

# Heat transport in a three-stage thermal energy system using phase change material slurries

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Received 15 Aug 2007

Accepted 20 Feb 2008

**ABSTRACT:** This study investigated the feasibility of creating a phase-change slurry in which a phase-change material is microencapsulated and suspended in a carrier fluid. The heat transportation, pumping power consumption, viscosity, and pressure loss of the flowing slurries were measured in order to determine the most suitable concentration of micro encapsulated phase change material (MCPCM) used in the slurry over the range 5–40%. The effects of repeated use of liquid-solid phase-change particles upon melting and solidifying were studied using a small-scale rig of a closed loop circuit comprised of heating and cooling sections. Results indicated that the use of a MCPCM slurry can improve the performance of a working fluid by up to 52% as compared to a single-phase fluid. However, increasing the concentration of the MCPCM to 40% was found to have little effect on heat transport. MCPCM slurry containing a high concentration of MCPCM had a high apparent viscosity. Use of an ionic surfactant was found to be effective in reducing the viscosity. Results also showed that a 20–30% concentration was the most suitable concentration for the working fluid due to the associated heat capacity and reasonable pressure drop. The use of such a slurry could reduce the power consumption of the pump by 16%. Stratification between the solid particles and the carrier fluid was a major drawback and made it difficult to use a conventional open system. This problem was overcome by combining an open and a closed system into a three-stage (open-closed-open) operation.

**KEYWORDS:** phase-change material, phase-change slurry, thermal storage, latent heat.

## INTRODUCTION

The use of working fluids in thermal energy systems is well known. Many conventional systems comprise a long section of piping to convey working fluids between heat source and sink through heat exchangers. In such systems, a single-phase working fluid is used as a medium to transfer thermal energy. Generally, the systems are operated within a small temperature range, requiring high volumetric flow rates and therefore consuming a large amount of pumping power. Increasing the convective heat transfer coefficient would permit the use of a smaller volumetric flow rate and smaller heat exchangers. If a phase-change material (PCM) could be suspended in the heat transfer fluid as small solid particles and transported through a heat exchanger, the heat transfer coefficient and thermal capacity of the working fluid could be improved<sup>1</sup>. Over decades, many papers have been published on theoretical or experimental approaches to clarify the merits of this medium<sup>1–8</sup>. These studies focus mainly on heat capacitance and the heat transfer coefficient and although they indicate promising applications, they are limited in scope. The data necessary for the design of a thermal energy system using phase-change slurry

are not available in the literature. The major challenge in applying this slurry for a convective heat transfer system is to show how to circulate the particles continuously and successfully through the heat transfer flow circuit. This study employs a small-scale rig with a closed loop circuit integrating both heating and cooling sections instead of a one-way-flow rig as used by many previous studies. The effects of repeated use of liquid-solid phase-change particles upon melting and solidifying could be studied.

## EXPERIMENTAL INVESTIGATION

### Microencapsulated phase change material (MCPCM)

The MCPCM used in this study was a paraffin wax of *n*-eicosane with a melting point of 35 °C. The *n*-eicosane was encapsulated in millions of durable capsules of 15–40 microns in diameter. The capsules comprised 80–85% of the material weight and had an impermeable shell wall of less than one micron. Table 1 shows the specifications of the MCPCM<sup>9</sup>. As a carrier fluid for the MCPCM, water could be used without any inconvenience. It was easy to handle, had low viscosity and no effect on the phase-change material or the microcapsule wall.

**Table 1.** Physical properties of the MCPCM particles<sup>9</sup>

|                | Density<br>(kg/m <sup>3</sup> ) | Specific Heat<br>(kJ/kg°C) | Thermal<br>conductivity<br>(W/m°C) | Latent heat<br>(kJ/kg) | Temperature of fusion<br>(°C) |
|----------------|---------------------------------|----------------------------|------------------------------------|------------------------|-------------------------------|
| MCPCM (solid)  | 899                             | 2.13                       | 0.179                              | 180                    | 35                            |
| MCPCM (liquid) | 899                             | 1.88                       | 0.170                              | 180                    | 32–35                         |

