

Modeling of Solar Thermal Energy Storage System Using Inorganic Phase Change Materials

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ABSTRACT

The thermal behavior of an energy storage system is investigated theoretically, in which the heat is stored as latent or sensible heat. A heat energy storage unit is charged using a collector to investigate the efficiency of the system. Water is used as the medium of heat transfer from the solar collector to the system and also employed as a working fluid for the sensible heat. Inorganic phase change material (PCM) Sodium thiosulphate is used as latent heat storage material. Mathematical models of various units are developed in the proposed system. The variation in the temperature with the time for the heat storage tank in closed-loop active solar water-heating system are obtained.

Keywords: PCM, Solar energy, Inorganic PCM, Organic PCM, Sensible heat.

NOMENCLATURE

$\dot{m}$ = mass flow rate, kg/s
 $(\rho VC_p)_l$ = heat capacity of water in tank, kJ/K
 $(\rho VC_p)_t$ = heat capacity of tank, kJ/K
 m_p = mass of phase change material, kg
 C_p = specific heat of storage material, kJ/kg.K
 T_l = load/storage unit Temperature, K
 dT = temperature difference, K
 L = latent heat of storage material, kJ/kg.K
 T_a = ambient temperature, K
 T_{co} = collector outlet temperature, K
 T_{ci} = collector inlet temperature, K
 dt = time difference
 $(UA)_c$ = product of overall heat transfer coefficient and the area of heat exchanger coil, W/K
 $m_p C_{ps}$ = sensible heat capacity of PCM in solid state, kJ/K
 $m_p L$ = latent heat capacity of PCM, kJ/K
 $m_p C_{pl}$ = sensible heat capacity of PCM in liquid state, kJ/K
 q_u = rate of useful heat gained from collector, W
 q_{load} = rate energy discharged to load, W

1. INTRODUCTION

In later a long time, as a result of rising vitality fetched and climate alter concerns, there's developing require for wide spread application of sun-based vitality. Sun based energy is one the foremost clever sources of vitality for long-term. One of the reasons for usually that the whole vitality we get each year from the sun is around 35,000 times the whole vitality utilized by man. Be that as it may, almost 1/3 of this vitality is

either ingested by the external climate or reflected back into the space [1-3]. But the irregular nature of sun powered vitality and the vitality necessities require the capacity of warm vitality. The require for capacity for sun powered vitality applications is extreme, particularly when the sun powered accessibility is least. Vitality capacity framework has a colossal potential to extend the viability of vitality change gear utilize and for facilitating large-scale fuel substitutions within the world's economy. The significant benefits of using these systems are reduction in the cost, energy consumption, maintenance cost, size of equipment and pollutants [4-6]. There are different options to store the solar heat energy in the form of sensible, latent or heat of reactions. The nanoparticles also enhance the rate of heat transfer as compared to that of water [7 – 9].

1.1 ENERGY STORAGE

Heat energy from the solar can be stored in the two forms, either by raising the temperature of medium or by phase change process. The former method is termed as energy storage in terms of sensible heat, the temperature of the energy storage medium increases at the time of charging the system, while decreases during the discharging process.

1.1.1 Sensible heat storage

The energy is stored in the tank by supplying the hot water to the tank which rises the temperature of heat storing medium. The amount of heat stored as a sensible heat is a function of the heat capacity of the medium and the temperature potential

$$Q = \int m C_p dT \quad (1)$$

1.1.2 Latent heat storage:

Energy storage in this method is a function of phase transformation, during which heat is absorbed or released. The phase transformation can be from liquid to gas or vice versa. The volume of the latent heat stored in the PCM medium can be estimated by

$$Q = \int_{T_i}^{T_m} m C_p dT + mL + \int_{T_m}^{T_f} m C_p dT \quad (2)$$

1.1.3 Thermo chemical energy storage:

This method depends on the vitality retained and discharged in defiance and transforming atomic bonds in a chemical response. The heat stored in the chemical reactions depends on the product of capacity, the endothermic energy, and the degree of change.

$$Q = a_r m \Delta h_r \quad (3)$$

1.2 PHASE CHANGE MATERIALS

A huge number of materials are accessible in the required temperature range to store the energy. The phase change materials are classified in different categories, as given in figure 1. There are numerous natural and inorganic materials, and can be distinguished as PCM to be employed for the specific range of phase change temperature as well as the required latent of phase transformation.

