Energy and Buildings 127 (2016) 512–520

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Two performance indices of TES apparatus: Comparison of MPCM slurry vs. stratified water storage tank

Shuo Zhang [a,b], Jianlei Niu [a,*]

[a] Department of Building Service Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, PR China
[b] Business Environment Council Limited, 77 Tat Chee Avenue, Kowloon Tong, Hong Kong

ARTICLE INFO

Article history:
Received 12 December 2015
Received in revised form 16 April 2016
Accepted 27 May 2016
Available online 3 June 2016

Keywords:
MPCM slurry
Helical coil
Stratified water storage tank
Charging rate
volumetric thermal storage capacity
Overall heat transfer coefficient

ABSTRACT

Microencapsulated phase change material (MPCM) slurry, which has a higher thermal storage capacity than water, was introduced as a storage medium in a coil-in-tank, but the key question is whether a competitive charging/discharging rate could be achieved. In this paper, two key indices, the volumetric thermal storage capacity at a given temperature difference and the charging/discharging rate variation over time, are newly defined. From the experimental results, it is estimated that the volumetric thermal storage capacity of the MPCM slurry is nearly twice that of water in the temperature range of 8–18 °C. Finally, the overall heat transfer coefficient of the slurry storage device as a shell-tube heat exchanger was measured, and the external average convective heat transfer coefficient was also calculated. The two coefficients exhibited visible peaks during the phase change process with high-speed stirring and were much higher than that of water. However, the overall charging/discharging rates of the MPCM storage tank were observed to be much lower than the idealized stratified water storage tank (SWST), indicating that the design of an MPCM slurry thermal storage device needs to be further optimized.

1. Introduction

The major design criteria for an efficient thermal energy storage (TES) apparatus include a high thermal storage capacity and a good heat transfer rate between the phase change material (PCM) and the heat transfer fluid [1]. Water has been widely used as a sensible storage medium for its easy availability, stability and low price. To maximize the utilization of the stored energy, thermal stratification caused by thermal buoyancy is introduced in a water storage tank, which is known as a stratified water storage tank (SWST) [2]. By incorporating the thermal stratification, the temperature difference between inlet and outlet of the SWST is maximized during the whole charging/discharging process. Therefore, the charging/discharging rate of the system is maximized, which is an attractive advantage for industry applications. However, the disadvantage of water storage is that the thermal storage capacity is low since the only sensible heat capacity is used. Large volume water tanks have to be used, which will strongly affect the utilization potential and the economy of the water storage applications. For this reason, various novel materials have been investigated as storage media in TES apparatus. Starting from early 1980s, paraffin series as phase change materials (PCM) have been considered as potential media, as they possess good storage density, good chemical stability, little supercooling, low cost, and flexible working temperature that can easily be suited to both building cooling/heating and hot water applications [3].

Till today, a barrier to the wide use of PCM is the low conductivity of most PCM, leading to low charging/discharging rate of TES systems [4]. Consequently, the system response time is long, and thermal energy cannot be stored/released in the limited time to meet the utilization requirement. To expand the industrial application, research was initially conducted concerning the understanding of heat transfers/exchanges in the PCM during solid/liquid phase transition in the required operating temperature range [5]. In addition, several approaches have been developed for the purpose of heat transfer enhancement, including design optimization of the container for holding the PCM [6,7], adding powders or fibers of high conductivities [8,9], immersing porous metal/graphite matrix [10], and PCM encapsulation [11]. One way to enhance heat transfer is to use a microencapsulated phase change material (MPCM) water-slurry as the thermal storage medium. The surface area to volume ratio of MCPM slurry is large, therefore the cooling can be quickly absorbed/released from the core to the carrier fluid, which means a higher heat transfer rate compared with traditional TES system using bulk PCM. In addition, compared with pure water

* Corresponding author.
E-mail addresses: shuo.zhang@connect.polyu.hk (S. Zhang), jian-lei.niu@polyu.edu.hk (J. Niu).

http://dx.doi.org/10.1016/j.enbuild.2016.05.085
0378-7788/

Nomenclature

A	Heat transfer area of heat exchanger (m^2)
c_p	Specific heat capacity (kJ/(kg K))
d	Diameter of tube (m)
D	Diameter of coil (m)
E	Energy (J)
ΔE	Cooling energy storage (J)
E_V	Volumetric thermal storage capacity (J/m^3)
F	Correction factor
ΔH	Latent heat storage (J)
h	Heat transfer coefficient (W/(m^2 K))
l	Thickness (m)
Lf	Latent heat of fusion (kJ/kg)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
q	Charging/discharging rate, rate of heat flow (W)
R	Thermal resistance (W/°C)
T	Temperature (°C)
ΔT	Temperature difference (°C)
U	Overall heat transfer coefficient (W/(m^2 K))
ΔU	Sensible heat storage (J)
V	Volume (m^3)
$\dot{v}$	Volume flow rate m^3/s

