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# Efficient optimization of a longitudinal finned heat pipe structure for a latent thermal energy storage system

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ABSTRACT

Phase Change Materials (PCMs) are gaining importance in energy storage applications. However, many PCMs are poor thermal conductors and thus can benefit from the optimal use of appropriate fins. This work introduces a PCM-fin structure optimization framework. Typically, the non-linear solidification process increases the complexity associated with solving the mathematical equations for the PCM-fin structure optimization problem, making it computationally expensive. In this paper a modeling approach called Layered Thermal Resistance (LTR) model is extended and developed in 2D cylindrical geometry in order to enable efficient PCM-fin structure optimization. The finned LTR model represents the nonlinear transient solidification process by analytic equations. This significantly reduces the computational cost associated with optimization. A finned heat pipe structure modeled by the finned LTR approach is optimized based on minimizing cost while meeting operational requirements. The optimal results imply that thinner fins result in lower system cost and that there is a thickness limit for the fins to be economically welded on a heat pipe. The finned LTR model also gives the optimal cost of material usage for a large scale latent thermal energy storage system in terms of dollars per kilowatt and it was found that the system cost is slightly lower by using carbon-steel as the construction material for the heat pipes and fins than by using Al 6061.

## 1. Introduction

Increasing research is focused on thermal energy storage systems due to their important role in clean energy technologies and the need to match renewable energy to load patterns. For example, thermal energy storage systems are needed to address the mismatch between the supply and demand of solar energy. Providing “cold storage” produced at lower costs during off peak hours of the day, is a practical way to reduce utilities’ burden to produce enough electricity during high demand hours [1,2].

Many mature and industrial applications of thermal energy storage systems use sensible energy. Phase Change Materials (PCMs) are receiving more attention due to their high-energy densities. PCM can store or release energy at near isothermal conditions that are thermodynamically superior. However, the low conductivity of PCM materials is a barrier for many practical applications, especially for large scale systems. Researchers are eager to resolve this issue by employing different heat transfer enhancement techniques, i.e., including high conductivity foams or metal matrices into the PCM [3], dispersing high conductivity particles in the PCM [4], or using microencapsulation of the PCM [5]. Extensive research has been conducted to study the shell and tube systems with fins in the PCM since they can be simple and compact [6–12].

Embedding Heat Pipes (HPs) between the PCM and the Heat Transfer Fluid (HTF) is also an approach that attracts a lot of research. Faghri [13,14] patented methods to embed HPs into PCM to enhance the performance of thermal energy storage systems and heat exchangers. Horbaniuc et al. [15] analytically modeled the solidification of PCM within a longitudinally finned HP storage system. Liu et al. [16] experimentally studied a circumferentially-finned HP heat exchanger with latent heat storage similar to that of Horbaniuc et al. Shabgard et al. [17] developed a thermal network model for a HP embedded latent thermal energy storage (LTES) unit. The same authors also used a thermal network model to analyze a LTES system with embedded HPs and cascading PCMs [18]. Christopher et al. [19] defined the HP effectiveness and experimentally investigated a LTES system utilizing HPs or fins. Nithyanandam [20] developed a thermal resistance network model of a shell and tube LTES with embedded HPs and parametric

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**Nomenclature**

| | |
|---|---|
| $T_{hp}$ | heating temperature at the boundary |
| $T_m$ | PCM melting temperature |
| $S_1$,$S_2$ | heat transfer area (shrinking liquid-solid interface) |
| $q(i)$ | heat flux |
| $R_1$,$R_2$ | thermal resistances for different heat paths |
| $R_1^*$ | thermal resistance includes both the fin and PCM domains |
| $R_t$ | total thermal resistance of a system |
| $R_f$ | fin thermal resistance |
| $\eta$ | fin efficiency |
| $\xi$ | parameter for fin efficiency calculation |
| $L_m$ | latent energy of PCM |
| $Cp_{pcm}$ | heat capacity of PCM |
| $k_{pcm}$ | conductivity of PCM |
| $k_{fin}$ | conductivity of fin |
| $\rho_{pcm}$ | density of PCM |
| $\rho_{hp}$ | density of heat pipe material |
| $\rho_f$ | density of fin material |
| $t(i)$ | discrete solidification time for PCM layers |
| $t_s$ | total solidification time |
| $D_r(i)$,$L(i)$ | locations of solid fronts |
| $c$ | fin and PCM thickness |
| $dV(i)$ | layered PCM volumes |
| $\theta$ | half spacing angle of a cell between two longitudinal fins |
| $f$ | resistance tuning surface in 2D |
| $\alpha$ | resistance tuning value |
| $t_{LTR}$ | PCM solidification time estimated by LTR model |
| $t_{CFD}$ | PCM solidification time estimated by CFD model |
| $t_{op}$ | discharging time requirement |
| $\varepsilon$ | prediction discrepancy |
| $T_{cell}$ | temperature of a discrete element |
| $T_{upper}$ | upper PCM melting temperature |
| $T_{lower}$ | lower PCM melting temperature |
| $\psi(0)$ | dimensionless superheating parameter |
| $T_{ini}$ | initial temperature of the PCM domain |
| $\gamma$ | PCM liquid fraction |
| $h$ | heat transfer coefficient on the PCM side |
| $G$ | cooling load target |
| $C_{pcm}$ | cost of PCM |
| $C_{hp}$ | cost of heat pipe |
| $C_f$ | cost of the fin |
| $M_{pcm}$ | the amount of PCM to be used |
| $M_{hp}$ | the amount of heat pipe material to be used |
| $M_{fin}$ | the amount of fin material to be used |
| $V_{pcm}$ | total PCM volume |
| $H_p$ | height of each heat pipe |
| $N_p$ | total number of heat pipes |
| $w_{hp}$ | wall thickness of the heat pipe |
| $r_0$ | inner radius of the heat pipe |
| $N_f$ | total number of fins welded to a heat pipe |
| $r_1 = r_0 + w_{hp}$ | outer radius of the heat pipe |
| $r_2$ | radius of the longitudinal fin welded on the heat pipe |
| $w$ | thickness of the longitudinal fin |
| $g$ | cost equation |

