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Optimal design of PCM thermal storage tank and its application for winter available open-air swimming pool

Yantong Li[a], Gongsheng Huang[a], Tao Xu[b,*], Xiaoping Liu[c], Huijun Wu[b]

[a] Department of Architecture and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong
[b] Academy of Building Energy Efficiency, School of Civil Engineering, Guangzhou University, Guangzhou 510006, China
[c] School of Civil Engineering, Hefei University of Technology, Hefei 230009, Anhui, China

HIGHLIGHTS

- A general procedure of optimizing PCM thermal storage tank was proposed.
- A new heating system for open-air swimming pool for cold season was developed.
- With optimization the tank volume can be significantly reduced.
- The developed heating system can bring considerable economic benefits.

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ABSTRACT

This paper presents a general procedure to optimize the design of a PCM storage tank, including the specification of design objectives, the identification of decision variables (for optimization), the construction of computer simulation platform and the final decision making. The general procedure was demonstrated by applying it to an open-air swimming pool, where the design objective was to minimize the volume of the PCM storage tank when it was required to enable heat storing to maintain the water temperature of an open-air swimming pool inside the thermal comfortable range during its open period in winter season. After identifying decision variables, a computer simulation platform was developed using TRNSYS and MATLAB to investigate the effects of the decision variables on the volume of the PCM storage tank. Case studies show that the proposed optimization is able to efficiently reduce the volume of the PCM storage tank without sacrificing the thermal storage capacity. Therefore, this study provides useful guidelines to optimize the design of a PCM storage tank.

1. Introduction

Thermal storage materials are significant for energy management and therefore have gained wide applications in our daily life. For instance, Tian et al. [1] reviewed different thermal storage materials which could be used in the solar collectors. Xu et al. [2] summarized different approaches in which thermal storage materials were applied in the solar thermal power plants. Currently, there are three major types of energy storage materials, including sensible, latent and thermo-chemical materials [3]. Compared with sensible and thermo-chemical heat storage materials, phase change materials (PCM) have the advantage of high energy storage density and are able to maintain temperature (nearly) constant during the phase change process [4]. Therefore, it has been widely used in many systems for storing thermal energy. For example, Bouadila et al. [5] experimentally investigated the effect of different weather conditions on the thermal performance of the solar collector with PCM. Nabavitabatabayi et al. [6] numerically compared the thermal performance of the PCM storage tank with different types of PCMs. They reported that the enhanced PCMs could improve the performance of the PCM storage tank. Alvarez et al. [7] proposed several solutions to improve the performance of the conventional night cooling system with PCM, which includes increasing the contact area between PCM and air, and increasing convective heat transfer coefficient. Mosaffa et al. [8] analyzed the influence of the air inlet temperature and flow rate on the energy and exergy performance of the free cooling system with multiple PCMs. Lei et al. [9] reported that using PCM could effectively reduce the cooling load of buildings in tropical climatic regions. Mi et al. [10] analyzed the energy and economic performance of PCM wallboards in different cities of China. Xu et al. [11] investigated the thermal performance of the building with a

* Corresponding author.
E-mail address: 736848541@qq.com (T. Xu).