In any case, but for the dissolving point within the working range, majority of PCMs don't fulfill the criteria required for a satisfactory capacity media (warm, physical, dynamic and chemical properties). The common sense utilize of idle warm capacity is restricted due to low warm conductivity of PCM, variety in thermo-physical properties beneath amplified cycles, stage isolation, sub cooling, incongruent dissolving, volume alter and tall taken a toll [1].

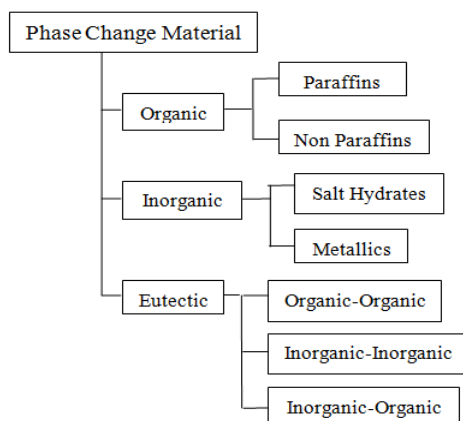


Figure 1:Classifications of PCMs

In common inorganic compounds have nearly twofold volumetric inactive warm capacity (250–400 kg/dm³) than the natural compounds (128–200 kg/dm³) [1]. The hydrates of salt can be used as amalgams of inorganic material and water producing a normal crystalline strong of common equation $AB \cdot nH_2O$. The change in the amount of solid and liquid concentration in the salt hydrates is really a lack of hydration of the combination, in spite of the fact that this prepare takes after melting or solidifying thermodynamically.

Table 1: Different materials used as PCM materials

MATERIAL	MELTING TEMP. °C	LATENT HEAT KJ/kg
$CaCl_2 \cdot 6H_2O$	30	192
$LiNO_3 \cdot 3H_2O$	30	250
$Na_2SO_4 \cdot 10H_2O$	32	250
$Na_2CO_3 \cdot 10H_2O$	35	257
$Na_2HPO_4 \cdot 12H_2O$	35	281
$Ba(OH)_2 \cdot 8H_2O$	48	265
$Na_2SiO_3 \cdot 5H_2O$	48	168
$Na_2HPO_4 \cdot 7H_2O$	48	160
$Na_2S_2O_3 \cdot 5H_2O$	48	210
$K_2HPO_4 \cdot 3H_2O$	48	128
$MgSO_4 \cdot 7H_2O$	49	202

Considering the advantages of Inorganic phase change materials over the other some of the materials have been listed in the required range of temperature of 30-50⁰ C as shown in the table 1. The conditions considered for PCM selection are as follows:

- Temperature of phase transformation in the chosen temperature range
- Phase transformation energy change must be high
- Higher values of thermal conductivity and specific heat
- Change in volume should be small on phase transformation
- Non-toxic, non-flammable and non-explosive material
- Low cost
- Large-scale availability
- Less Literature Available on the selected material

Considering the above points $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ is selected as phase change material for the theoretical modeling of the storage system.

3. SOLAR THERMAL ENERGY STORAGE SYSTEM

Experimental set up consists of a solar collector and a thermal energy storage unit, a water tank and a pump, as shown in figure 2. The collector is well insulated and collects the solar energy and transfer heat energy to water. This hot water passes to the thermal energy storage unit. Storage unit consists of steel cylinder of diameter 150 mm having thickness 3 mm and length 500 mm insulated with glasswool containing copper coil of 10 mm diameter, as depicted in figure 2. The pitch diameter of copper coil is 75 mm. A copper coil thermocouple is attached for measuring the temperature of storage media. In the storage unit, hot water passes through a coil and heat transfers from copper coil to the storage media. HTF loses heat energy and is stored in the storage unit during charging (day time). During night time or early morning's cold water is passed through storage unit to recover the stored energy.