## EXPERIMENTAL APPARATUS AND METHOD

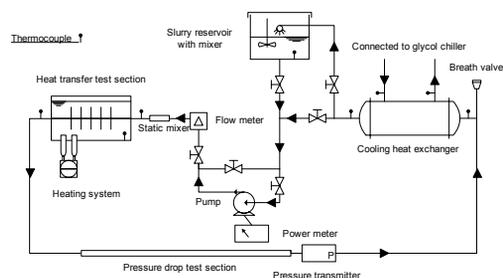
Fig. 1 shows the schematic diagram of the experimental apparatus. The heat-transfer test section was filled with water and insulated with 19-mm neoprene insulation to prevent heat loss. Two 3 kW-heaters were mounted at the bottom of the heating reservoir to continuously supply heat for the system and were monitored by the voltmeter and ammeter. The cooling heat exchanger was connected to the closed-loop chilled water/glycol circuit. The power meter was used to monitor the power consumption of the pump. The differential pressure transmitter was connected across a 1.5 m copper pipe to measure the pressure losses of the flowing slurry. The electric mixer was used at the beginning of the test in the slurry reservoir to mix the water and MCPCM into a homogeneous mixture. The static mixer was installed in front of the heat transfer test section in order to ensure a well mixed suspension. The test section was made up of a helically coiled copper tube (with a diameter of 12 mm and a wall thickness of 0.8 mm) instead of a straight tube because of the space limitation in the heating tank. The length of the tube was found to be approximately 330–350 diameters (a distance that was long enough to capture the phase change phenomena). The hydrodynamic entry section was 15–20 mm diameters to ensure that the flow entering the test section was developed<sup>10</sup>. The experiment was conducted to monitor the rate of heat transfer into the system provided by the heaters, instead of measuring the rate of heat removed from the system by the flowing slurry. This was to minimize uncertainty in the measurements of local bulk mean temperature of

the slurry during phase change. Under steady state conditions, the change in total energy of a control volume during a process is zero. Thus, the amount of energy leaving the control volume (from the flowing slurry neglecting the heat losses) must be equal to the amount of energy entering it (from the heaters). Hence, the heat transport of the slurry can be determined from the rate of heat transfer into the system provided by the heaters. When the MCPCM slurries with 10–40% volume concentration (0.089–0.356% mass concentration) were pumped through the test section at a specific flow rate, the current of the AC power supply of the heaters was varied until the temperature of the heating reservoir remained constant for 30 minutes. Six K-type thermocouples were used at different locations to indicate the bath temperature. A submerged pump was used in the reservoir to help circulate water through the tank to achieve the uniform temperature.

Flow rates of the slurry were measured by a turbine flow sensor, and were in a range of 2–6 l/min. The slurry was circulated through the heating section where the solid PCM in the shells melted into a liquid phase releasing latent heat. To ensure that the entire phase change phenomenon occurred in the test section, the temperature of the slurry leaving this section was maintained above the PCM melting point. The slurry was then pumped through the cooling coil heat exchanger where the liquid particles re-solidified and were ready to use again. The temperature of the slurry leaving the cooling section was maintained at approximately 30 °C by the glycol chiller. This temperature was lower than the melting temperature of *n*-eicosane (35 °C) due to the supercooling phenomena. The temperatures of the slurry at the inlet and outlet of the test section and cooling reservoirs and that of the glycol chiller were monitored using the K-type thermocouples attached to the outer tube wall. They were taped securely to the pipes and insulated. In the experiment, the operation temperatures were in the range of 10–60 °C and the error of calibration of the thermocouples was found to be within  $\pm 0.251$  °C of the fluid temperature. The thermocouples were connected to a DT500 datalogger that scanned every 5 seconds and sent the data to a PC via an RS-232 interface using the DeLogger Plus software.

