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ScienceDirect

Solar Energy 102 (2014) 318–332

SOLAR ENERGY

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# Thermal analytical model of latent thermal storage with heat pipe heat exchanger for concentrated solar power

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Received 19 May 2013; received in revised form 3 November 2013; accepted 11 November 2013
Available online 6 December 2013

Communicated by: Associate Editor Doerte Laing

## Abstract

An analytical model is developed for predicting the transient thermal behavior of a latent thermal energy storage (LTES) system in which circular fins are attached to the heat pipes. Thermal energy is stored or released by the heat pipe heat exchanger, and pure conduction is assumed for the charging and discharging modes. Considering the thermal environment required to concentrated solar power (CSP), potassium nitrate ($KNO_3$), which has a phase-change temperature of 335 °C, is used as the phase-change material (PCM). Themal model used to estimate the heat transfer rate and the transient temperature variation in the PCM contained in each row of the heat pipe heat exchanger. Both melting and solidification are simulated under pure conduction. Row-by-row heat transfer is considered to assist estimation of row number of the entire LTES system. The developed model is also evaluated by comparing its predictions with the experimental results of a valid previous study. The discrepancies were observed to be less than 8%.

*Keywords:* Latent thermal storage; Phase-change material; Solar power plant; Heat pipe; Thermal modeling; Thermal resistance

## 1. Introduction

To improve the management and supply of solar power, many studies have been conducted on the design and fabrication of systems used for collecting, transporting, and storing solar energy (Michels and Pitz-Paal, 2007; Kamimoto et al., 1980; Vaivudh et al., 2008; Montes et al., 2009; Duffie and Beckman, 1980). Among the studied systems is the latent thermal energy storage (LTES) system, which is used to store thermal energy during the day and release it at night, thereby enabling the continuous utilization of solar power. LTES technology is used to store and release the latent heat generated during the melting and solidification of a phase-change material (PCM). A material that undergoes phase change within a specific temperature range can be used for LTES if it satisfies a number of criteria regarding, for example, its procurement and handling costs and the operation temperature of the system. It has particularly been established that, in the absence of quality degradation such as decomposition within the temperature range of the phase change, an LTES system has a higher heat storage capacity than single-phase and pack-bed energy storage systems (Duffie and Beckman, 1980).

The temperature of the heat transfer fluid (HTF; generally vapor or air) used for LTES in a concentrated solar power (CSP) system should be maintained between 250 °C and 500 °C (Michels and Pitz-Paal, 2007). Traditionally, alkali nitrate salts or chloride eutectic compositions, which have phase-change temperatures above

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http://dx.doi.org/10.1016/j.solener.2013.11.008

## Nomenclature

| | |
|---|---|
| $A$ | area (m$^2$) |
| $c$ | specific heat (kJ/kg C) |
| $D$ | fin density (fins/m) |
| $d$ | diameter (m) |
| $f$ | friction factor |
| $G$ | mass velocity (kg/s m$^2$), $G = \dot{m}/\sigma A_{fr}$ |
| $h$ | heat transfer coefficient (W/m$^2$ °C) or enthalpy (kJ/kg) |
| $H$ | height (m) |
| HP | heat pipe |
| HPHEX | heat pipe heat exchanger |
| HTF | heat transfer fluid |
| $j$ | index of number of row or Colburn factor |
| $k$ | thermal conductivity (W/m °C) |
| $L$ | length (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $N$ | heat pipe number per row |
| $p$ | pipe or fin pitch |
| $P$ | pressure (Pa) |
| $pr$ | Prandtl number |
| $Q$ | heat transfer rate (W) |
| $R$ | thermal resistance (°C/W) |
| $Re$ | Reynolds number |
| $r$ | radial position (m) or radius (m) |
| $s$ | fin space (m) |
| $St$ | Stanton number |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $u$ | velocity (m/s) |
| $V$ | volume (m$^3$) |
| $v$ | specific volume (m$^3$/kg) |
| $X$ | tube bank pitch (m) |
| $X_D$ | tube bank diagonal pitch (m), $[(X_T/2)^2 + X_L^2]^{1/2}$ |

*Greek symbols*

| | |
|---|---|
| $\delta$ | fin thickness (m) |
| $\eta$ | fin efficiency |
| $\mu$ | fluid dynamic viscosity (m$^2$/s) |
| $\phi$ | porosity of capillary screen wick structure |
| $\kappa$ | local volume fraction of fins at the LTES |
| $\rho$ | density (kg/m$^3$) |
| $\upsilon$ | specific volume (m$^3$/kg) |

*Subscripts*

| | |
|---|---|
| *a* | ambient |
| *c* | charging |
| *d* | discharging |
| *cap* | capillary structure |
| *cap-HPHEX* | capillary structure in the HPHEX |
| *cap-LTES* | capillary structure in the LTES |
| *cap-o* | capillary structure outer diameter |
| *cap-i* | capillary structure inner diameter |
| *eff* | effective |
| *eq* | equivalent |
| *evap* | evaporator |
| *f* | fluid or fin |
| *f-fin* | between HTF and fins |
| *fin-pcm* | between fin and pcm |
| *fr* | frontal |
| *h* | hydraulic |
| *i* | inner |
| *j* | HP row inex |
| *L* | length |
| *W* | width |
| *l* | liquid |
| *sl* | solid–liquid phase change |
| *m* | mean value |
| *max* | maximum value |
| *min* | minimum value |
| *o* | outer or overall |
| *p* | pipe or pressure |
| *pcm* | phase change material |
| *T* | total |
| *wf* | working fluid within HP |
| *w-HPHEX* | HP wall in the HPHEX |
| *w-LTES* | HP wall in the LTES |

250 °C, have been used as thermal storage materials (Kenisarin, 2010; Ferri et al., 2008). Although there are PCMs that can be used at various operation temperatures, their detailed thermophysical properties are not fully understood (Kenisarin, 2010; Shabgard et al., 2010).

To control the time of the temperature rise of a PCM and enhance its thermal performance, an extended surface is used in many applications (Bergantz, 1992; Lacroix, 1993; Hamada et al., 2003; Agyenim et al., 2010; Liu et al., 2006). PCMs with better thermophysical properties have also been developed by mixing different PCMs in specific proportions (Kenisarin, 2010).

Shell-and-tube heat exchangers are commonly used in LTES systems (Bergantz, 1992; Lacroix, 1993; Hamada et al., 2003; Agyenim et al., 2010). Additionally, an LTES system with a heat pipe heat exchanger (HPHEX) that possess an excellent heat transfer efficiency has also been successfully developed (Liu et al., 2006; Shabgard et al., 2012; Robak et al., 2011).

Theoretical studies were conducted on a heat pipe (HP)-based LTES system. Sharifi et al. (2012) conducted a study on the heat transfer numerical model of an LTES system using a single HP and using sodium nitrate as the PCM. The numerical model was used to derive detailed governing