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Reliability and heat transfer performance of a miniature high-temperature thermosyphon-based thermal valve

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ABSTRACT

Latent heat thermal energy storage systems have the advantages of near isothermal heat release and high energy density compared to sensible heat, generally resulting in higher power block efficiencies. Until now, there has been no highly effective and reliable method to passively extract that stored latent energy. Most modern attempts rely on external power supplied to a pump to move viscous heat transfer fluids from the phase change material (PCM) to the power block. In this work, the problem of latent heat dispatchability has been addressed with a redesigned thermosyphon geometry that can act as a “thermal valve” capable of passively and efficiently controlling the release of heat from a thermal reservoir. A bench-scale prototype with a stainless steel casing and sodium working fluid was designed and tested to be reliable for more than fifty “on/off” cycles at an operating temperature of 600 °C. The measured thermal resistances in the “on” and “off” states were 0.0395 K/W and 11.0 K/W respectively. This device demonstrated efficient, fast, reliable, and passive heat extraction from a PCM and may have application to other fields and industries using thermal processing.

1. Introduction

Human energy needs have exceeded 17 TW in 2016 [1] and are predicted to increase 28% by 2040 [2]. Of that energy use, 85% is derived from fossil fuels [1]. Fossil fuels however are limited in quantity and release carbon exhaust gasses into the atmosphere, potentially causing dramatic and dangerous changes to our climate [3]. Clean and persistent solar energy is an obvious alternative solution to supply the human energy demand. However, a critical hurdle to the large-scale implementation of solar energy has been storage [4], since some regions and climates have a peak power demand that does not match the peak solar supply [5].

The majority of solar energy being harvested today is with the use of photovoltaics (PV) [6]. The power harvested by PVs is either used immediately by residences and industries or diverted to the electrical grid when there is surplus. Storage for PV typically uses large electrochemical batteries. These unfortunately are challenged with high cost, short lifetime, toxicity, and scarcity of materials [7]. Until the cost and performance of PV storage batteries becomes competitive with current energy production, alternative solar power storage strategies must be considered [8].

Recently, concentrated solar power (CSP) is proving to be a competitive storage method to electrochemical batteries. CSP can be stored as either sensible or latent heat. Sensible heat storage is an ancient concept [9] and is as simple as the sun warming a solid stone wall during the day which then warms a home at night [10] or using the thermal energy to directly heat fluids for residential/commercial heating [11,12]. Presently, most grid-scale storage of CSP uses the thermal energy to heat a flowing fluid (typically a salt or oil) to a high temperature, store it in a tank, and then use that hot fluid to drive a steam Rankine cycle [13]. Though effective, sensible heat storage suffers from the drawback of being a variable temperature process, which adversely affects the efficiency of most electrical generation systems that use its thermal energy [14]. Additionally, pumping liquids presents a parasitic electrical loss to overcome the viscous effects of the flowing fluid and a relatively high cost of pumping equipment.

Alternatively, storing CSP as latent heat has several advantages over sensible heat storage. The melting/freezing of a phase change material (PCM) typically occurs across a narrow temperature range, making it a nearly isothermal process. Most electrical gener-

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ation systems benefit from this constant temperature heat extraction with larger energy conversion efficiencies [14]. Additionally, the latent heat of fusion is typically high compared to the energy stored by sensible heat. For these advantages, many researchers have recently focused on improving the efficiency and practicality of latent heat thermal energy storage (LHTES) systems [15–20].

One hurdle to larger-scale implementation of CSP LHTES has been the challenge of dispatchability. In order to provide energy to a utility grid, the speed and reliability of thermal power extraction from a PCM is critical. Heat pipes and thermosyphons have been considered by many to be an effective heat transfer technology for CSP applications [21–23] and for heat extraction from a PCM [24–28]. In 1997, Laing and Träbing demonstrated a sodium heat pipe that served as a solar receiver capable of transferring 9 kW of heat at 820 °C to a Stirling engine [21]. Later, Shabgard et al. performed a numerical analysis to show how thermosyphons can assist cascaded latent thermal storage systems [22]. In 2015, Bo, Kim, and Kang experimentally demonstrated a sodium loop heat pipe that transferred 800 W at approximately 600 °C to an alkali-metal thermal to electric converter [23]. In 2011, Nithyanandam and Pitchumani modeled enhanced heat transfer from a PCM to a fluid using heat pipes [24]. The same year, Robak, Bergman, and Faghri experimentally demonstrated the effectiveness of heat pipe fins to charge and discharge a wax-based PCM at approximately 50 °C [25]. Also at the same time, Weng et al. used a miniature heat pipe in conjunction with similar wax-based PCMs to reduce the cooling power consumption of electronic components [26]. In 2015, Behi showed the effectiveness of a copper/water heat pipe in transferring heat to and from a paraffin PCM at around 40 °C [27]. Similarly, Motahar and Khodabandeh used a copper/water heat pipe to demonstrate enhanced heat extraction from a wax PCM at 28 °C [28].

