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Experimental demonstration of a dispatchable latent heat storage system with aluminum-silicon as a phase change material

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HIGHLIGHTS

- Design and construction of a dispatchable latent heat thermal storage system.
- Heat transfer near uniform temperature via heat pipes and aluminum-silicon PCM.
- On/off heat flow control using a valved thermosyphon.
- Integration of subsystems with small temperature drops at interfaces.

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ABSTRACT

In this work, we present the design, construction, and experimental results of a prototype latent heat thermal energy storage system. The prototype consists of a thermal storage tank with 100 kg of the aluminum-silicon eutectic as a phase change material, a valved thermosyphon that controls heat flow from the thermal storage tank to the power block, and thermoelectric generators for conversion of heat to electricity. We tested the prototype over four simulated days, where each day consisted of four phases of operation: charging, discharging, simultaneous charging and discharging, and storage. Our results show three major conclusions. First, the thermal energy storage system was able to receive and distribute heat with small temperature gradients – less than 5 °C throughout the thermal storage tank. Second, the valved thermosyphon was able to effectively control heat transfer, demonstrating an on/off thermal conductance ratio of 430. Third, the interfaces between subsystems had small temperature drops: of the ~ 560 °C temperature drop from the thermal storage tank to the heat rejection system, ~ 525 °C occurred across the power block. This work overcomes the challenges of integrating previously-developed subsystems together, providing a proof-of-concept of this system.

1. Introduction

Energy storage is likely to play a prominent role in future electric grids that will generate a significant portion of their supply from renewable sources. By compensating for the variability of generation from photovoltaics and wind power, energy storage can reduce the cost of grid operation and resolve the inefficiencies of turning generators on and off [1]. In doing so, energy storage may also create the added benefit of reducing carbon emissions from the electricity sector.

Of the potential options for energy storage, thermal energy storage (TES) combined with concentrated solar power (CSP) appears to be one of the lowest-cost solutions. Current costs for TES are 20–25 $/kWh, and many pathways are being investigated that have potential to reduce cost to 15 $/kWh [2]. This cost becomes larger when the efficiency of converting heat to electricity is considered, but still outperforms the most likely alternative technology to provide grid-scale energy storage: electrochemical batteries. Battery costs are ~ 300 $/kWh today, and are likely to remain above 150 $/kWh based both on experience rates [3] and on limits of material costs [4].

Sensible heat storage with molten salt as a storage material is the state-of-the-art for TES with CSP, and has been implemented in commercial plants that are operating today, such as the 110 MW Crescent

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Dunes plant in Tonopah, Nevada. This technology takes advantage of inexpensive materials and mature processes, but is limited to relatively low temperatures (∼ 550 °C) and large plant sizes (> 100 MW) [5]. Further development for improved efficiency and reduced cost would require new salt storage materials and new components throughout the system that are compatible with high temperatures.

Latent heat storage (LHS) is a potential alternative that can achieve higher energy densities than sensible heat storage and can operate nearly isothermally, which is appealing for both cost reduction and for high power block efficiency. No commercial CSP plants currently use LHS, but significant research-level progress been made in both phase change materials (PCMs) and heat transfer designs for LHS systems. Within materials development, both salts and metal alloys have received attention [6–9]. Salts can be low cost materials, but have low thermal conductivity, which increases the cost of heat exchangers and has encouraged research on thermal conductivity enhancements [8–12]. Metals solve this issue because they have high thermal conductivity, but are very corrosive, and no systems have been demonstrated as stable for extended periods of time. Within heat transfer design development, difficulty is presented by the solid-liquid phase change, but several solutions have been experimentally explored: traditional heat exchangers with pumped fluids [13–15], encapsulated PCMs [16–18], pool boilers [19,20], and heat pipes [21–29]. The first two of these approaches are actively driven systems, whereas pool boilers and heat pipes are passive. Here we focus on the latter, because they avoid parasitic power usage and reduce maintenance requirements.

A comprehensive review of the combination of heat pipes with LHS is provided by [21]. This review shows that the first experimental endeavors for combining solar power, high temperature heat pipes, and latent heat storage were completed for space applications. These efforts included salt PCMs with melting temperatures from 766–980 °C, heat pipes with sodium and potassium as heat transfer fluids, and organic Rankine, Brayton, and Stirling engines for the power block [22–26]. Notably, the National Aerospace Laboratory in Japan demonstrated a system efficiency of 20% using LiF as a PCM, sodium heat pipes, and a Stirling engine [26]. Since the review provided by [21], several new projects have also added to this field of work. In particular, Temple University and Infinia Corporation built a latent heat storage system with a Stirling engine, designed for a terrestrial parabolic dish solar concentrator. They demonstrated some initial success, but experienced dry-out issues with their heat pipe design [27]. Sandia National Laboratories also investigated latent heat storage with Dish Stirling [28,29]. They found potential for cost-competitiveness, but required further work on flexible high temperature heat transfer pipes and material compatibility between their Cu-Mg-Si PCM and containment materials.

