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Synthesis and characterization of a narrow size distribution nano phase change material emulsion for thermal energy storage

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ABSTRACT

This paper introduces a novel nano phase change material emulsion (NPCE) which was synthesized by direct miniemulsion method. A series of NPCEs using *n*-octadecane as phase change material were prepared with 10 wt.%, 20 wt.%, 30 wt.% and 40 wt.%, respectively. Prepared NPCEs were characterized by particle size analyzer, transmission electron microscopy (TEM), differential scanning calorimeter (DSC), thermal conductivity meter and rheometer. The TEM image shows that all the NPCEs are successfully synthesized with well dispersed nanoparticles. The DSC results indicate that the melting behaviour of *n*-octadecane is close to NPCEs and the supercooling is observed in all the NPCEs. Particle size and rheological analyses demonstrate that prepared NPCEs present a narrow size distribution and an extreme stable form. In comparison with the conventional phase change material slurry (PCS) and microencapsulated phase change material slurry (MPCS), the NPCE tends to be much more stable and importantly it can be synthesized in a cost-effective form in terms of method and materials.

1. Introduction

Thermal energy storage plays an important role in attaining energy savings and reducing the environmental impact related energy utilization. One area attracting increasing interest is the development of phase change material (PCM). Phase change material has been widely investigated and utilised for thermal energy storage due to ability to absorb and release a large amount of latent heat during the phase change process with only small temperature variations (Al-Jandal and Sayigh, 1994; Hasan and Sayigh, 1994; Karaipekli and SarI, 2008; Tian and Zhao, 2010; Zhao and Wu, 2011). When the PCM is dispersed into a carrier fluid, it forms a two-phase suspension-phase change slurry (PCS) and the application of PCS to the thermal energy storage system become quite simple. As the ratio of surface area to volume of PCM particles is relatively large, the heat transfer rate per unit volume to or from the material in the particles is high. In order to increase the energy storage capacity, two-phase slurry is preferred which is inspired by the fact that the latent heat storage associated with the solid–liquid phase change is more efficient than the sensible heat storage of the liquid phase (Zhang et al., 2010).

Phase change material slurries have been well investigated in both theoretical and experimental studies by many previous researchers. An early theoretical and experimental studies by Royon et al. (2000) indicated a good agreement of simulated results with experimental values using PCS in both cold storage and distribution. In a later study by Royon and Guiffant (2008), they developed a simple model to describe the forced convection heat transfer with millimetric PCS in a circular duct flow. Roy and Avanic (2001a, 2001b) developed two different effect specific heat models for both laminar and turbulent forced convection heat transfer of a PCS in a circular duct with constant wall heat flux, respectively. Frusteri et al. (2005) utilised carbon fibre to enhance the thermal conductivity of a PCM based storage system with the hot-wire method. Xing et al. (2005) developed a two-phase, non thermal equilibrium-based model to simulate laminar heat transfer of PCS with micro-PCM in a micro-channel. Lenert et al. (2011) proposed a numerical model to enhance heat transfer of microencapsulated phase change material slurry (MPCS) for thermal systems.

All above studies investigated the heat transfer characteristics and applications of PCS and MPCS. In recent years, nano-PCM has been of scientific interest and has considerable practical applications. Nano-PCM is able to reduce the viscosity of the fluid and avoid blocking of the pipe system in comparison with micro-PCM. In addition, nanoparticles have higher surface area to volume

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Nomenclature

ΔH_c	heat of crystallization (kJ/kg)	T	temperature (°C)
ΔH_f	heat of fusion (kJ/kg)	T_m	melting temperature (°C)
k	thermal conductivity (W/(m °C))	T_c	crystallizing temperature (°C)

ratios than microparticles which can provide a stronger "driving force" to speed up the thermodynamic process. Importantly, PCM nanoparticle can be synthesized in a cost-effective form in comparison with PCM nanocapsule (Zhang et al., 2012; Sarı et al., 2015) as the shell material and polymerization stage will be eliminated.

Sidik et al. (2014) carried out a comprehensive review on the preparation methods of nanofluids and they indicated that the enhancement of the thermal conductivity for nanofluids has been the most attractive factor, meanwhile they also concluded that the stability and preparation cost of nanofluids were major challenges for commercializing nanofluids. Another recent review by Chieruzzi et al. (2016) summarized different types of nanofluids for thermal energy storage as well as various methods for preparing nanofluids, they indicated that the heat capacity enhancement and great thermal properties of nanofluids could achieve storage material reduction. Dhaidan et al. (2013) investigated the melting effect of nanoparticle enhanced phase change material experimentally and numerically, and they indicated that the effective thermal conductivity was enhanced with more nanoparticles in PCM. A study by Rao et al. (2013) demonstrated that both excessive thick and thin shells were disadvantageous for nano-encapsulated PCM, and particle size played an important role in the heat transfer enhancement of nanoparticle-enhanced PCM. Altohamy et al. (2015) utilised a water based nanofluid (50 nm Al_2O_3) PCM for cool storage and the results indicated that nanoparticle concentration had a great effect on the thermal properties of PCM. Tang et al. (2016) synthesized a phase change material composites with graphene nanoplatelets and the thermal conductivity of PCM composites was 2.5 times higher than that of pure PCM. Another two recent studies by Singh et al. (2017) and Colla et al. (2017) demonstrated that adding appropriate amounts of Aluminum Oxide (Al_2O_3) and Carbon Black into PCM would enhance the thermal properties of pure PCM, and thereby these nano-PCMs were suitable for energy storage applications.