### Summary of data acquired

The devices used in the present study were calibrated with heat inputs of 1.2, 2.4, 3.6, and 4.8 kW, which were monitored by the voltmeter and the ammeter. The rate of heat removed by the working fluid was found to be equal to the electrical power

**Fig. 1** Schematic diagram of the experimental apparatus.

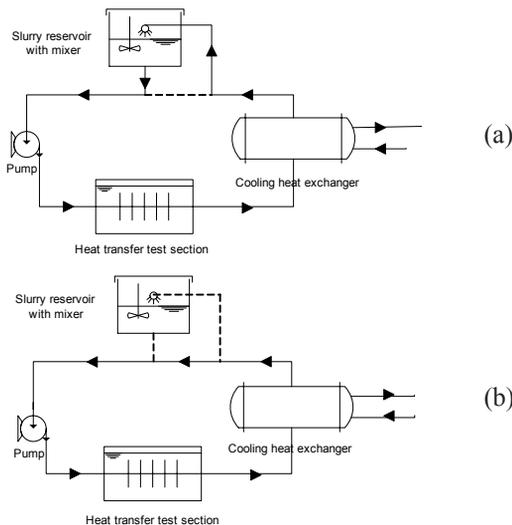


Fig. 2 (a) Open system (b) Closed system.

supplied to within  $\pm 5\%$ .

A major problem in the study was stratification of solid particles in the suspended fluid due to gravity or centrifugal forces. During the operation, phase separation between water and the particles occurred and was observed in the slurry reservoir. As the density of the suspended particles was lower than the density of water, they naturally separated from the water and rose to the surface. Only at high slurry flow rates was the pumping pressures sufficient to disturb and mix the suspension into homogeneity. This phenomenon could reduce the number of phase change particles flowing back into the system and decrease the amount of latent energy available. The use of an ordinary open system (Fig. 2a) in the application would therefore not be appropriate, and a new system combining both the open and closed system was proposed to overcome the problem.

The criterion used in the experiment was to divide the operation into three stages. The first stage used an open system to prepare the MCPCM slurry and to feed it into the system. A mechanical mixer was used in the slurry reservoir to mix the slurry into homogeneity. To reduce segregation, 1% of the particles were replaced by an additive. The additive also reduced the apparent viscosity. During the operation, the system was switched to the second stage, a closed system, where the slurry path was diverted from the slurry reservoir. In this case, the slurry was circulated inside the closed circuit (Fig. 2b) of 15 mm diameter pipe. Thus, without the container, there was no place for the slurry to sepa-

rate and forced circulation from the pump also helped to stir and mix the solution. The third stage of the operation involved switching the system to the open system again. This time, the mixer was turned off in order to deposit most of the particles back into the container overnight and so prevent particle blockage when the pump was turned off, especially at the junctions. Without this stage, the piping system was clogged by the particles making it difficult for the slurry to circulate through the system.

RESULTS AND DISCUSSION

Differential scanning calorimeter (DSC)

Fig. 3a shows a typical DSC curve of pure paraffin wax with a 35 °C melting point. One thermal cycle conducted is shown as a heating and cooling curve. The latent heat of fusion was observed as the curve rapidly rose when the MCPCM melted and rapidly fell when it crystallized. The latent heat of fusion of the paraffin waxes was in good agreement with the data provided by the manufacturer (174 kJ/kg). However, the crystallization temperature of the material was smaller than the melting

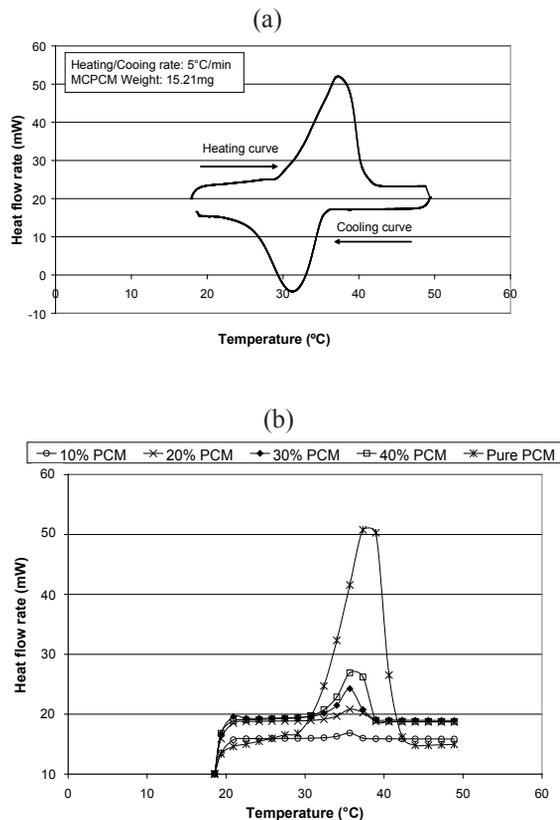


Fig. 3 DSC thermograms of (a) pure MCPCM (b) 10–40% MCPCM slurries (heating only).

temperatures by around 6–7 °C, thus, showing that supercooling was occurring.

