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Research Paper

Design of a thermosyphon-based thermal valve for controlled high-temperature heat extraction

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ABSTRACT

Conventional concentrated solar power (CSP) is a reliable alternative energy source that uses the sun's heat to drive a heat engine to produce electrical power. An advantage of CSP is its ability to store thermal energy for use during off-sun hours which is typically done by storing sensible heat in molten salts. Alternatively, thermal energy may be stored as latent heat in a phase-change material (PCM), which stores large quantities of thermal energy in an isothermal process. On-sun, the PCM melts, storing energy. Off-sun, the latent heat is extracted to produce dispatchable electrical power.

This paper presents the design of a thermosyphon-based device with sodium working fluid that is able to extract heat from a source as demand requires. A prototype has been designed to transfer 37 kW of thermal energy from a 600 °C molten PCM tank to an array of 9% efficient thermoelectric generators (TEGs) to produce 3 kW of usable electrical energy for 5 h. This "thermal valve" design incorporates a funnel to collect condensate and a central shut-off valve to control condensate gravity return to the evaporator. Three circumferential tubes allow vapour transport up to the condenser.

Pressure and a thermal resistance models were developed to predict the performance of the thermal valve. The pressure model predicts that the thermal valve will function as designed. The thermal resistance model predicts a 5500× difference in total thermal resistance between "on" and "off" states. The evaporator and condenser walls comprise 96% of the "on" thermal resistance, while the small parasitic heat transfer in the "off" state is primarily (77%) due to radiation losses.

This simple and effective technology can have a strong impact on the feasibility, scalability, and dispatchability of CSP latent storage. In addition, other industrial and commercial applications can benefit from this thermal valve concept.

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1. Introduction

With evidence indicating that the continued large-scale combustion of fossil fuels for energy generation causes detrimental global temperature and climate changes, there is a growing demand for alternative, sustainable energy sources [1].

Solar energy is one of the largest and most readily available alternative energy sources. Two of the most widely used methods of harvesting solar energy are the use of photovoltaic (PV) cells and the use of concentrated solar power (CSP). PV cells convert light directly into electrical potential which can be used immediately or stored for later use in a chemical battery. CSP uses mirrors or lenses to focus a large solar area onto a receiver heating a material to either drive a power cycle or thermochemical reaction.

CSP can also be used to deliver an electrical energy with the use of a thermoelectric generator (TEG). TEGs are solid-state devices that operate using the Seebeck effect to produce an electrical current from a temperature gradient [2]. Although less efficient than traditional thermal power cycles, TEGs offer advantages of low cost, high reliability (no moving parts), and small space requirement.

A major disadvantage of harvesting solar energy is the fact that the greatest consumer electrical energy demand occurs both before and after the sun is at peak elevation [3]. PV electrical energy can be stored in a chemical battery, as pumped hydro, or as compressed air for off-peak use. The thermal energy from CSP can also be stored, but in a "thermal battery" as sensible or latent heat [4].

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Nomenclature

A	area (m^3)
μ	viscosity (Pa·s)
H_v	heat of vaporization (kJ/kg)
h	height (m)
g	gravitational acceleration (m/s^2)
γ	heat capacity ratio
M	molar mass (kg/mol)
ρ	density (kg/m^3)
P	pressure (Pa)
r	radius (m)
R	thermal resistance (K/W)
$\bar{R}$	universal gas constant (J/mol·K)
R_g	specific gas constant (J/kg·K)
σ	Stefan-Boltzmann constant ($W/m^2 \cdot K^4$)
σ_l	surface tension (N/m)
T	temperature (°C)

Properly insulated, thermal energy can be stored for extended times with minimal loss. The problem exists, however, in how the stored heat can be extracted only when demand requires. This has traditionally been particularly challenging for latent heat energy storage systems.

