments of 1 °C over a period of 2 hours. It was observed that until 290 °C no changes in phase occurred, i.e. both substances stayed in the solid phase. A slight change in colour of potassium nitrate was observed.

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The maximum temperature of the heat transfer fluid reached was 320 °C. But due to heat losses from the system, the operating temperatures ranged from 250 °C to 290 °C. For these reasons a mixture of sodium nitrate and potassium nitrate were used to reduce the melting point to 218 °C when the mixture partially melted. The comparison of the heat storage capacity of molten salt (60 % sodium nitrate and 40 % potassium nitrate), potassium nitrate and sodium nitrate illustrates that the molten salt has a higher heat storage capacity and a lower melting point, at 224 °C. Also, the average heat storage capacity per unit mass of molten salt at temperature range 222 °C to 250 °C is greater than sodium nitrate and potassium nitrate by factors of 1.20 and 1.8 respectively.

4. Results

4.1 Calorimeter results

A typical radial temperature history during a heat storage stage of mixture of 60 % sodium nitrate and 40 % of potassium nitrate versus time is shown in figure 5. Since the system is heated from the shell-side of the heat storage tank, the temperature at the shell side rises rapidly and the phase transition occurs in the temperature range 210 ºC to 250 ºC. As can be seen, the temperature of the melted PCM increases sharply until the radial temperature distribution becomes uniform due to the convection in the liquid after the PCM has melted.

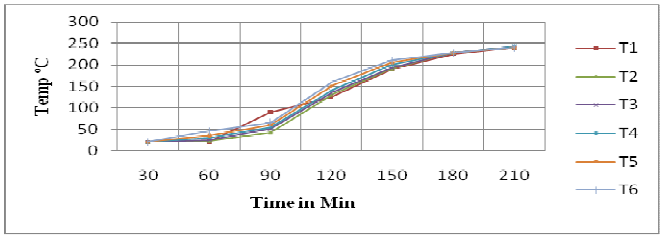

Figure 5: Temperature history during a heat storage stage using molten salt

The system was discharged using air at 1.5 atm as heat transfer fluid an hour after stopping the charging process. A typical temperature history during the heat discharging stage in the radial direction is shown in figure 6. When the system is cooled by air, the temperature is uniformly distributed in the radial direction until the temperatures reach the phase transition temperature 220 – 250 °C. The temperature around the heat transfer pipe decreases linearly with time. However, a distinct phase transition without super cooling across the radius can be found near the heat transfer pipe. Thereafter the temperature drops sharply. The total amount of heat recovery, Q, during the heat release stage can be calculated from equation 2.

4.2 Charging of electric heat storage system

Temperature histories during a heat storage stage of electric heat storage for 2 days at 300 W charging power are illustrated in figure 7. Almost an overlap occurred (T1, T2, T3, and T4) because the system was tested without proper insulation and due to this we can see clearly the gap between the T_t which presents the average temperatures near to the top. The other temperatures are from near the middle of the heat storage tank and T_b represents the average temperature of the heat sensor near the bottom and far from the heating source. Because of the big heat loss the difference in ΔT becomes more pronounced as the charging of the system progresses. When the temperatures in the middle and the top of the heat storage reach melting point, the salt surrounding near the wall of the heat storage tank starts to act as insulation. Note that the graph in figure 7 starts at about 80 °C since we are not interested in the temperature below that, i.e. the warm up temperature.

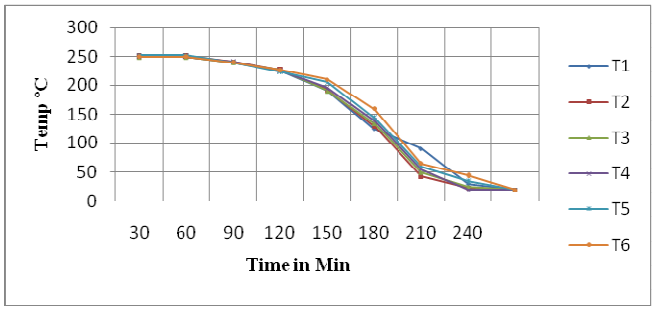

Figure 6: Temperature history during a heat discharge stage using air

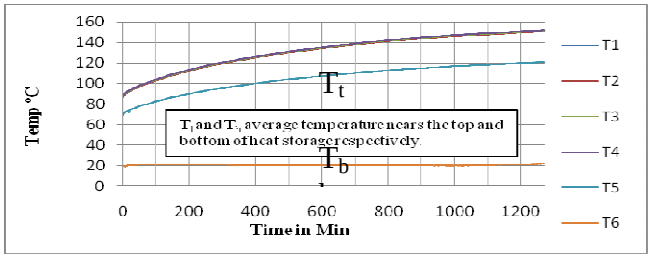

Figure 7: Temperature histories during a heat storage stage using electrical heating

4.3 Discharging of electric heat storage system

Two different methods were used to discharge the heat storage tank. The first was a steam discharging process, and the second was an air discharging process.

