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Cost estimation and sensitivity analysis of a latent thermal energy storage system for supplementary cooling of air cooled condensers

Chunjian Pan[a,*], Natasha Vermaak[a], Carlos Romero[a], Sudhakar Neti[a], Sean Hoenig[b], Chien-Hua Chen[b], Richard Bonner III[b]

[a] Energy Research Center, Lehigh University, Bethlehem, PA 18015, USA
[b] Advanced Cooling Technologies, Inc., Lancaster, PA 17601, USA

HIGHLIGHTS

- A novel phase change material (PCM) based cooling application is proposed.
- A modeling method for a finned heat pipe assisted PCM system in 3D is developed.
- Optimal design and cost sensitivity analysis of the system are presented.

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Air cooled condensers
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Finned heat pipe embedded PCM
Cost optimal design

ABSTRACT

As a booming economy drives the need for more electricity, demands on freshwater for thermoelectric power generation also grow. Facing the limited freshwater resources, alternative dry cooling technologies that reduce water consumption are becoming more prevalent. However, the performance of air cooled condensers (ACCs) is seriously deteriorated at ambient temperature. To address this challenge, a novel application of a Phase Change Material (PCM) based cooling system for supplementary cooling of ACCs is proposed. In order to evaluate the system cost, a solidification modeling approach called a Layered Thermal Resistance (LTR) model is extended to 3D in cylindrical coordinates for the first time. The LTR model efficiently estimates the behavior of a finned heat pipe module for the PCM-based cooling system. In the present work, a new nonlinear optimization problem is formulated, based on the LTR model, to estimate system cost and conduct sensitivity analysis. Overall, it is found that the material cost of the finned heat pipe-assisted PCM tank is around 30 $/kW for a 10-h solidification time requirement, which is a promising cost for the system to be accepted in the market. Based on the sensitivity analyses, it is found that the latent energy of the PCM has first-order impact on the system cost.

1. Introduction

Phase Change Materials (PCMs) have received increasing attention in the application of thermal energy storage systems due to their high-energy densities [1]. There are many research studies focused on using PCMs for cooling applications. Among them, popular applications include passive cooling for building envelopes using lower temperature PCMs [2,3]. A comprehensive review of PCM based cooling technologies that enhance the efficiency of photovoltaic power systems can be found in Chandel et al. [4]. Zhao [5] studied a PCM based internal cooling system for a cylindrical Li-ion battery pack. Arshad [6] investigated the thermal performance of PCM-based pin-finned heat sinks for electronic cooling. Ibrahim [7] experimentally tested a solar absorption cooling system assisted with ice storage. Ice storage for air conditioning in buildings has already been successfully implemented in several applications. In addition to electricity bill savings, cold energy produced and stored at lower costs during off-peak hours of the day can reduce the burden to produce enough electricity during high demand hours [8]. Researchers are continually working on further optimization of the ice storage-based air conditioning systems [9,10]. Luo [11] further reported that a large-scale ice-thermal storage system can be used as a smart load for fast voltage control and demand-side management in power systems with intermittent renewable power.

In this paper, an innovative application of a PCM-based cooling system (see Fig. 1) for supplemental cooling/cool storage of air cooled condensers (ACCs) in power plants is proposed for the first time. The system does not involve the dissipation of water to the atmosphere and enables power plants to maintain their high efficiency even in hot

* Corresponding author.
E-mail address: chp313@lehigh.edu (C. Pan).

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Nomenclature

A	geometric factor
C	cost of materials
C_p	heat capacity of PCM
dT	driving temperature difference
D,E,H	locations of 3D discrete solid fronts
G	cooling load target
h	height of the longitudinal fin between two circular fins
HP	height of a single heat pipe
k	conductivity
K	number of discrete layers
L	latent energy
M	material mass
N	quantity
q	heat flux
r_0	inner radius of the heat pipe
r_1	outer radius of the heat pipe
r_2	radius of the longitudinal fin welded on the heat pipe
R	thermal resistance
S	heat transfer area (Shrinking liquid-solid interface)
t	solidification time
T	temperature
u	heat transfer coefficient within the PCM
ΔV	layered PCM volumes
V	total material volume
w	fin or heat pipe thickness

Greek symbols

α	resistance tuning parameter
θ	half angle between two neighboring longitudinal fins
ρ	density
ε	prediction discrepancy
γ	PCM liquid fraction
η	fin efficiency
σ	thickness out of the paper