This paper introduces a novel nano phase change material emulsion (NPCE) using direct miniemulsion method. The aim of this work was to investigate the characteristics and thermo-physical properties of prepared NPCEs, and to establish whether proposed NPCE can be utilised as a heat transfer fluid for thermal systems. The morphology, particle size distribution, stability, thermal and rheological properties of NPCEs were thoroughly investigated.

2. Method and materials

2.1. Materials

N-octadecane with a purity of 99 wt.% was purchased from Sigma-Aldrich. Sodium dodecyl sulphate (SDS) was commercially supplied by VWR international Ltd, UK. All chemicals were utilised as received.

2.2. Synthesis of nano-PCM emulsions

The nano phase change material emulsion was synthesized by direct miniemulsion method, which has been employed in a previous study for preparing PCM nanocapsule (Zhang et al., 2012). However, the polymerization stage of direct miniemulsion method was escaped in this paper; thereby prepared NPCEs compose of homogenized *n*-octadecane nanoparticles instead of PCM nanocapsules. Four kinds of NPCEs were prepared with the mass ratio of PCM to water and surfactant: 10:90:2, 20:80:2, 30:70:2, 40:60:2, respectively. Regarding to synthesis of 40 wt.% NPCE, a stock of surfactant solution was prepared by dissolving 0.4 g of SDS in 12 g of deionised water and stirred for a few minutes at 50 °C until the solution became transparent. Then 8 g of *n*-octadecane was heated to 50 °C and mixed with SDS solution. After 10 min pre-emulsification under vigorous magnetic stirring at 50 °C, the mixture was finally sonicated with a tip sonicator (Branson Digital Sonifier) in a water bath at 70% amplitude for 10 min (with 30 s probe on and 1 min probe off) while the mixture was gently stirred by a magnetic stirrer. The rest three of NPCEs were synthesized with different mass ratios of PCM to water and surfactant using the same fabrication method as 40 wt.% NPCE.

2.3. Characterization of nano-PCM emulsions

The particle size distribution and particle dispersion index (PDI) of NPCEs were measured by dynamic light scattering (DLS) technique using a laser particle size analyzer (Nano-Zetasizer, Malvern Instruments) at 10 °C and 40 °C in order to ensure three full heating and cooling cycles of each NPCE sample were completed. The NPCE was diluted with deionised water in a glass cuvette before the measurement, and the sensitivity of the particle size and PDI measurements is 0.1 mg/mL. The PDI describes the heterogeneity of the sample, it can range from 0 (monodisperse) to 1 (polydisperse).

The sample morphology was obtained using a Jeol 2010F transmission electron microscopy (TEM) at an accelerating voltage of 200 kV. A 3 μL of dispersion was diluted with 3 mL deionised water and then a 3 μL of diluted sample was placed on a 200 mesh copper lacey formvar carbon coated EM grid (Fisher Scientific UK). After sitting at room temperature for 1 min, the sample was blotted using a filter paper. The grid was then plunged into liquid ethane and stored with liquid nitrogen for imaging.

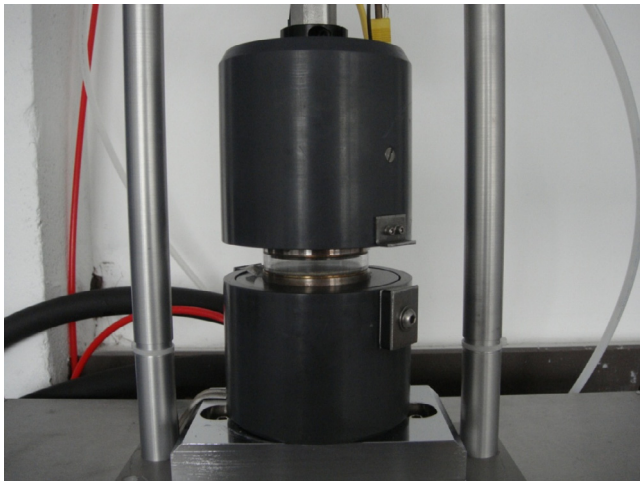

Fig. 1. The bespoke test cell is held under a compressive load between two metal surfaces.