studies of the influence of the heat pipe. The same authors [21] also created a transient three-dimensional computational model for the system to guide design efforts. Nithyanandam [22] also provided numerical simulations to illustrate their methodology for design and optimization of the shell and tube LTES with embedded HPs for required storage costs. Sharifi [23] considered three operational modes (charging, discharging and simultaneous charging and discharging) of a vertical cylindrical enclosure PCM unit with concentric HPs at its center. Naghavi [24] experimentally investigated a solar water heater system with a latent heat storage tank embedded with HPs. Tiari [25–27] numerically studied the finned HP-assisted LTES unit in 2D and 3D. Almsater [28] used finned heat pipes to enhance heat transfer performance in concentrating solar thermal power applications.

Although a lot of researchers have numerically and experimentally studied finned HP-assisted LTES systems, limited research has been focused on the optimization of a finned HP, i.e. optimizing the length and number of fins. In terms of optimization methods, Veelken [29] used combined numerical modeling and a genetic algorithm to find optimal fin positions on a contact surface with non-uniform heat loads. Pizzolato [30] employed a topology optimization framework to find the optimal spatial layout of high conductivity material within PCMs. Lohrasbi [31,32] proposed to use a response surface method (RSM) which requires establishing a relationship between the design variables of interest and the objective function. By estimating the effects of each parameter on the objective function, it provides a more efficient approach for parametric studies. RSM has also been applied to optimize a microchannel heat sink [52]. The use of central composite design (CCD) in microchannel heat sink optimization is also studied in [53]. In many cases, optimizations have often been based on parametric studies through simulations [33–37]. Multiple simulations need to be carried out for variations of the design parameters of interest. Due to the transient nonlinear behavior of PCM solidification or melting, the process is computationally expensive and can only guarantee near-optimal solutions. In this paper, an analytical Layered Thermal Resistance (LTR) model [38] is extended for the first time, to a 2D cylindrical geometry to support the efficient optimization of PCM-fin energy storage structures. The LTR model describes the nonlinear transient solidification process with algebraic equations, thus significantly reducing the computational complexity of the optimization problem. Moreover, most of the previous optimization analyses of the fin-PCM structure [31–37] are based on improving heat flux and increasing fin efficiency. In this paper, the focus is instead on directly optimizing system cost while the role of heat flux is indirectly addressed by setting the discharging time requirement. The LTR model can be used to easily incorporate this objective function and constraint in the optimization framework. With this framework, a more relevant engineering comparison among different fin configurations becomes possible. This novel modeling approach has wide applications for the optimal design of latent energy storage systems with fins. In this paper, the LTR mode is used for the first time to find the optimal dimensions of a finned heat pipe.

The content of this paper is organized as follows. In Section 2, the LTR model for a 2D cylindrical geometry is developed. Section 3 introduces coupling fins to the LTR model. In Section 4, the finned LTR model is employed to solve the finned HP optimization problem followed by a discussion of the results. Section 5 presents the conclusions.

## 2. Layered thermal resistance model in 2-D cylindrical coordinates

The Layered Thermal Resistance (LTR) model was first proposed in [38] for rectangular and cuboidal geometries; it is based on a thermal resistance network analysis [17,20,22]. In this section a new extension to PCM solidification with constant cooling temperatures at the boundaries in a cylindrical coordinate system is developed in order to represent tube-shell configurations. Fig. 1 shows the geometry of interest, which is cooled at the two sides with constant temperature boundary conditions and has zero heat flux at the remaining two sides. The key component of the LTR model is the assumption that the liquid PCM is solidified in a layer by layer manner and that the final