In the designs mentioned above, heat pipes were useful for their very high effective thermal conductivity, but did not allow for complete control of heat flow and did not result in entirely dispatchable power generation. However, recent advances have allowed heat pipes to be more controllable, with designs such as variable conductance heat pipes, pressure controlled heat pipes, and diode heat pipes, among others [30]. In previous work, we also demonstrated a valved thermosyphon that could control the flow of the internal heat transfer fluid and thereby act as a “thermal valve” [31,32].

Building upon the progress in latent heat storage and heat pipes discussed above, we developed and investigated a concept called Solar Thermal Electricity via Advanced Latent heat Storage (STEALS) [33–38]. This concept is depicted in Fig. 1. In an effort to overcome previous issues encountered when integrating latent heat storage with a dish concentrator, STEALS locates its thermal storage on top of a small scale solar power tower. A heliostat field reflects sunlight to a cavity receiver, where heat is absorbed at the bottom of a thermal storage tank. Heat is distributed to a PCM by heat pipes within the thermal storage tank. Above the PCM is a valved thermosyphon, which acts as a “thermal valve” between the thermal storage tank and the power block. This valved thermosyphon allows complete de-coupling of sunlight collection and power production, unlike other storage systems that keep running after the sun goes down but are not able to turn on and off on demand. The STEALS design is attractive because it has low operation and maintenance requirements, and our techno-economic analysis has demonstrated that it has the potential for low cost, dispatchable electricity generation at a modular scale (< 1 MW) [33].

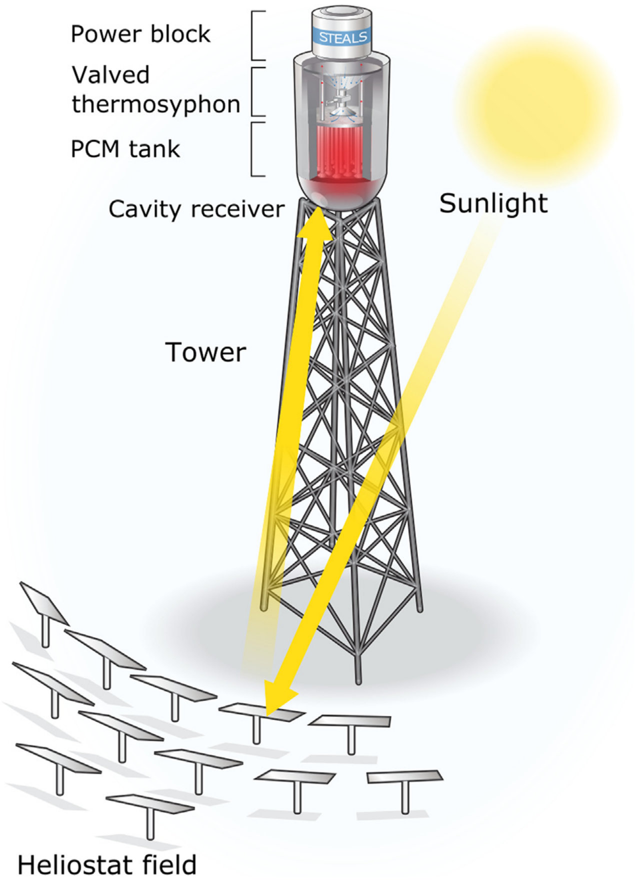

Fig. 1. Solar Thermal Electricity via Advanced Latent Heat Storage (STEALS) integrates a thermal storage system (including a tank of phase change material (PCM) and a valved thermosyphon for heat flow control) with a power block and a cavity receiver on a solar power tower. STEALS uses a heliostat field 1000× smaller than conventional solar power towers, and passive heat transfer mechanisms via heat pipes and thermosyphons.

In this paper, we present the design and construction process of a prototype of the STEALS system, and give experimental results from 4 consecutive simulated days of operation. Heat was input from a resistive heater, delivered to an aluminum-silicon phase change material by sodium heat pipes, and controllably dispatched by a valved thermosyphon to thermoelectric generators which converted the heat to electricity. Our results provide a proof-of-concept of the STEALS technology: the thermal storage system was able to receive and distribute heat with small temperature gradients, the valved thermosyphon was able to effectively control heat transfer, and we observed small temperature drops at interfaces between subsystems.

2. Prototype design and construction

Our prototype design involves a thermal storage tank with 100 kg of aluminum-silicon alloy and sodium heat pipes for even heat distribution. This thermal storage tank is connected to a valved thermosyphon for heat flow control, and thermoelectric generators (TEGs) for conversion of heat to electricity. Fig. 2 shows the computer-aided design of