4.3.1 Steam discharging unit

One of the methods which we used was dropping water inside the heat transfer pipe after at least 4 hours of full charge of heat storage. 3.2 litres was converted to dry steam at 2.6 bar pressure which can be used for cooking different types of food.

4.3.2 Electric charging unit

Discharging of the electric heat storage system was carried out by pushing air at two bar pressure through the heat transfer pipe inside the heat storage tank.

Figure 8 shows the temperature histories of slow charging of an electric heat storage tank. This was obtained from the data recorded by a data logger and a graph drawn using Microsoft Excel software.

Since the system is heated from inside by a convoluted heat transfer pipe, the temperature on the heating pipe side rises rapidly and the phase transition occurs in the temperature range 210 ºC to 250 ºC. As can be seen, the temperature of the sodium and potassium nitrate salt mixture rises without any phase change until the temperature reaches above 220 ºC and the temperature of

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melted PCM increases sharply until the radial temperature distribution becomes uniform due to the convection in the liquid after the PCM has melted.

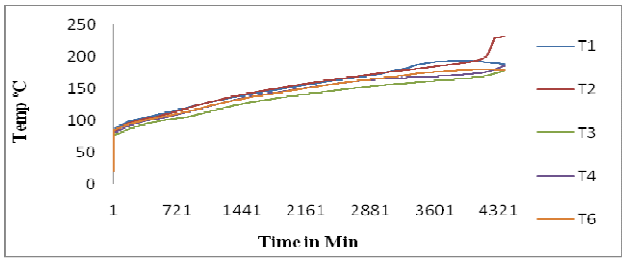

Figure 8: Charging temperature for 3 days at 300 W

4.4 Backup liquid petroleum gas burner for solar cooker

It is assumed that on a bad weather day the maximum hot air temperature available to the thermal storage unit is approximately 150 °C. The amount of heat received from the collector is not sufficient to melt the mixture of sodium nitrate and potassium nitrate. In this case the air temperature has to be constantly monitored. The reason being that the higher the airflow rate the cooler the element becomes.

An added advantage of the solar cooker is that the stovetop in the top of the heat storage tank is at a higher temperature than the ambient air. Because of heat transfer from the heat storage tank, this was assumed to be 100 °C. The initial temperature of the stovetop was therefore set at 100 °C. Tests were also conducted with the stovetop at room temperature to give us directly comparison with a test conducted on a Cadac Handi Stovetop cooker. A Cadac Cooker was used to determine the gas consumption from a normal home use perspective. Results show that at full throttle the Handi Cooker takes approximately seven minutes to bring a litre of water to the boil. This is at a gas flow rate of 227 g/h, using 26 g of LPG.

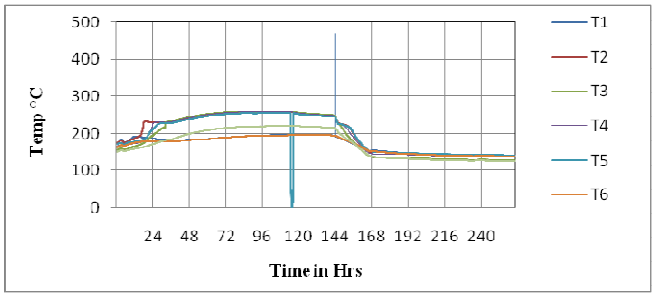

Figure 9: Charging and discharging the system

From figure 9 one can clearly see that during the period from point 24 to point 144, the salt mixture had completely melted; this was also confirmed with the melt check bar which was moving smoothly in all directions. - A stainless steel melt check bar of 8 mm diameter and 700 mm was used for checking the states of the heat storage salts. - The discharging process took place 4 hours after cutting off the power at point 140 till point 168 by dripping water inside the heat transfer pipe which was at 225 ºC to get 3 kW dry steam above 170 ºC.

Figure 10 shows charging and discharging of the oil heat transfer fluid heat storage system during solidification of the mixture of heat storage salts (60 % sodium nitrate and 40 % potassium nitrate).

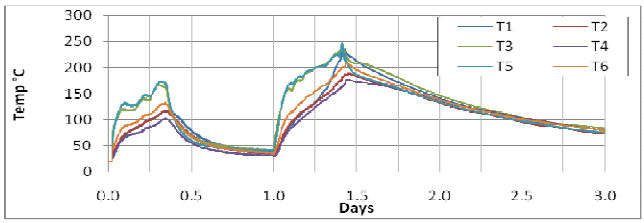

Figure 10: Charging and discharging of the oil system

As can be seen from the heat charging and discharging curves, phase salt temperature T3 and T5 behave similarly, as do T1 and T6 and also T2 and T4. This is due to their radial and longitudinal positions in the heat storage system tank. A fundamental requirement for the charging of the heat storage system is a higher temperature than can be obtained in the course of discharge, since heat transport/flux necessitates a temperature difference. The quality of the heat is dependent on the temperature at which it is available: the higher the temperature, the more diverse the uses to which the heat may be put. For this reason, it is desirable for the temperature level in the course of heat storage discharge to fall as little as possible. The heat transfer pipe temperature T10 after 1.5 days had a maximum value of 160 °C which is a relatively low temperature for transferring heat to the hot plate for cooking purposes. Despite this, it is adequate for heating water but not for cooking some food or frying which requires higher temperatures, and that is why at this stage we have to use the backup LPG system.

