A dynamic model of a sodium/salt PCM energy storage system

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1. BACKGROUND

Thermal energy storage (TES) implemented in Concentrated Solar Power (CSP) addresses the issue of time mismatch between energy demand and supply. With TES, CSP plants can be operated flexibly to ensure power supply matches demand, maximising revenue.

Direct two-tank TES with a molten eutectic mixture of $NaNO_3$ and KNO_3 is the currently dominant commercial choice in CSP. However, chemical stability issues limit operating temperatures which in turn limit the thermal conversion efficiency of the CSP plant's power cycle. It is therefore desirable to explore alternative storage/transport media such as liquid sodium which are suitable for high temperature applications (Coventry et. al. 2015).

In this work, we present a novel TES system involving a sodium heat pipe in direct contact with NaCl PCM. This combination is appealing due to high storage temperatures, low receiver losses and the potentially minimised cost of the storage subsystem.

2. INTRODUCTION

NaCl has a low cost and high melting point of around 1073K, which is also similar to the saturation temperature of sodium heat transfer fluid (HTF) at slightly sub-atmospheric pressures.

A dynamic system model of the HTF-PCM storage within a CSP system was implemented in OpenModelica evaluate key dynamic aspects of the system such as the temperature response of the PCM whilst heat is added/removed from the storage vessel, and movement of liquid sodium between the receiver and storage trays. Several design parameters which include PCM container dimensions, quantities of PCM and HTF material, and charging/discharging rates could then be optimised for maximum exergetic efficiency, and in future, minimum levelised cost of electricity (LCOE).

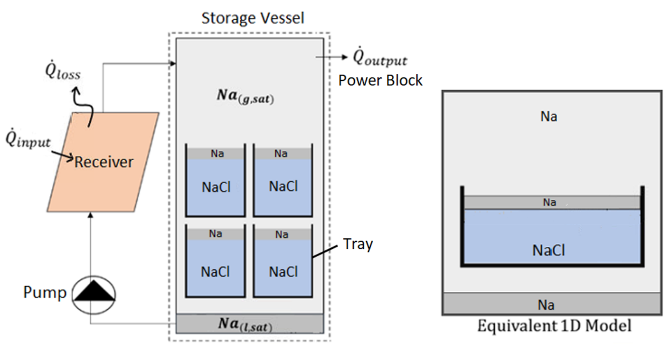

Figure 1: Left: Conceptual design of the TES subsystem. Right: Equivalent model used in simulation.

3. DESIGN CONCEPT

A simplified model of the HTF-PCM configuration includes a storage vessel containing saturated Na liquid-vapour at a temperature T_{Na} in contact with the top surface of the NaCl contained in trays (Figure 1). Heat is delivered to the isochoric vessel via a sodium boiler receiver at T_{Na}, which operates for 6 hours a day and is shut down for the remaining 18 hours. In the 18 hours, heat is discharged from the storage vessel into a Carnot power cycle at T_{Na}.

During the charging process, Na vapour condenses on top of a pool of Na liquid. Excess condensing sodium overflows from the sides of the tray walls to the bottom of the vessel, where it can be pumped back for re-boiling in the receiver. During discharging, liquid sodium is boiled off the top of the PCM surface and must be replenished by pumping from the bottom of the vessel.

4. MODEL ASSUMPTIONS

The sodium HTF was modelled as a single component, two-phase mixture at temperature T_{Na}. T_{Na} is calculated at each time step using specific enthalpy and specific volume constraints and equations provided by Fink and Leibowitz (1995).

The sodium receiver was modelled as an isothermal blackbody cavity receiver with fixed concentration ratio (CR) direct normal irradiance (DNI) for 6 hours each day. During the remaining 18 hours, the system the discharges at a rate $\dot{Q}_{output}$ which is set to 1/3 of $\dot{Q}_{input}$ or until the total energy stored by the vessel returned to zero.

During charging, the heat transfer process between HTF and PCM was assumed to be conduction-dominated due to the low Prandtl number of liquid metals, and thus modelled via an extra thermal resistance term. During discharging, the effective thermal resistance of the liquid Na layer was assumed to be zero due to the large heat transfer coefficient associated with pool boiling. The temperature gradient within the liquid Na pool is assumed to be small enough such that the effect on the two-phase Na HTF model is negligible.

