Analysis of a Multi-Stage finned PCM based storage system for Solar Thermal Power Generation

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Abstract
The sensible storage system utilizing a hot and cold tank is the current commercial technology for solar parabolic trough thermal plants. This technology is very expensive, because of its large storage material requirement, two tanks and heat exchanger. It also has high parasitics. The use of phase change material (PCM) offer higher storage capacity per unit mass. The wide operating temperature range (about 100°C) in parabolic trough plants meant that many PCMs with different melting points in series must be used. Investigation of using five PCMs with different melting point resulted into a storage system with storage material inventory higher than that of the two-tank system due to slow discharging rates. In this study, a multi-stage finned latent heat storage system model was developed and performance analysis was conducted. A model was developed for a four (NaNO3, KNO3/KCl, KNO3 and KOH PCMs) and five (NaNO3, KNO3/KCl, KNO3, KOH and MgCl2/KCl PCMs) stage cascaded storage system. Various charging and discharging mass flow rates were simulated and for each mass flow rate, the length of the storage system that will satisfy the boundary conditions of the plant at a periodically balanced state was determined. Results showed that using A HTF charging and discharging mass flow rate of 0.025kg/s and 0.03kg/s respectively has the highest percentage phase change of 70% meaning better utilization of storage material. Also the four stage cascade was found to have a percentage phase change of 56% which is lower than that of the five stage cascade. Considering a capacity of 875MWhth, which is the capacity suitable for the 6 hours operation of a 50MWc parabolic trough plant, a storage material inventory of about 25,000 tonnes is required corresponding to a net volumetric specific capacity of 72.8 kWh/m3 which is about 2.5 times that of the existing two tank system. This clearly shows the higher storage density of the multi-stage finned LHS system. The LHS system is passive and thus has very low parasitics compared to the two-tank system.

Keywords: Parabolic trough, Latent heat storage, Cascaded, Concentrated Solar Power

1. Introduction
Parabolic trough technology is the most matured concentrated solar power technology with most commercial plants in the world utilizing it [1; 2]. There is need for a cheap thermal storage system so as to make this technology a mainstream power generation technology. The current commercially viable technology for thermal storage for this technology is the two-tank system [3; 4] utilizing molten salt as the storage material which is expensive due to the storage material inventory, the requirement of two tanks (hot and cold tank) and heat exchanger. The molten salt has to be kept above its melting temperature (>200°C) always. PCMs offer higher potential capacity due to their high latent heat of fusion and thus have potential for smaller system volumes, more efficient heat transfer due to almost a constant temperature of operation. The challenge with PCMs is that potential and suitable materials in these temperature range (between 293°C to 393°C) are inorganic salts whose thermal
conductivities are approximately 0.5 W/mK [5]. This leads to low power densities during cycle operation. Thus, to make these potential materials utilizable, their thermal conductivities must be enhanced [6].

The wide operating temperature range (from 293°C to 393°C) in parabolic trough plants meant that many phase change materials (PCMs) with different melting points in series must be used [6,7]. Investigation of using five PCMs with different melting point resulted into a storage system with storage material inventory higher than that of the two-tank system due to slow discharging rates [7]. Thus, there is need for heat transfer enhancement in PCM based storage systems in order to effectively utilize them in parabolic trough plants.

Various methods have been reported for thermal conductivity improvement in PCM based storage systems. These include: Micro-encapsulation in which the PCM is mixed with substances such as graphite with higher thermal conductivity to form a composite having higher thermal conductivity [5, 8-10]; Macro encapsulation which involves putting the PCM in small enclosures, thus increasing the surface area of contact between the PCM and the Heat Transfer Fluid (HTF) [11] and the use of extended surfaces (fins)[12, 13] The most practical thermal conductivity enhancement method for high temperature applications (>100°C) is the use of fins [9;12]. In [14], considering the discharging process, the best radial finned configuration for a PCM based storage system was obtained and empirical correlations for heat transfer were produced.

There is the need to determine the performance of a multi-stage PCM based storage system using fins as thermal conductivity booster, to see whether it can perform better than the existing two tank system. In this study, model of a multi-stage finned PCM based storage system was developed and performance analysis was conducted using the operating temperatures of parabolic trough plant in order to ascertain the viability of the system.

2. Storage System Configuration

The storage system consists of five finned PCM storage modules connected in series with each having a different PCM (Figure 1a). Each module is a vertical cylindrical enclosure containing storage elements (parallel finned tubes) as shown in Figure 1b. In PCM module, the space between fins is occupied by the phase change material. Many storage elements assembled in parallel forms a PCM module (Figure 1c). The performance of a module can thus be obtained by considering a single storage elements since elements in a module are identical. In [14], performance of different finned configuration showed that HTF-pipe outer and inner diameters of 0.012 m and 0.008 m, respectively, outer radius of fin of 0.0488 m, a fin thickness of 0.001 m and a distance between fins of 0.01 m results in the best heat transfer improvement. Thus, these values were used here. The thermophysical properties of the five (5) phase change materials considered are presented in Table 1.
3. Modelling