Fig. 3b shows the DSC thermogram of the MCPCM slurries of 35 °C paraffin wax (10–40 %). The samples weighed between 14.79 mg and 15.53 mg and were heated at a rate of 5 °C/min from 20 °C to 50 °C. Evaluation of the peak around 36–37 °C showed that the paraffin wax released its latent heat of fusion at this point. Although an enhanced heat flow rate was observed between 30 °C and 42 °C, scanning electron microscope images of the micro capsules showed that the phase-change particles melted and solidified at temperatures of approximately 35 °C and 32 °C, respectively<sup>11</sup>. Increasing the concentration of the phase-change particles increased the enthalpy of the working fluid. This can be observed from the curves around the PCM melting temperature where the most concentrated MCPCM slurry showed the highest peak.

### Viscosity

Viscosities of the MCPCM slurries were measured using a Bohlin CS rheometer with parallel plates. Five samples were tested: pure water 0%, 10%, 20%, 30% and 40% MCPCM slurry. Tests were conducted with slurry temperatures of 25°C and 50°C, *i.e.*, below and above the melting point of *n*-eicosane. A temperature bath with a magnetic stirrer was used to heat and mix the samples for at least 15 min prior to measuring the viscosity in order to achieve a uniform temperature and homogeneity.

Results shown in Fig. 4 describe the relationship between the shear rate and apparent viscosity. In the case of pure water, the viscosities were in good agreement with values cited elsewhere. The figure shows that the viscosity of the slurry depended on the temperature and concentration of the slurry. The viscosity decreased with increasing temperature and a slurry containing a high concentration of MCPCM had a high viscosity compared with the carrier fluid. At  $T < T_f$  (solid core PCM) the slurry viscosities for 10–20% MCPCM were found to be approximately 1–3 times higher than the viscosity of pure water. For 30–40% concentration, the viscosities were found to be 5–10 times higher than that of pure water. However, at  $T > T_f$ , (liquid core PCM) the slurry viscosity for 10–30% MCPCM was slightly higher than for pure water. The viscosity increased nonlinearly with the particle volume fraction.

At high concentration, the viscosity of the slurry increased with decreasing shear rate, *i.e.* non-Newtonian behaviour was observed. Slurries

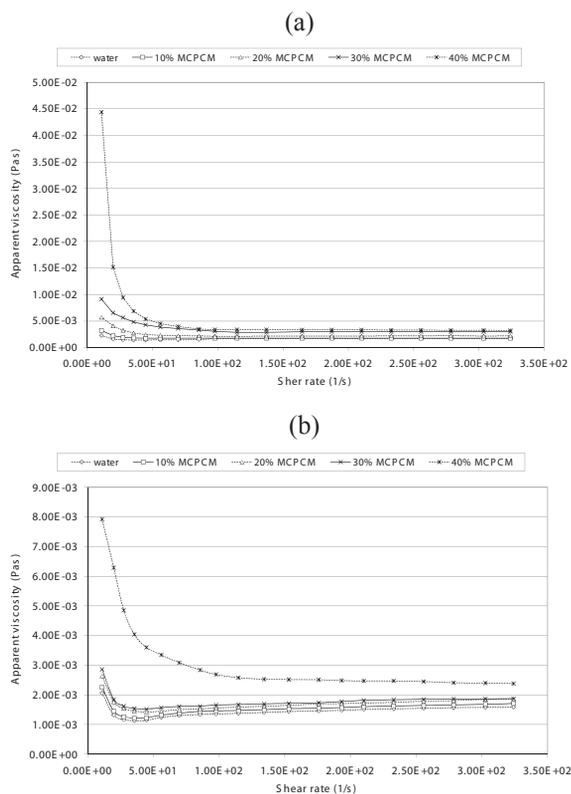


Fig. 4 Apparent viscosity of water and 10–40% MCPCM slurry against shear rate at (a) 25 °C (b) 50 °C.