In the case of sensible heat storage system, as can be seen from figure 11 the input of heat is associated with gradual heating of the storage material (and vice versa during discharge), whereas latent heat is stored and discharged at the melting temperature of the PCM, e.g. for heat storage salts (above 220 °C). To see the effect of the flow rate and inlet fluid temperature on the outlet fluid temperature distribution, we increased the flow rate to 10 litre/min and the inlet fluid temperature to 310 ºC. This means that the duration of the heat charge decreases with the increasing flow rate or increasing inlet fluid temperature.

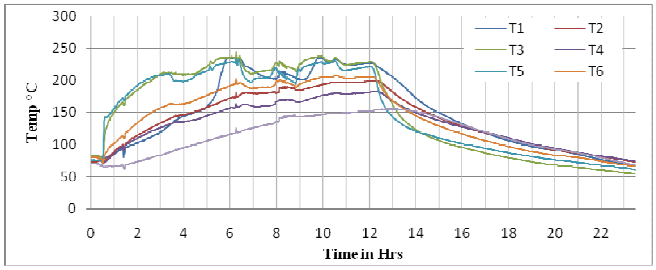

Figure 11: Sensible and latent heat charging and discharging of the system

Figure 12 shows the charging and discharging of the oil heat transfer latent heat storage system which were repeated over 90 times for a period of 3.5 years. From an enormous number of experiments carried out over a long period, it was established that the system was stable.

During charging, the storage outlet temperature is limited by the heat transfer oil maximum operation

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temperature which could be exceeded when heated up in the parabolic trough loop. With the introduction of an expensive synthetic heat transfer oil, capable of increasing the operating temperature from the former 310 ºC up to 400 ºC, the direct storage technology becomes uneconomical. During discharging, the storage outlet temperature is limited by the inlet temperature.

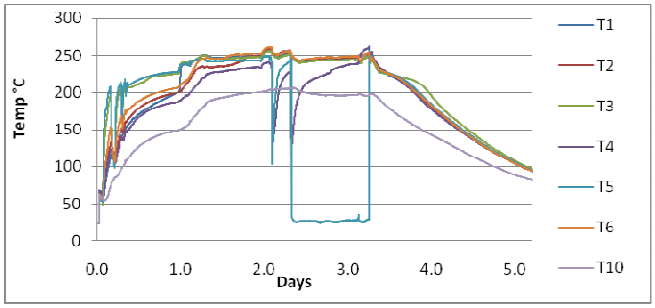

Figure 12: Charging and discharging of the oil system latent heat storage

In this latent heat storage system, the solid-liquid interface moves away from the heat transfer surface during discharging. During this process, the surface heat flux decreases due to the increasing thermal resistance of the growing layer of the solidified medium. In the case of solidification, conduction is the only transport mechanism, and in most cases, it is particularly poor. In the case of melting, natural convection can occur in the molten layer and this generally increases the heat transfer rate compared to the solidification process.

However, the generally low heat transfer rate can be increased considerably by using a suitable heat transfer enhancement technique. There are several methods to enhance the heat transfer in latent heat storage systems. Thus finned pipes with different configurations were used to improve the charge/discharge capacity of the heat storage system in this project. For this heat storage system oil was better as heat transfer fluid. We can cook using heat storage at evening for about 2 h depended on the type of food required to cook. The storage therefore does provide a solution for solar cooking after sunset.

5. Conclusions

The following conclusions were established:

- The results of heat charge/discharge experiments using a vertical heat exchange unit showed that the available enthalpy bounding the phase conversion temperature range was not quantitatively affected by the way the temperature of the thermal medium varied during heat charge and discharge. However, rapid cycles of heat charging and discharging showed big differences in available enthalpy. To allow adequate heat flow during rapid cycles of heat charging and discharging the overall heat transfer coefficient between the thermal medium and PCM needs to be increased.
- A mixture of sodium nitrate and potassium nitrate as latent heat storage offer an advantage compared to other heat stores, when the cycling temperature is close around the phase change temperature and the phase change can be used quite often.

Finally, the work presented in this paper will provide valuable guidance for the design of future thermal energy storage unit and cooking system. The improvements suggested, especially those pertaining to the experimental and analytical model, should lead to greater accuracy and confidence in the design procedure adopted by future designer of thermal energy storage units.

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