In [8], various circumferential finned configurations have been investigated and the best fin configuration and heat transfer correlation that can be used for design was obtained considering the discharging process. Thus, this finned configuration and the heat transfer correlation for the discharging process were used in this study. For the charging process, a heat transfer correlation obtained for each phase change material by [15] was used for determining the heat transfer rates in/out of the PCM

In the modelling, a single storage element was considered (Figure 1c). A storage element is divided into axial segments inorder to take care of the changes in the HTF temperature as it moves through the HTF pipe. (Figure 2a). Various axial segments can be assembled in series to form an element and elements with different PCMs can be put in series to form a multi-stage storage element. The model for an axial segment is splitted into; Model for the flow of the HTF in pipe and that for the PCM/fin annular gap. A modelica based simulation package, Dymola was used for the modelling and simulation.

Table 1: Thermo-physical properties of PCMs considered [6]

| Medium          | Constituents (% by mass) | \( T_m \) °C | \( \lambda \) kJ/kg | \( \rho \) kg/m³ | \( k \) W/mK | \( c_p \) kJ/kgK |
|-----------------|--------------------------|---------------|---------------------|------------------|--------------|-----------------|
| NaNO₃           |                          | 306           | 172                 | 2261             | 0.5          | 1.10            |
| KNO₃/KCl        | 95.5/4.5                 | 320           | 74                  | 2100             | 0.5          | 1.21            |
| KNO₃            |                          | 335           | 95                  | 2109             | 0.5          | 0.953           |
| KOH             |                          | 360           | 134                 | 2040             | 0.5          | 1.34            |
| MgCl₂/KCl/NaCl  | 60/20.4/19.6             | 380           | 400                 | 1800             | 0.5          | 0.96            |
The energy balance of the HTF flow is given by:

\[
\dot{m}c_{p,\text{htf}}(T_{\text{htf,in}} - T_{\text{htf,out}}) = \dot{Q} + \dot{m}_{\text{htf}}c_{p,\text{htf}} \frac{dT_{\text{htf}}}{dt}
\]  (1)

where

\[
T_{\text{htf}} = \frac{T_{\text{htf,in}} + T_{\text{htf,out}}}{2}
\]

The heat transferred through the HTF pipe wall to the PCM (\(\dot{Q}\)) as shown in equation (1) is given by:

\[
\dot{Q} = h_{\text{f}}2\pi r_{i}dz(T_{\text{htf}} - T_{\text{wi}}) = 2\pi dzk_{w} \left( \frac{T_{\text{wi}} - T_{\text{wo}}}{\ln \left( \frac{r_{o}}{r_{i}} \right)} \right)
\]  (2)

Using the effective heat capacity method [16] in modelling the heat exchange during phase change. The phase change was assumed to occur over a small range of temperature \(\Delta T_{m}\). Thus, during phase change, the specific heat capacity is:

\[
c_{p,pcm,m} = \frac{\lambda}{T_{\text{liquid}} - T_{\text{solid}}} + \frac{c_{p,pcm,s} + c_{p,pcm,l}}{2}
\]  (3)

The transient PCM temperature change is calculated from:

\[
\dot{Q} = m_{pcm}c_{p,pcm} \frac{dT_{pcm}}{dt}
\]  (4)

where

\[
c_{p,pcm} = \begin{cases} c_{p,pcm,s} & T_{pcm} < T_{\text{solid}} \\ c_{p,pcm,m} & T_{\text{solid}} < T_{pcm} < T_{\text{liquid}} \\ c_{p,pcm,l} & T_{pcm} > T_{\text{liquid}} \end{cases}
\]

The heat transfer rate from the HTF pipe to the finned annular gap was calculated using:

\[
\dot{Q} = hA(T_{\text{wo}} - T_{\text{pcm}})
\]  (5)

During charging and discharging, the effective coefficient of heat transfer (\(h\)) is obtained by [15] were used. Using these heat transfer functions a model was developed for a four (NaNO3, KNO3/KCl, KNO3 and KOH phase change materials) and five (NaNO3, KNO3/KCl, KNO3, KOH and MgCl2/KCl phase change materials) stage cascaded storage system considering a single storage element. Since the storage system capacity depends on the HTF mass flow rate various charging and discharging mass flow rates (0.025kg/s - 0.035kg/s) were simulated in order to ascertain the mass flow rate that will give the highest
storage material utilization for the five-stage cascade (table 2). For each mass flow the length of the storage system that will satisfy the boundary conditions of the plant at a periodically balanced state was determined. Comparison was then conducted between the five and four stage cascades. During charging, HTF inlet temperature of 393°C which is the HTF outlet temperature of the solar field and outlet temperature of 290°C – 330°C were used since the HTF inlet temperature to the solar field cannot exceed 330°C to avoid solar field HTF overheating. During Discharging HTF inlet temperature of 286°C was used. This is the design point HTF temperature from the power block. HTF outlet temperature of ≥350°C was ensured since this is the minimum temperature for the operation of the turbine.