Heat transfer within the PCM was modelled using a numerical scheme involving 1D finite-difference, enthalpy formulation with mushy node idealisation (Sharma et. al. 2009; Dutil et. al. 2011). This numerical scheme was described to have relatively simple implementation, with a single governing equation for both solid and liquid phases. All PCM trays were assumed to experience identical heat transfer, and as such, were represented using a single equivalent tray (Figure 1).

The numerical scheme was validated against an exact Neumann solution to the Stefan Problem (Alexiades & Solomon, 1993). The output of the numerical scheme with constant properties was observed to converge to the exact solution as the mesh resolution was increased.

To simulate a real-world TES configuration, the temperature distribution within the PCM was determined at each time-step using a enthalpy-temperature relationship; which was then used to determine temperature-dependent properties such as density ρ (kg/m^3) and thermal conductivity k (W/m·K). Due to the high operating temperature of the system and the semi-transparent characteristic of liquid NaCl, the k values of effective radiative-conductive heat transfer (RCT) were used.

5. EXERGY CALCULATIONS

To obtain a measure of round trip exergy efficiency, the rate of exergy into and out of the HTF-PCM control volume was calculated at each timestep with $T_0 = 300$ K as the reference temperature. The exergy destruction within the PCM (between the nodes) via conduction was also calculated to determine if exergy is destroyed mainly during charging or discharging.

6. MODELICA IMPLEMENTATION

The set of ordinary differential equations with respect to time were solved using OpenModelica with the *dassl* solver with a tolerance of 1×10^{-6}.

Table 1. System design parameters

Parameter	Value
Concentration Ratio	1000
Receiver Area	5×10^{-3} m²
Direct Normal Irradiance, DNI	1000 W/m²
Initial volume of NaCl @ 300K	0.1 m³
Total vessel volume	10.1 m³
Mass of Na	30.0 kg
Initial Temperature of all components	1050 K
Wall	$1.5 \times L_{NaCl}$

The NaCl PCM was assumed to have a uniform cross-sectional area, A_{NaCl} and a depth L_{NaCl}. A parametric study on the effect of L_{NaCl} given constant initial volume was performed to investigate the effect of PCM dimensions on the exergetic performance of the overall storage subsystem.

7. RESULTS

An exergy efficiency X_{out}/X_{in} of 91.9% was achieved using PCM of depth 0.02 m; this decreases to 86.4% at 0.10 m.

At higher PCM depths, a larger temperature difference is required to sustain the heat flux from the HTF to the PCM due to increasing thermal resistance between the HTF and the PCM's melting front. This causes the temperature of the HTF to increase rapidly as heat is added to the system during the charging phase. This leads to increased radiative losses at the receiver and large temperature gradients within the PCM. The large temperature gradients lead to high exergy destruction rates within the PCM.

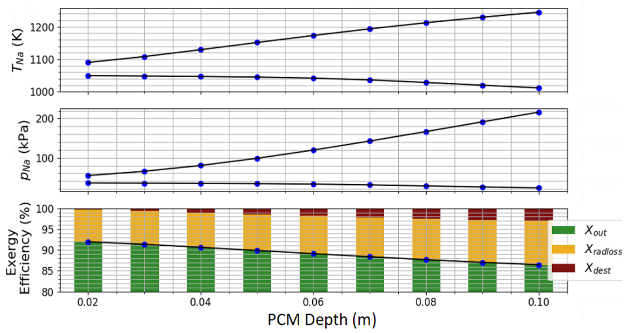

Figure 2: Daily variation in temperatures and pressures and charge-discharge exergy efficiency with respect to PCM tray depth.

A direct consequence of temperature variation in the two-phase equilibrium sodium is the variation in pressure within the storage vessel. Minimising the maximum pressure and pressure variation of the HTF would be advantageous in reducing material costs of the storage vessel and avoiding material fatigue of its components.

8. CONCLUSION AND FURTHER WORK

The depth of the PCM has a significant effect on the daily temperature and pressure variations of the HTF, which in turn affect exergy efficiency of the CSP system. This is consistent with the fact that heat transfer between the HTF and PCM is limited by the heat conduction within the PCM.

The benefit of using thin trays of PCM would be counteracted by the increased material costs needed to fabricate the trays. As such, a cost vs. performance optimisation would allow the best design to be determined.

Further work would involve an annual performance simulation of a complete CSP plant which utilizes the sodium/salt PCM storage concept. Parameters such as PCM depth, ratio of HTF to PCM and different control strategies would be optimized for minimum LCOE.

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