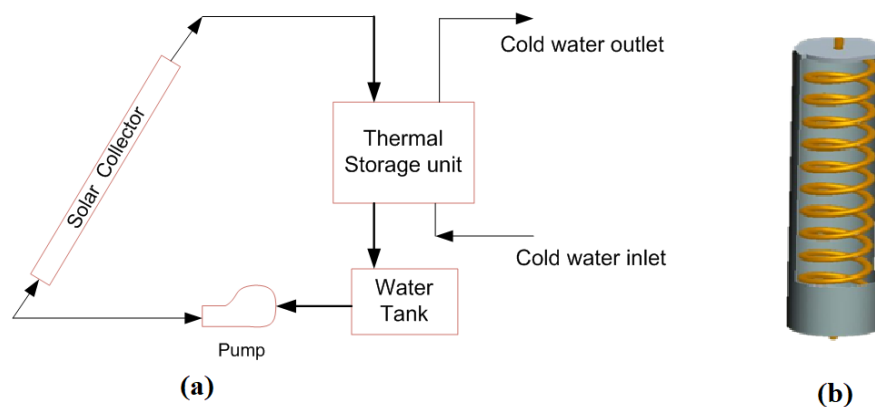


Figure 2: (a) Schematic of experimental setup, and (b) Storage unit

4. MATHEMATICAL MODEL

A model was developed to estimate the energy stored in the system using water as sensible heat storage material and salt hydrate as a latent heat storage material. In storage unit, storage material fills the annular shell space with mass m and heat capacity C_p , while the working fluid flows inside the coil and exchanges heat with the PCM.

4. Energy Equation for PCM as latent heat storage material

Consider storage tank is filled with salt hydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$). Energy balance equation for PCM storage tank can be obtained by adding latent heat term to Eq. 1. Hence Energy equation for a storage tank charging & discharging continuously is

$$\left[(m_p C_{ps} + m_p L + m_p C_{pl})_m + (\rho V C_p)_t \right] \frac{dT_1}{dt} = q_u - q_{load} - (UA)_t (T_1 - T_a)$$

Substituting the values of q_u & q_{load}

$$\left[(m_p C_{ps} + m_p L + m_p C_{pl})_m + (\rho V C_p)_t \right] \frac{dT_1}{dt} = \dot{m} C_p (T_{co} - T_1) \left[1 - \exp[-(UA)_c / \dot{m} C_p] \right] - \dot{m}_1 C_p (T_1 - T_i) - (UA)_t (T_1 - T_a) \quad (10)$$

Deducing the charging & discharging equations from above equation.

4.1.1 Charging:

During charging PCM gets heat from HTF which is flowing at a mass flow rate of $\dot{m}$ and at a temperature of T_{co} as shown in Fig 7 continuously collects heat energy from collector. By absorbing the energy supplied by HTF, PCM will undergo phase change and energy is stored as latent heat. By supplying heat energy further PCM temperature will increase and energy is stored as sensible energy. During charging there will be no load on the system. Thus by neglecting load term we get

$$\left[(m_p C_{ps} + m_p L + m_p C_{pl})_m + (\rho V C_p)_t \right] \frac{dT_1}{dt} = \dot{m} C_p (T_{co} - T_1) \left[1 - \exp[-(UA)_c / \dot{m} C_p] \right] - (UA)_t (T_1 - T_a) \quad (11)$$

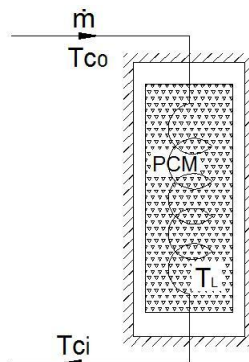


Figure3: Charging of storage unit with PCM as LHS material

4.2.2 Discharging:

During the night time HTF from load will be entering into storage unit with mass flow rate $\dot{m}$ and with temperature T_i and collect heat from storage unit as shown in fig 8. While discharging there will be no heat addition. Hence Eq.10 will be modified to

$$\left[(m_p C_{ps} + m_p L + m_p C_{pl})_m + (\rho V C_p)_t \right] \frac{dT_1}{dt} = -\dot{m}_1 C_p (T_1 - T_i) - (UA)_t (T_1 - T_a) \quad (12)$$

