ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

# Investigation of thermo-fluidic performance of phase change material slurry and energy transport characteristics☆

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## HIGHLIGHTS

- A mathematical model based on the Eulerian-Eulerian approach is built to study the MPCM slurry.
- Influences of particle diameter on the solid volume fraction, velocity and pressure drop are studied.
- Thermo-fluidic characteristics of the MPCM slurry flow are investigated.
- Energy transport performance of the MPCM slurry is investigated and compared with that of water.

## ARTICLE INFO

*Keywords:*
Micro-encapsulated phase change material slurry
Eulerian-Eulerian model
Flow and heat transfer
Energy transport

## ABSTRACT

Thermal or cold storage is a promising way to alleviate the peak-valley difference of the electricity load and improve the energy efficiency. The thermal or cold storage by micro-encapsulated phase change material (MPCM) slurry is one of the effective measures to be implemented in waste heat recovery and heat transport system etc. due to its high energy storage density and excellent heat transfer performance. The thermo-fluidic performances of the MPCM slurry flowing through the horizontally circular pipe under constant heat flux are numerically investigated based on the Eulerian-Eulerian approach in the present study. It is found that the numerical results are in good consistence with the experimental results from the aspects of flow and heat transfer. The influences of particle diameter on solid volume fraction distribution, solid velocity distribution and pressure drop of the MPCM slurry are investigated under isothermal condition. And then the temperature distribution of the MPCM slurry and liquid volume fraction of the PCM in MPCM are presented to analyze the heat transfer performance of the MPCM slurry. The particle diameter also imposes significant influences on the heat transfer between the two phases and average heat transfer coefficient of the MPCM slurry. The largest pressure drop and the highest average heat transfer coefficient appear when the particle diameter of the MPCM decreases to 1 μm. Further investigations at different Reynolds numbers are carried out to study the variation of local heat transfer coefficient along the pipe. Finally, the comparison of energy transport performances between the MPCM slurry and water are presented based on the ratio of transported heat to pumping power. The MPCM slurry shows better energy transport performance than pure water when the Reynolds number is above 7865.

## 1. Introduction

Energy shortage has become an increasingly prominent issue due to the rapid development of global demand and depletion of conventional fossil fuels. Developing renewable energy and improving the energy utilization efficiency are drawn great attention as the effective approaches to solve the energy crisis [1]. There is always an imbalance between the energy supply and demand both in time and space domains during the process of energy conversation and utilization, for example, the intermittency of solar energy and wind energy, peak-valley difference of the electric power load, etc. Energy storage technique which can alleviate such problems is becoming much more attractive. Thermal energy as the most common energy form occupies an essential position in the field of energy storage [2]. There are commonly three methods for thermal energy storage: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES) and thermochemical energy storage. LHTES based on phase change material (PCM) has been extensively studied owing to the advantages such as large heat capacity due to the presence of latent heat and nearly isothermal characteristic during the phase change process [3]. There are

☆ The short version of the paper was presented at ICAE2016 on Oct 8–11, Beijing, China. This paper is a substantial extension of the short version of the conference paper.

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http://dx.doi.org/10.1016/j.apenergy.2017.08.146
Received 4 January 2017; Received in revised form 20 April 2017; Accepted 12 August 2017
0306-2619/ 

Please cite this article as: Ma, F., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.08.146

**Nomenclature**

| | |
|---|---|
| $A$ | thermal conductivity ratio of liquid phase to solid phase, – |
| $B$ | modified volume fraction ratio of solid phase to liquid phase, – |
| $C$ | auxiliary parameter, – |
| $C_D$ | drag force coefficient, – |
| $C_L$ | lift force coefficient, – |
| $C_{td}$ | turbulent dispersion force coefficient, – |
| $c_p$ | specific heat capacity, J/(kg K) |
| $D$ | diameter of pipe, m |
| $e_{ss}$ | particle-particle restitution coefficient, – |
| $\boldsymbol{F}_D$ | drag force, N |
| $\boldsymbol{F}_L$ | lift force, N |
| $\boldsymbol{F}_{td}$ | turbulent dispersion force, N |
| $d$ | diameter, m |
| $\boldsymbol{g}$ | gravitational acceleration, m/s$^2$ |
| $g_0$ | radial distribution function, – |
| $h$ | heat transfer coefficient, W/(m$^2$ K) |
| $h_{sl}$ | volumetric heat transfer coefficient, W/(m$^3$ K) |
| $H$ | enthalpy, J/kg |
| $\Delta H$ | latent heat, J/kg |
| $\boldsymbol{I}$ | unit vector or unit tensor |
| $k_{\theta s}$ | diffusion coefficient, – |
| $K$ | auxiliary parameter, – |
| $L$ | radial distance, m |
| $\boldsymbol{n}$ | external normal direction, – |
| $Q$ | transported heat or heating power, W |
| $P$ | pressure, Pa |
| $Pr$ | Prandtl number, – |
| $q$ | heat flux, W/m$^2$ |
| $Re$ | Reynolds number, – |
| $S$ | ratio of distance to radius, – |
| $W$ | pumping power, W |
| $\boldsymbol{v}$ | velocity, m/s |
| $t$ | time, s |
| $T$ | temperature, K |
| $x$ | axial distance, m |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | volume fraction, vol% |
| $\beta$ | auxiliary constant, $7.26 \times 10^{-3}$ |
| $\gamma_{\theta s}$ | collisional dissipation of energy, kg/(m s$^3$) |
| $\gamma_{sl}$ | momentum exchange coefficient, – |
| $\zeta$ | bulk viscosity, Pa s |
| $\theta_s$ | granular temperature, K |
| $\lambda$ | thermal conductivity, W/(m K) |
| $\mu$ | viscosity, Pa s |
| $\mu_{t,i}$ | the fluid-particulate dispersion tensor, m$^2$/s |
| $\rho$ | density, kg/m$^3$ |
| $\sigma_{sl}$ | dispersion Prandtl number, – |
| $\boldsymbol{\tau}$ | shear stress, Pa |
| $\phi$ | energy exchange coefficient, – |