Greek symbols

τ	Time (s)

Subscripts

c	Charging
ch	Chiller
d	Discharging
e	End
err	Error
ex	External
i	Initial
in	Inlet, internal
lab	Laboratory
loss	Heat loss
m	Mean
out	Outlet
p	Radiant cooling panel
sl	MPCM slurry
t	Storage tank, storage medium
w	Water

storage, an MPCM-in-water slurry has a significantly-enhanced equivalent heat capacity, even at low mass fractions [12].

Several past studies were conducted to investigate the flow and melting heat transfer characteristics of MPCM slurry in a horizontal circular tube. Yamagishi et al. [13,14] experimentally investigated the MPCM slurry made of octadecane ($C_{18}H_{38}$), and found that in the case of a laminar MPCM slurry flow, the heat transfer performance degraded compared with that of a turbulent flow. Alvarado et al. [12,15] conducted turbulent flow heat transfer experiments to determine the convective heat transfer coefficient of MPCM slurry, which is made of *n*-tetradecane ($C_{14}H_{30}$), at various mass fractions. The convective heat transfer coefficient of water is higher than MPCM slurry at an identical heat flux, because the lower viscosity in water promoted turbulence better. In addition, it was observed that the heat transfer coefficient of MPCM slurry increased considerably during the phase change process. In our previous study [16,17], flow and convective heat transfer test were conducted with slurries of MPCM mass ratios of up to 30%. The MPCM slurry was made of microencapsulated $C_{16}H_{33}Br$ with an average particle diameter of 10.1 μm. The pressure drop and local heat transfer coefficients were measured, and the influences of capsule fractions, heating rates, and flow structures on heat transfer performance were also studied. In another previous study [18], It was found that the local heat transfer behaviors varied significantly along the flow direction of the slurry. In laminar flow conditions, the heat transfer coefficient of MPCM slurry was significantly higher than that of single-phase fluid. In the case of turbulent flow, local heat transfer coefficients exhibited more complicated phenomena at low turbulent conditions. The local heat transfer behavior was significantly influenced by the heating rate across the test section and the turbulent degree of the fluid.

For building cooling applications reported in our previous studies [19,20], it was assumed that the MPCM slurry directly circulated between the storage tank and the radiant cooling panels in office rooms. Although an excellent energy saving performance can be achieved, a potential and likely essential drawback in practical applications is that the shell of the microcapsules may be damaged after a number of circulations through a high-speed pump. A more practical design would be to introduce a heat exchanger in the storage tank, so that the MPCM slurry stored in the tank is not circulated through the pump and piping system [21]. With such a design, it is expected that any potential adverse impacts of the micro-capsule damage will be confined within the storage tank, and that regular replacement and recycle of the PCM and cleaning of the storage tank can be implemented. However, more investigations are needed regarding the convective heat transfer of the MPCM-in-water slurry to evaluate whether an overall competitive charging/discharging rate can be achieved. From the scientific literature, it is found that only a limited number of studies on the natural convection process outside a helical coil are available. Heinz et al. [22] found that, even with the lowest used mass fraction of 20%, the natural convection heat transfer coefficients of MPCM slurry are much lower than that of water because of the high viscosity. Similar results were obtained by Huang et al. [23], who indicated that, by using the MPCM slurry with higher mass fractions as thermal storage medium, the natural convection in the TES tank was suppressed. As a result, the rate of heat transfer of the helical coil heat exchanger reduced significantly. Diaconu et al. [24] found a significant increase of the heat transfer coefficient for MPCM slurry during the phase change process, which can go up to five times in comparison to the single-phase fluid water.

In this reported study, a small-scale air conditioning system integrated with a coil-in-tank TES was constructed to obtain reliable experimental data of the thermal storage and heat transfer behaviors of MPCM slurry, validated with experimental data of a coil-in-tank water system. Forced convection of the MPCM slurry outside the pipes was introduced by adding an axial propeller/stirrer with variable rotating speeds and the overall heat transfer coefficient of the heat exchanger and the convection between the MPCM slurry and the external surface of the helical coil were also investigated.

More importantly, two new indices, the volumetric storage capacity and charging/discharging rate, were defined to evaluate the performance of a cooling storage system. At a given charging/discharging temperature difference, the two indices respectively indicated the thermal storage density and the heat transfer behavior of a specific TES unit. The widely applied stratified water storage tank design was used as a benchmark to estimate the performance of the novel coil-in- tank MPCM slurry cooling storage system.