Subscript

1, 2, 3	three heat flow paths within a 3D bulk PCM
c	circular fin
cell	a discrete element cell
CFD	computational fluid dynamics model
f	both longitudinal and circular fins
hp	heat pipe
hppcm	PCM volume of a single heat pipe
l	longitudinal fin
lower	lower PCM melting temperature
LTR	layered thermal resistance model
m	PCM melting temperature
op	required solidification time
pcm	phase change material
s	bulk PCM solidification time
total	total thermal resistance
upper	upper PCM melting temperature

Superscript

i	discrete index
*	thermal resistance incorporated with fin and fin efficiency

seasons. As a booming economy drives the need for more electricity, demands on freshwater for thermoelectric power generation also grow. However, freshwater is limited and is becoming more valuable for our growing global population. This constraint will affect future electricity generation. Thus, alternative dry-cooling technologies that reduce water consumption are needed. However, the performance of air-cooled condensers (ACC's) is very sensitive to wind conditions and is not optimal at ambient temperatures [12]. That is ACCs become less effective when ambient temperature is higher (see Fig. 2). Consequently, the existing ACCs may fail to condense all the steam (direct) or sufficiently cool the process coolant water (indirect).

To address these challenges confronted by ACCs, a novel cooling concept by incorporating the use of PCMs is proposed in this paper for the purpose of supplementary cooling when the ACC's performance is deteriorated. The ACC's performance is most affected during hot summer daytimes. During the night, temperatures can be more than 10 °C lower than daytime, especially in relatively dry regions. Thus the idea is to turn the night-time lower temperature into cooling energy that can be used for cooling during daytime. The proposed approach is to use a PCM reservoir to store the cooling resource (freezing) during night-time and to provide cooling energy (melting) during the daytime. A suitable PCM candidate under investigation is $CaCl_2\cdot 6H_2O$, which has

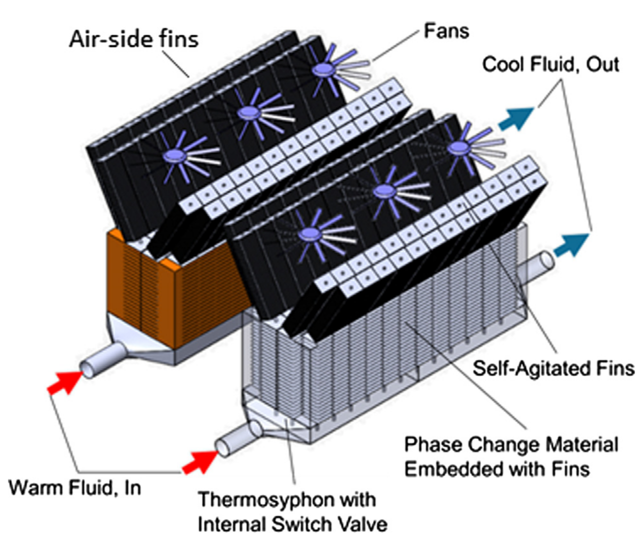

Fig. 1. The concept design for the PCM cooling units.

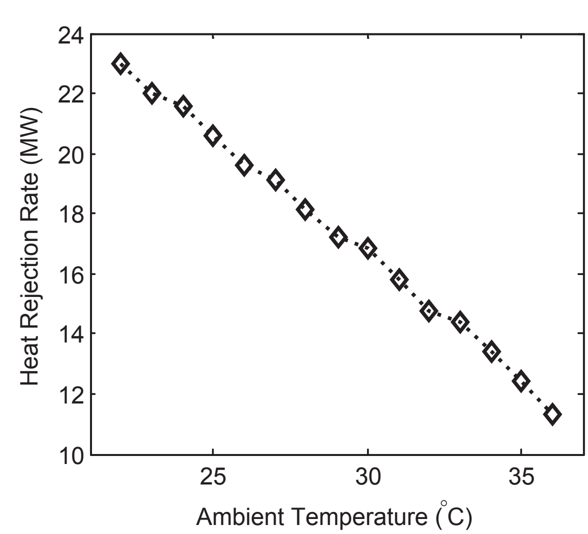

Fig. 2. ACC heat rejection under fluctuations of ambient temperatures [12].