of very fine particles often exhibit non-Newtonian rheological behaviour due to flocculation of the particles<sup>12</sup>. However, particle flocculation could be inhibited by the addition of a dispersing agent<sup>8</sup>. An ionic surfactant of 1 vol. % was therefore added to the slurries. Fig. 5 shows the apparent viscosity for a 20 and 40% MCPCM slurries, with and without the additive, plotted against shear rate. Using the additive improved the degree of particle dispersion and effectively reduced the apparent viscosity. With the additive present, the slurry behaved practically as a Newtonian fluid. Adding 2% additive did not produce any further reduction in slurry viscosity.

### Pressure drop

Tests were conducted with water and 5–40% MCPCM slurries at flow rates between 2–6 l/min in a circular pipe of 15 mm diameter. The temperature of the fluid in the test section was below the melting temperature of *n*-eicosane and was held at 25 °C. The pressure drops per unit length (mm H<sub>2</sub>O/m) were measured for water and 5–40% MCPCM slurries with a spacing of 1.5 m. Results are shown in Fig. 6. It was found that the pressure drop increased over the entire

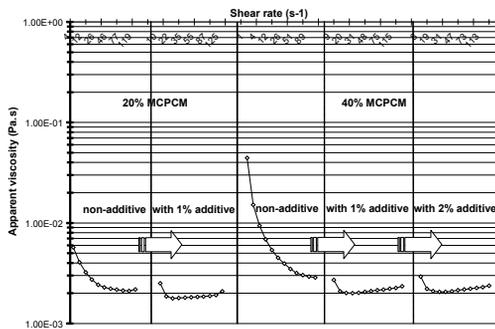
range of flow rates as the concentration increased. This can be attributed to the increasing slurry viscosity due to the increasing particle concentration. The pressure drop of 10% MCPCM slurry was found to be higher than the pure water in low flow rate. However, when the flow rate increased, the pressure drop of the water approached the pressure drop of the MCPCM slurry. The increased viscosity of the MCPCM slurry caused the transition from laminar to turbulent flow to occur at higher flow rates compared to that of the pure water<sup>5</sup>. Thus, at a certain flow rate, the flow of the pure water was turbulent, while the flow of the MCPCM slurry was still in the laminar region.

**Heat transportation of MCPCM slurries**

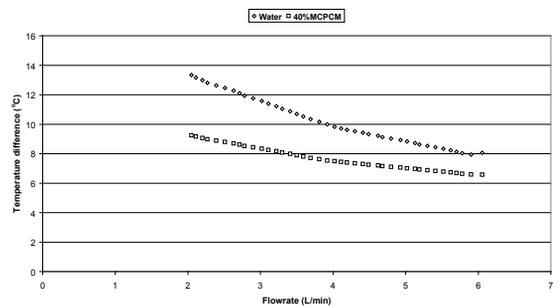
To minimize uncertainty in the measurement of the local bulk mean temperature of the flowing slurry, the investigation monitored the rate of heat transfer into the system provided by the heaters under the steady state condition. The heat transport of the slurry was determined from the product of the voltage and current readings. The temperature of the slurry entering the test section was held at 30 °C due to the supercooling phenomenon and maintained at above 37 °C in the test section to ensure that all the MCPCM

had melted. Fig. 7 shows a comparison of the temperature difference between the outlet and inlet of the test section, for water and 40% MCPCM slurry. With the MCPCM, the overall temperature difference was smaller for pure water under the same flow rate condition because the slurry had greater thermal capacity. When the MCPCM was used, most of the energy was absorbed by the phase-change particles associated with PCM melting.