A recent development has shown through model [29] and with an experimental prototype [30] a thermosyphon-based thermal valve for selectively and passively extracting thermal energy from a PCM. This sodium-based device was tested in transferring latent heat from a storage tank of Al/Si PCM at 577 °C to an array of thermoelectric generators. In that experiment, a heat flux of 3.28 kW/m^2 was demonstrated, far below that predicted [29], and for only several “on/off” cycles.

In the following work, a smaller version of this thermosyphon-based thermal valve was designed, fabricated, and tested to demonstrate improved heat flux transfer with extended reliability. In Section 2 of this paper, the details of the prototype device design are explained along with the construction and experimental methods. Then, in Section 3, the details of the theoretical models of this smaller scale device are presented to show the predicted functionality of the prototype. The experimental results are then presented in Section 4, demonstrating the thermal valve cycling “on” and “off” reliably for an extended duration and with continued high heat flux. After that, in Section 5, the experimental results are discussed explaining the implications of the collected data. Finally, Section 6 presents conclusions to offer insights into large-scale implementation of this technology and which avenues of research and development should be pursued in future studies.

2. Experimental setup

2.1. Device

The concept of this thermosyphon-based thermal valve was explained in detail in previous literature [29,30]. The thermal valve prototype design tested here is shown in Fig. 1a. Similar in functionality with a thermosyphon, the evaporator surface is the bottom disc area and the condenser surface is the top disc area. An inverted cone funnels the condensate droplets formed on the inner condenser surface down to the liquid tube. The condensate is then either blocked by a closed shut-off valve, as in the “off” state, or flows through the open valve, as in the “on” state. In the “on” state, the condensate continues down the liquid tube where it is then distributed in a ring over the inner evaporator surface by the diverter cone. From there, the liquid spreads over the evaporator surface due to gravity and the capillary pumping pressure developed in the wick. Heat is then absorbed through the evaporator and the liquid vaporizes and flows through the three vapor tubes where it releases its latent heat of vaporization on the condenser plate. The cycle then repeats as long as the heat source maintains a high enough temperature for evaporation and the heat sink maintains a low enough temperature for condensation.

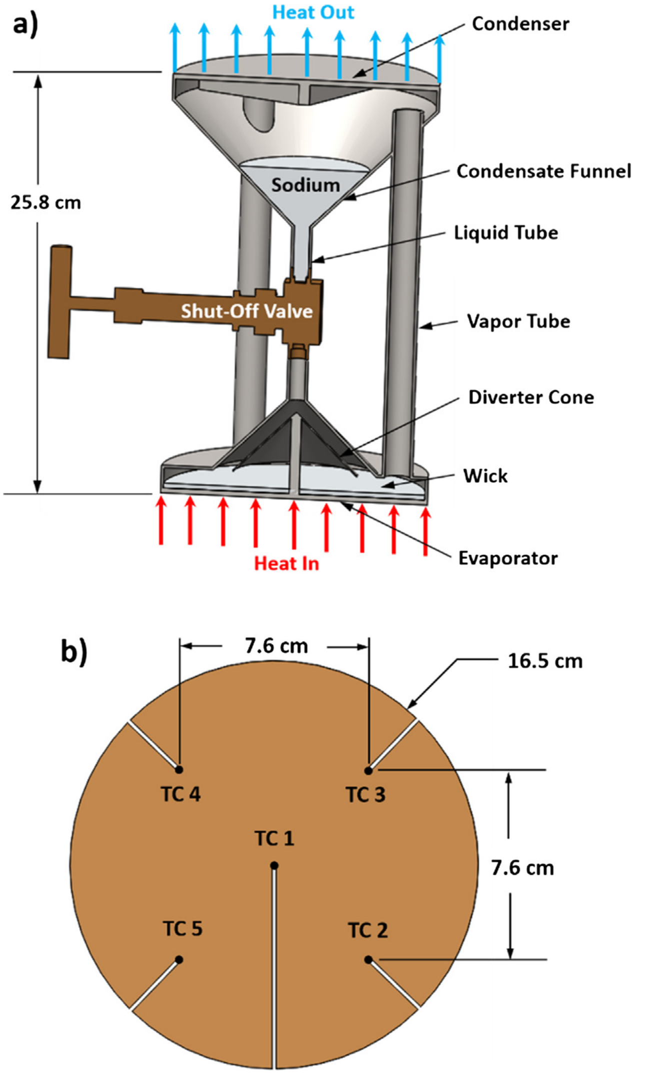

Fig. 1. (a) Cross-sectional view of the thermal valve showing the heat in through the evaporator and the heat out through the condenser. (b) Copper thermocouple (TC) spacer showing the layout of TCs on the evaporator and condenser plates.

The body of the 25.8 cm high, 16.5 cm diameter prototype vessel was fabricated from 1.5 mm thick stainless steel SS304 sheet while the evaporator and condenser plates were 3 mm thick to support the vacuum load at the elevated operational temperature. The conical structures, including the condensate funnel, diverter cone, and the diverter cone shell, were formed in two halves by creating many folds, then fitted and TIG welded together. The shut-off valve was a commercially available high-temperature