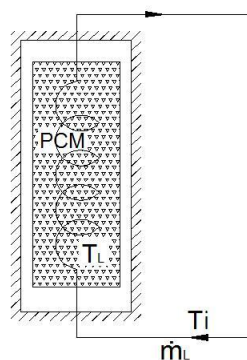


Figure 4: Discharging of storage unit with PCM as LHS material

Solving equations 7,8,11,12 by integrating the differential equation with initial conditions $t=0, T_1=T_{li}$, Assuming q_u, q_{load}, T_a as constants for getting the relation between load (storage unit) temperature and time. C programs have been written for solving these equations to get the theoretical results.

5. RESULTS& DISCUSSIONS

The temperature distributions of storage media were calculated during the charging and discharging processes for different mass flow rate conditions. For these calculated temperatures, the heat stored in the tank in terms of sensible heat and latent heat was also calculated.

5.1 Sensible Heat Storage (SHS)

The temperature distributions of sensible heat storage medium, water, are estimated during charging and discharging process. In addition, the effects of mass flow rates during charging and discharging process are studied, separately.

5.1.1 Charging process

The temperature histories of sensible heat storage medium during the charging process (heat addition) are obtained, as shown in fig5. As depicted from the figure, it can be observed that the temperature of medium is increased with the time as well as mass flow rate, and the difference in temperature at any instant further widened with the time. This may be due to the direct relationship between the rate of heat transfer and mass flow rate, as higher increment in the temperature indicated the higher heat transfer rate.

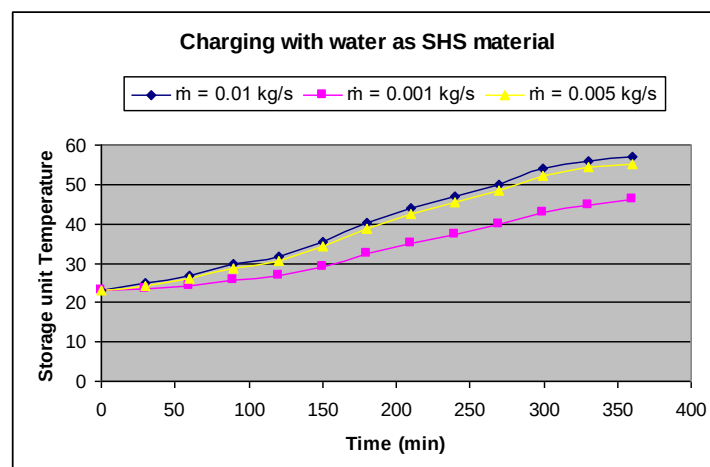


Figure 5: Charging with water as SHS material

5.1.2 Discharging process

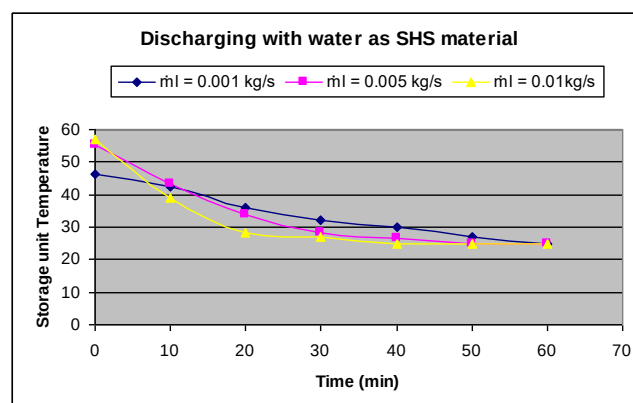


Figure 6: discharging with water as SHS material

Change in temperature of medium during the heat recovery process for continuous discharging method are obtained at different mass flow rates, as shown in figure 6. A decrement in the temperature of the storage medium was observed with the time and maximum reduction was occurred for the maximum mass flow rate.