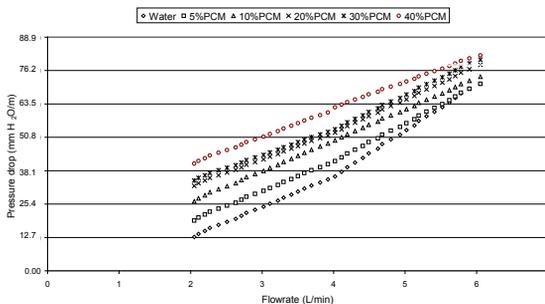
Fig. 8 compares the measured heat transport of 5–40% MCPCM slurries and water for flow rates between 2–6 l/min. The use of latent heat provided by the MCPCM was found to improve heat transport of the slurries compared to pure water. For example, at 2.7 l/min, the heat transport of the 30% MCPCM slurry was about 52% higher than that of pure water, *i.e.*, 3.85 and 2.5 kW, respectively. However, increasing the MCPCM from 30 to 40% only resulted in a 2–5% improvement in performance. This could be due to increased slurry viscosity impeding the radial migration of solid MCPCM particles associated with the turbulent fluid motion. This would result in a decrease in the number of solid MCPCM particles melting near the tube wall and therefore a decrease in heat transfer augmentation<sup>13</sup>. The



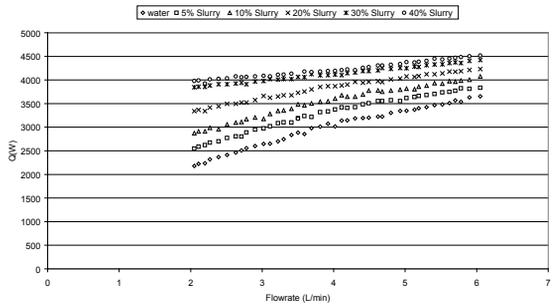
**Fig. 5** Apparent viscosity for 20% and 40% MCPCM slurries with and without additive at a temperature of 25 °C.



**Fig. 7** Temperature difference between the outlet and inlet of the test section for water and 40% MCPCM slurry.



**Fig. 6** Pressure drop plotted against volumetric flow rate for water and 5–40% MCPCM slurry at 25 °C.



**Fig. 8** Measured heat transport *via* water and 5–40% MCPCM slurries as a function of flow rate.

**Table 2.** Pumping power requirement for various flow rates and slurry concentrations

| Slurry concentration | Pumping power (W) |         |         |
|----------------------|-------------------|---------|---------|
|                      | 2 l/min           | 4 l/min | 6 l/min |
| Pure Water           | 70.02             | 77.51   | 84.01   |
| 5% MCPCM Slurry      | 71.27             | 77.70   | 84.02   |
| 10% MCPCM Slurry     | 71.22             | 78.94   | 85.69   |
| 20% MCPCM Slurry     | 72.61             | 78.87   | 85.66   |
| 30% MCPCM Slurry     | 73.20             | 80.11   | 86.28   |
| 40% MCPCM slurry     | 73.35             | 79.89   | 87.83   |

heat transfer augmentation associated with the phase change depended not only on the fraction of solid particles in the slurry, but also on the degree of turbulence<sup>13</sup>. As the flow rate increased, heat transport also increased. However, the higher flow rate increased pumping power, and the improvement in heat transport became proportionally smaller as the flow rate increased. For example, at 2 l/min the heat transport of 20% MCPCM slurry was approximately 40% higher than that of the pure water. This is compared to an 18% improvement at 6 l/min. In the present application, a concentration between 20–30% would give the best working fluid because of its sufficiently high heat capacity and acceptable pressure drop.

Table 2 shows the energy consumption of the pump for pure water and slurries with MCPCM concentration between 5–40%. Higher flow rates required greater energy consumption, as expected. Furthermore, it is interesting to note that the increase in pressure drop due to the high concentration of MCPCM did not require significantly more pumping power. The power needed to pump 30% MCPCM slurry at 2 l/min was just 4.5% more than that to pump pure water.

In conclusion, increasing the thermal capacity of a working fluid by the use of a phase-change material could decrease the flow rate, resulting in a decrease of pumping power consumption. For example, to deliver 3.5 kW, the use of 20% MCPCM slurry could reduce the flow rate requirement by as much as 52%, from 5.7 to 2.7 l/min, compared with pure water. This would result in a decrease in energy consumption of the pump by around 16%.

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