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Nomenclature

A_c	cross area (m^2)
A_{cod}	conductive heat transfer area (m^2)
A_P	heat transfer area of tube wall (m^2)
A_{pool}	surface area of swimming pool (m^2)
ARE	average relative error (%)
C_e	operational cost of traditional system (HKD)
C_i	initial investment of proposed system (HKD)
C_P	operational cost of proposed system (HKD)
cp_P	specific heat of the PCM (kJ/kg·°C)
cp_f	specific heat of heat transfer fluid (kJ/kg·°C)
cp_l	liquid specific heat of PCM (kJ/kg·°C)
cp_s	solid specific heat of PCM (kJ/kg·°C)
D_{out}	outer diameter of PCM tubes (m)
e	heat transfer effectiveness (–)
HTF	heat transfer fluid
H_m	specific enthalpy of PCM (kJ/kg)
H_p	enthalpy of PCM (kJ/kg)
i	Iteration number in the PCM storage tank (–)
j	Iteration number of the experimental sample (–)
h_c	convection heat transfer coefficient (W/m^2·°C)
h_{eva}	evaporation heat transfer coefficient (W/m^2·Pa)
h_f	convective heat transfer coefficient of HTF (W/m^2·°C)
h_{fp}	effective convective heat transfer coefficient (W/m^2·°C)
k_f	thermal conductive coefficient of HTF (W/m·°C)
k_l	liquid thermal conductive coefficient (W/m·°C)
k_s	solid thermal conductive coefficient (W/m·°C)
k_{soi}	thermal conductivity of the soil (W/m·°C)
G_{sol}	solar irradiance (W/m^2)
L_{cod}	characteristic length of the swimming pool (m)
l	length of PCM tubes (m)
m	number of experimental sample (–)
m_f	mass flow rate of HTF (kg/s)
m_{re}	mass flow rate of refilling fresh water (kg/s)
N	Number of discrete element in the PCM storage tank (–)
Nu	Nusselt number (–)
n	number of PCM tubes (–)
n_{min}	minimum number of PCM tubes (–)
OSR	operational cost saving ratio (%)
PCM	phase change material
P_{amb}	partial vapor pressure of ambient temperature (Pa)
Pr	Prandtl number (–)
P_{sat}	saturated vapor pressure of pool surface temperature (Pa)
Q_{tank}	heat stored in the PCM storage tank (kJ)
q_{PCM}	heat gained from PCM storage tank (kW)
q_{actual}	actual heat transfer rate (kW)
q_{cod}	heat loss resulting from conduction (kW)
q_{cov}	heat loss resulting from convection (kW)
q_d	dimensionless conduction heat transfer rate (–)
q_{eva}	heat loss resulting from evaporation (kW)
q_{max}	maximum heat transfer rate (kW)
q_{rad}	heat loss resulting from radiation (kW)
q_{refl}	heat loss resulting from refilling water (kW)
q_{sol}	heat gained from solar (kW)
q_{tot}	total heat transfer rate (kW)
Re	Reynolds number (–)
R_f	thermal resistance of HTF (m^2·°C/W)
R_w	thermal resistance of tube walls (m^2·°C/W)
R_P	thermal resistance of PCM (m^2·°C/W)
T_a	ambient temperature (°C)
$T_{cold,in}$	inlet temperature on the cold side (°C)
$T_{cold,out}$	outlet temperature on the cold side (°C)
T_f	temperature of HTF (°C)
$T_{hot,in}$	inlet temperature on the hot side (°C)
$T_{hot,out}$	outlet temperature on the hot side (°C)
$T_{i,exp}$	experimental temperature (°C)
$T_{i,sim}$	simulated temperature (°C)
T_m	phase change temperature (°C)
T_p	temperature of PCM (°C)
T_{pool}	water temperature of swimming pool (°C)
T_{re}	temperature of refilling fresh water (°C)
T_{sky}	equivalent sky temperature (°C)
T_{soi}	soil temperature (°C)
T_0	initial temperature (°C)
t	time (s)
SPP	simple payback period (years)
V_s	volume of one element (m^3)
V_{min}	minimum volume of PCM storage tank (m^3)
V_{pool}	volume of the swimming pool (m^3)
V_{wind}	wind velocity (m/s)
$V_{without}$	volume of water tank (without PCM) (m^3)
v_f	mean velocity of HTF (m/s)
x	distance (m)
α_{sol}	effective solar absorptance coefficient (–)
ε	water fraction in the PCM storage tank (–)
ε_f	water emissivity coefficient (–)
ε_{sky}	sky emissivity coefficient (°C)
ρ_P	density of PCM (kg/m^3)
ρ_f	density of heat transfer fluid (kg/m^3)
ρ_m	density of PCM (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2·K^4)
φ_{saving}	volume saving ratio (%)

novel concrete blocks with the composite PCM. They reported that PCM could improve the indoor thermal comfort of the buildings.

There are many designs to implement PCMs in energy storage systems. One typical design is the *PCM storage tank*. The storage tank can be in the form of shell-and-tube. For example, in the study of Fornarelli et al. [12] and Tehrani et al [13], PCMs were filled in cylindrical tubes and heat transfer fluids (HTF, such as water) pass through the center of the tube. The melting process of the PCMs was analyzed using the technique of computer fluid dynamics (CFD). In the studies of Peng et al. [14], Wu et al. [15] and Amin et al [16], PCMs were encapsulated into spheres and the storage unit was shaped in the form of packed bed.

Another typical design is *PCM slab*. PCM slabs are usually used in the free cooling system, in which air flows through the gap between two PCM slabs to transfer heat [7]. For example, Faheem et al. [17] used ventilated hollow cores to increase the contact area between the air and the PCM slab to enhance the heat transfer. Navarro et al. [18] developed a type of PCM slab, which contained air channels integrated with PCM tubes.

PCMs can also be designed as *PCM wallboard.* For example, in the study of Lei et al. [9], PCM wallboards were compared when they were installed on exterior wall and interior wall. Mi et al. [10] developed a kind of PCM wallboards where the PCMs were filled between the mortar and reinforcement concrete. Kuznik et al. [19] designed a PCM wallboard, where the PCMs were placed between the polystyrene and the plaster. In the study of Barzin et al. [20], PCM wallboards were placed under the floors.

Although PCMs have gained wide applications, how to optimize the PCM unit design is still a challenge because the PCM unit design should not only consider the thermal properties of PCM unit itself, but also the operation characteristics of the system which hosts it. In current literature, a few studies can be found to address this issue. For example, Haillot et al. [21] and Padovan et al. [22] used genetic algorithm (GA)