*Subscripts*

| | |
|---|---|
| ave | average value |
| bulk | MPCM slurry |
| e | effective value |
| l | liquid |
| s | solid |
| sl | interaction between solid and liquid phases |
| lo | local |
| 0 | initial state |
| p | phase change material |

many different kinds of PCMs in a broad range of phase change temperature. However, the characteristics of instability, supercooling and phase separation of the conventional PCMs such as paraffin, molten salt, etc. limit the extensive application. Micro-encapsulated PCM (MPCM) can overcome these defects through encapsulating the PCM (core material) with a layer of thin shell which can reduce the exposure of the PCM to the ambient and can increase the stability of the PCM. MPCMs with different cores and shells have been prepared to match the requirements of practical applications [4–6].

The MPCM slurry is prepared through uniformly dispersing the MPCM particles into carrying fluid, e.g., water, oil, etc. Compared with the applications of conventional PCMs which need additional heat transfer fluid (HTF) and more heat transfer segments for energy charging and discharging, the MPCM slurry can be used as not only the energy storage medium but also the HTF. More importantly, the surface-to-volume ratio of the PCM increases significantly due to small size of the MPCM. The performance of the MPCM slurry as the HTF is usually better than that of mere carrying fluid because of the large heat transfer area and high heat capacity [7]. In addition, the flow rate of the HTF using the MPCM slurry in place of water can be significantly reduced at the same amount of transported heat because of large heat capacity of the MPCM slurry, which implies that the pumping power is decreased. Therefore, the MPCM slurry can find a broad range of applications in energy conversion of refrigeration and air-conditioning, etc. [8].

For better utilization of the MPCM slurry, many researches have been devoted to study the thermo-fluidic performances of the MPCM slurry [9–14]. Goel et al. [9] experimentally studied the heat transfer performance of the MPCM slurry in a circular duct in laminar flow. The influences of volume fraction of the MPCM, Stefan number, etc. on heat transfer performance were analyzed and the results showed that the wall temperature of duct with the MPCM slurry was reduced about 50% compared with that of water. Choi et al. [10] studied the flow and heat transfer characteristics of phase change emulsion in turbulent flow, and they proposed a three-region melting model to evaluate the emulsion temperature along the tube. The results indicated that the heat transfer coefficient of emulsion increased when the emulsion temperature was lower than phase change temperature and decreased rapidly when the emulsion temperature was higher than phase change temperature. Delgado et al. [11] measured the thermal and rheological behaviors of the MPCM slurry at different mass fractions and investigated the influence of mass fraction on the performance of the MPCM slurry from the aspects of flow and heat transfer. They found that the pressure drop increased sharply as the mass fraction of the MPCM achieved 30 wt%. The results also indicated that the pumping power of the HTF at the same heating load rose with the increase of mass fraction. And the MPCM slurry with 20 wt% displayed the most excellent heat transfer performance, which was improved by 47% on heat transfer coefficient compared with water.

The performance of the MPCM slurry as working fluid in the thermal energy storage system was also investigated by many researchers. Diaconu et al. [12] built an experimental set-up to assess the feasibility of the MPCM slurry adopted in a latent heat storage system. The thermal properties of the MPCM slurry were confirmed by the measurement of the DSC firstly to make sure the suitability of the MPCM slurry for air-conditioning application. The natural convection heat transfer characteristics of the MPCM slurry in a storage tank in which there was a vertical helically-coiled tube were investigated to compare with those of water. The results indicated that the natural convection heat transfer coefficient of the MPCM slurry was apparently