



# Preparation and characterization of nano-sized phase change emulsions as thermal energy storage and transport media



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## HIGHLIGHTS

- The nano-sized phase change emulsions are prepared by using D-phase method.
- The thermo-physical and transport properties are experimentally investigated.
- The influence of surfactant on the melting temperature and latent heat of water is clarified.
- The phase change emulsion can be used as the heat transfer fluid in a thermal energy storage system.

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## ABSTRACT

Phase change emulsion (PCE) is a kind of two-phase heat transfer fluid with phase change material (PCM) dispersed in carrier fluid. It has received intensive attractions in recent years due to the fact that it can be used as both the thermal energy storage material and transport medium simultaneously in a thermal energy storage system. In the present study, nano-sized PCEs are prepared by the D-phase method with n-hexadecane and n-octadecane as PCMs. The thermo-physical and transport properties are characterized to facilitate the applications. The droplet size distribution of the PCE is measured by a Photon Correlation Spectroscopy, and the results show that the droplet size distributions are similar at different mass fractions. The rheological behavior and viscosity of the PCE are measured by a rheometer, which shows that the PCEs at mass fractions below 30.0 wt% are Newtonian fluids, and the viscosities are dependent on both the mass fraction and temperature. The differential scanning calorimetry (DSC) is employed to analyze the phase change characteristics of the PCE, and the results indicate large supercooling degree of water and PCM in the PCE. The melting temperature and latent heat of water in the PCE are much smaller than those of pure water. The thermal conductivities of the PCE with different mass fractions at different temperatures are measured by the transient hot-wire method. Furthermore, the energy transport characteristics of the PCEs are evaluated on the basis of the measured thermo-physical and transport properties. The results suggest that the PCEs show a drastic reduction of pumping power compared with water at the same heat storage capacity.

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## 1. Introduction

In recent years, the rapid developments of economy and human society have led to increasing energy demands all over the world, resulting in the shortage of fossil fuels and consequent severe pollution. The energy consumed in buildings accounts for a large portion of the total energy consumption. For example, building sector consumed 32.0% of global energy demand in 2010 [1], where the major part is used for space heating and cooling. During the hottest

or coldest season, the intensified peak load of electricity demand imperils safe operation of electricity grid. Thermal energy storage (TES) is an effective technology to reduce the peak load by alleviating the mismatch between energy supply and demand caused by the spacial and temporal differences. Via TES, the spare electricity can be stored during the off-peak time as thermal energy which can be released during peak time to alleviate the burden on the electricity supply. As a result, the electricity will be more efficiently utilized.

The employment of phase change material (PCM) in TES is believed to be an effective way to enhance the thermal energy storage capacity and efficiency because the PCM has large heat storage

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**Nomenclature**

$c_p$	specific heat capacity ( $\text{kJ kg}^{-1} \text{K}^{-1}$ )	$\Delta P$	pressure drop (Pa)
$d$	diameter (m)	$\eta$	efficiency of the pump (–)
$f$	friction factor of the PCE	$\lambda$	thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )
$G$	volume flow rate ( $\text{m}^3 \text{s}^{-1}$ )	$\mu$	viscosity (Pa s)
$I$	constant direct electric current (A)	$\rho$	density ( $\text{kg m}^{-3}$ )
$L$	length of the hot-wire (m)	$\tau$	shear stress (Pa)
$N$	Hydrophile-Lipophile Balance value of surfactant	$\omega$	mass fraction (–)
$P$	pumping power (kW)		
$Q$	heat storage capacity (kJ)		
$R_0$	electric resistance of the hot-wire at $0^\circ\text{C}$ ( $\Omega$ )	<b>Subscripts</b>	
$T_0$	onset temperature on the DSC curve ( $^\circ\text{C}$ )	$e$	emulsion
$t$	time (s)	$l$	latent heat
$v$	velocity ( $\text{m s}^{-1}$ )	$p$	phase change material
		$pe$	phase change material in emulsion
<b>Greeks</b>		$s$	surfactant or sensible
$\alpha$	temperature-dependent coefficient ( $\text{K}^{-1}$ )	$t$	total
$\gamma$	shear rate ( $\text{s}^{-1}$ )	$w$	water
$\Delta h$	enthalpy change ( $\text{kJ kg}^{-1}$ )		