Due to their exceptionally high effective thermal conductivities, heat pipes are a natural choice for heat transfer enhancement options for PCM systems [5]. A recently presented design for a 43 MJ system uses a sodium charged heat pipe to transfer thermal energy to a salt-based PCM and to a dish Stirling engine [6]. The device was constructed from Haynes 230 and Inconel 625 alloys with a heat transfer of 11 kW and an operating temperature of 680 °C. The wicking structure was sintered Ni powder and #50/150 woven mesh. A similar scheme was devised and tested by Boo et al. in 2015 [7] using a stainless steel/sodium loop heat pipe to transfer 800 W of thermal load at 730 °C from an evaporator disc to a condenser disc a distance of 0.5 m. This system used an electrical heat source and an alkali-metal thermal to electric converter (AMTEC) power block. Similarly, a high-temperature latent heat thermal energy system (LHTES) was proposed and analysed by Shabgard [8]. Their modeling concluded that heat pipes can enhance the thermal performance of PCM for both charging and discharging. At the low-temperature scale, Robak [9] performed experiments with a wax PCM showing that the inclusion of heat pipes in the storage tank enhances heat transfer from the heat source into the PCM. In 2013, a mini-TEG/PCM system was constructed to maintain electrical power after the removal of a heat source [10]. In that device, a cavity for low temperature wax-based PCM was created with standard micro-fabrication techniques. The associated TEG was directly applied with Bi_2Te_3 ink. With that system, the delivery of electrical power was extended for several minutes beyond that system without PCM energy storage. All of the systems discussed above utilised heat pipes in some way to enhance heat transfer with a PCM, yet none of these previous attempts at latent thermal energy storage were able to control the "on/off" of the heat flow.

In this paper, an innovative design for the solution of the problem of delivering dispatchable thermal energy stored as latent heat in a PCM is detailed. Fig. 1 shows a schematic of our proposed thermal energy storage and extraction system.

First, the sun's rays are reflected with heliostats onto the bottom of an elevated PCM tank. Solar energy is absorbed by heat pipes in the tank that distribute heat to the PCM, which increases in temperature, and eventually melts. Between the PCM tank and the TEGs is a "thermal valve", designed to switch the flow of heat to the TEGs "on" and "off" as demand requires.

An array of design criteria for a prototype demonstration of this system have been developed. The required electrical TEG output is 3 kW for 5 h. The chosen solid/liquid PCM is an Al/Si alloy (4047) with a melting temperature of 577 °C [11] contained in a 0.914 m diameter tank with the same height. Al 4047 has a heat of fusion of 560 kJ/kg, a specific heat of 1741 J/kg·K, solid and liquid densities of 2553 and 2445 kg/m^3 respectively, and a thermal conductivity of 160 W/m·K [12,13]. The proposed TEGs are a series cascaded skutterudite (for high temperature on the condenser)/BiTe (for lower temperature on the heat exchanger). With a TEG efficiency of 9% and a thermal valve efficiency of 90%, the required heat input from the PCM is 37 kW. The thermal valve is constructed from stainless steel with a 4-layer woven mesh wick on the evaporator and the compatible working fluid is sodium (Na) [14]. Relevant design values are given in Table 1.

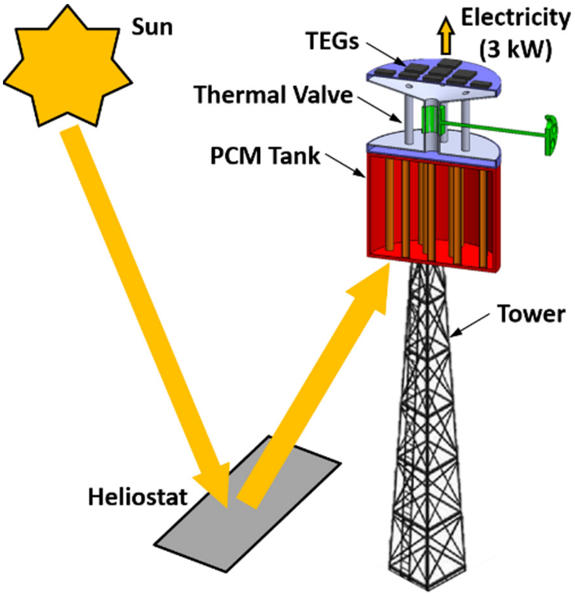

Fig. 1. Drawing of the proposed 3 kW dispatchable PCM/TEG thermal energy storage and power generation system.

Table 1
Parameters used to calculate the thermal valve design.

Quantity	Value
Vessel Material	Stainless Steel 304
Working Fluid	Sodium
Operating Temperature	600 °C
Heat Transfer	37 kW
Evap/Cond Diameter	0.914 m
Na, Mass Flow Rate	0.00873 kg/s
Na, Heat of Vaporization	4236 kJ/kg
Na, Liquid Density	805.4 kg/m^3
Na, Vapour Density	0.013 kg/m^3

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