4. Results and Discussion
The multi-stage storage system must fulfil the parabolic trough plant operating conditions as presented in section 2. Thus for each mass flow rate of PCM, various length of the storage module were simulated inorder to determine the length that satify the boundary conditions during charging (maximum of 330°C) and discharging (minimum of 350°C). Figure 3 presents the temperature and the corresponding length during charging and discharging for the six cases considered. For each mass flow rate the length that satisfy both the charging and discharging boundary conditions was determined (Table 2).

![Figure 3: Determination of the length of the storage system for a five stage system](image)

Table 2 presents the analysis of the various HTF mass flow rates simulated with the corresponding length of the storage system that satisfies the boundary conditions for the five stage cascade. It will be observed that Case 4 using A HTF charging and discharging mass flow rate of 0.025 kg/s and 0.03 kg/s respectively has the highest percentage phase change of 70% meaning better utilization of storage material.
Considering mass flow rate of HTF of 0.025 kg/s and 0.03 kg/s during charging and discharging respectively (Case 4), Figure 4 presents the comparison between the performance of a four stage and a five stage system. The four stage cascade was found to have a percentage phase change of 56% which is lower than that of the five stage cascade. Thus the five stage cascade (case 4) is the best configuration.

Considering a storage system capacity of 875 MWhth, which is the capacity suitable for the 6 hours operation of a 50 MWc parabolic trough plant, PCM inventory of about 25,000 tonnes is required corresponding to a net volumetric specific capacity of 72.8 kWh/m³. The molten salt used in the existing two-tank system has a volumetric specific capacity of 28.36 kWh/m³. This clearly shows the higher storage density of the cascaded finned LHS system. The PCM based storage system is passive and thus has very low parasitics. It will thus be expected that the performance of integrated storage with the plant will be higher.

Table 2: Analysis of Five Stage Cascaded LHS System For Different Design HTF Mass Flow Rates Considering a Single Storage Element

| Case | Mass flow rate of HTF (kg/s) | Length Of Storage Element (m) | Total Mass Of PCM (kg) | Phase Change (%) | Capacity (Actual) (MJ) | Capacity / Length MJ/m |
|------|-----------------------------|-------------------------------|------------------------|------------------|------------------------|------------------------|
|      | Charging                    | Discharging                   |                        |                  |                        |                        |
| 1    | 0.025                       | 0.025                         | 80                     | 1211.56          | 0.32                   | 107.295                | 1.34                   |
| 2    | 0.03                        | 0.03                          | 96                     | 1453.81          | 0.32                   | 130.771                | 1.36                   |
| 3    | 0.035                       | 0.035                         | 108                    | 1635.61          | 0.34                   | 152.437                | 1.41                   |
| 4    | 0.025                       | 0.03                          | 56                     | 848.1            | 0.70                   | 109.428                | 1.95                   |
| 5    | 0.03                        | 0.035                         | 68                     | 1029.83          | 0.67                   | 131.324                | 1.93                   |
| 6    | 0.025                       | 0.035                         | 172                    | 2423.13          | 0.19                   | 129.796                | 0.75                   |

CONCLUSIONS
The performance of a five stage PCM based storage system showed that the best charging and discharging mass flow rates for a single storage element are 0.025 kg/s and 0.03 kg/s respectively. A five stage system provides higher utilization of PCM than a four stage system. For 6 hours operation of a 50 MWc plant, 28,786 storage elements are required corresponding to a net volumetric capacity of 72.8 kWh/m³ which is 2.5 times higher than that of the existing commercially available sensible system. Considering that the PCM based storage system is a passive system and there is no need to keep the storage material molten at all times, it will have lower parasitics compared to the two tank system. This can potentially reduce the cost of storage in parabolic trough plants.
Figure 4: Performance Comparison between a Five and a Four Stage Storage Element

Nomenclature

\( A \) Outer surface area of the HTF pipe (m\(^2\))
\( c_p \) Specific heat capacity (J/kgK)
\( dz \) Height of a storage segment (m)
\( h \) Heat transfer coefficient (W/m\(^2\)K)
\( k \) Thermal conductivity (W/mK)
\( m \) Mass (kg)
\( \dot{m} \) Mass flow rate (kg/s)
\( \dot{q} \) Heat flux (W/m\(^2\))
\( \dot{Q} \) Heat transfer rate (W)
\( r_o \) Outer radius (m)
\( r_i \) Inner radius (m)
\( T \) Average temperature (°C)
\( T_m \) Melting temperature of the PCM (°C)
\( T_{solid} \) PCM temperature at the start of melting (°C)
\( T_{liquid} \) PCM temperature at the end of melting (°C)
\( \beta \) Liquid fraction
\( \lambda \) Latent heat of fusion (J/kg)

Subscripts

fc Forced convection
htf Heat transfer fluid
l Liquid
m Melting
pcm Phase-change material
s Solid
w HTF-pipe wall
wi Inner surface of the HTF-pipe
wo Outer surface of the HTF-pipe

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