5.2 Latent Heat Storage (LHS)

The temperature distributions during charging and discharging processes for latent heat storage medium ($Na_2S_2O_3 \cdot 5H_2O$) are obtained. The effects of mass flow rates on the rate of heat transfer were also investigated.

5.2.1 Charging process

An increment in the temperature of PCM material were detected and plotted in the figure 7, during the process of charging in the medium. It was also detected that the temperature of PCM material increased with the time and maximum energy addition was found for the maximum mass flow rate of heat transfer medium, water.

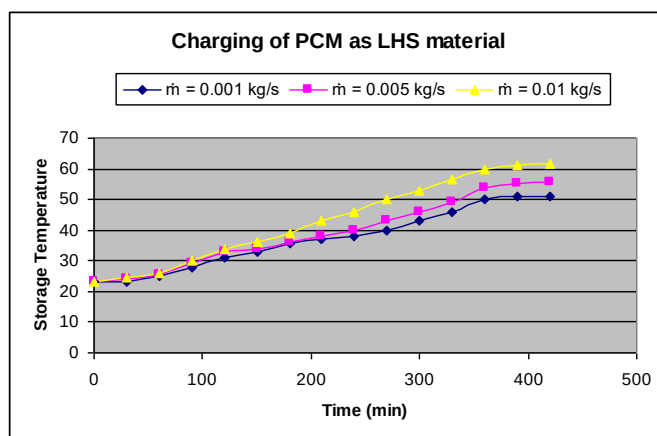


Figure 7: Charging with PCM as LHS material

5.2.2 Discharging process

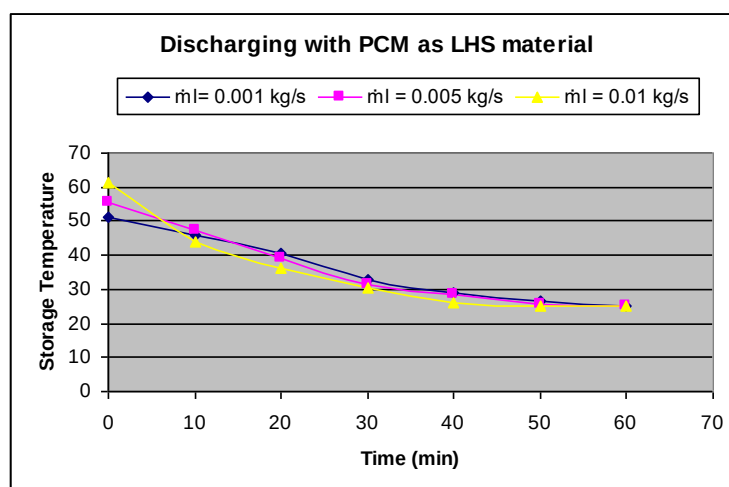


Figure 8: Discharging of energy with PCM as LHS material

The variation in the temperature of latent heat storage medium were observed and plotted in the figure 8, during the process of energy extraction from the medium. It was observed that the temperature of PCM material decreased with the time and maximum energy extraction was taken for the maximum mass flow rate of heat transfer medium, water.

6. CONCLUSIONS

A thermal energy storage system has been simulated to use of the hot water using the sensible and latent heat storage processes. The hot water from the flat plate solar collector is used to supply the energy to the thermal energy storage tank and the same is stored in the form of sensible and latent heat. The effect of mass flow rate of heat transfer fluid, water, on the charging and discharging processes are also obtained for the thermal energy storage unit. It is concluded that the mass flow rate of the heat transfer medium (water) has a substantial upshot on the heat addition and extraction rate from the solar collector, which also affected the charging of the thermal energy storage tank. Results are obtained for continuous discharging for SHS system and LHS system. It is concluded that the LHS system is more suitable for solar thermal power plant.

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