capacity due to the involvement of the latent heat, and the heat storage and retrieval can be realized at a nearly constant temperature [2–4]. For example, Arkar et al. [5] showed that a solar heating fraction as high as 63.0% can be achieved in an energy efficient and lightweight building with PCM. However, the shortcomings including the material leakage, metal erosion and extra requirement for heat transfer fluid hinder the direct application of PCM in TES. To address these problems, PCMs are generally encapsulated into micro-capsules with polymer or synthetic polymeric shells before application [2]. Different polymers have been used as shell materials of microencapsulated PCM (MPCM), such as polystyrene [6], poly(methyl methacrylate) [7], methylmethacrylate-based copolymers [8] and polyuria [9]. However, the low thermal conductivities of polymeric shells depress the heat transfer performance and reduce the efficiency of heat storage and release [10]. On the other hand, PCM-based latent TES usually needs an additional heat transfer fluid to exchange and transport heat between the PCM and heat sources during heat storage as well as between the PCM and user side during heat release, which apparently results in poor energy efficiencies on account of additional heat transfer segments. Thus, phase change material slurry (PCS) with the PCM particles dispersed in carrier fluid is proposed to overcome these defects. PCSs possess high energy storage capacity which is attributed to both the sensible heat capacity of the carrier fluid and the latent heat capacity of the PCM [11]. By using PCSs, the thermal energy can be charged and discharged more efficiently due to the convective heat transfer in comparison with mainly heat-conduction-dominated heat transfer in pure PCMs, and there is no need to use additional heat transfer fluid because PCS itself can function as heat transfer fluid simultaneously. Three kinds of PCSs have been widely investigated so far: ice slurry, microencapsulated phase change slurry (MPCS) and clathrate hydrate slurry (CHS). Ice slurry comprises of fine ice particles suspended in water or aqueous solution. In general, ice slurry is more suitable to the applications with temperature below  $0^\circ\text{C}$  which is too low for comfort cooling applications [12]. The typical example of CHS is Tetra-n-butyl Ammonium Bromide (TBAB) slurry with phase change temperature range of  $5\text{--}12^\circ\text{C}$  which is good for cold energy storage [13]. MPCS with the PCM microencapsulated in a polymeric capsule and dispersed in water is particularly difficult to maintain a stable homogeneous

flow state if the particles are not fabricated in a very small size and the PCM capsule entails an extra cost.

To overcome the above mentioned disadvantages of PCSs, phase change emulsion (PCE) as a novel PCS has received increasing interests in recent years. PCE is a two-phase heat transfer fluid composed of at least two non-miscible liquids which is usually a PCM dispersed in water [14]. The phase change temperature of the PCE can be modulated to accommodate the temperature range for heating or cooling application in a TES system by using different kinds of PCMs with different phase change temperatures. They generally do not contain hazardous substance and are environmentally compatible. Compared to the MPCS, the PCEs are able to avoid additional thermal resistance of the polymer shell. The size of dispersed particles of the PCE is usually very small, i.e., in micro-scale or even nano-scale, which is much smaller than those of conventional PCSs. Therefore, the surface-to-volume ratio of the particle is enlarged and consequently the heat transfer rate is increased [15,16]. Moreover, the PCE with good fluidity and large heat capacity results in reduction of mass flow rate at a specified heat storage capacity, therefore the energy consumption for transport can be reduced drastically [17].

Currently, the fabrication of PCE is mainly categorized into two approaches according to the amount of mechanical energy required: high-energy emulsification method and low-energy emulsification method. High-energy emulsification method which needs intense energy to disrupt the dispersed phase into droplets is generally achieved by high shear-force stirring, high-pressure homogenizers (HPH), microfluidizer or ultrasonic generators. In contrast, for low-energy method, only a small quantity of stirring energy is required in emulsification process thanks to the physico-chemical properties of the surfactant molecules. Meanwhile, it also allows for producing smaller droplet than high-energy method. Low-energy methods can be classified into “self-emulsion” method and “phase inversion” method according to whether phase inversion of spontaneous curvature of surfactant occurs during the emulsification process [18]. When the surfactant spontaneous curvature is changed from negative to positive or conversely during the emulsification process, the method is defined as “phase inversion” method. There are two ways to achieve the phase inversion: one is to change the temperature while keeping the mixture composition fixed (phase inversion temperature: PIT method) [19], and

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