Micro-encapsulated ~~Phase Change Material~~phase change material (MPCM) ~~Slurries:~~slurries: Characterization and ~~Building Applications~~building applications

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Abstract

Micro-encapsulated Phase Change Material (MPCM) slurries, acting as the heat transfer fluids or thermal storage mediums, have gained applications in various building thermal energy systems, significantly enhancing their energy efficiency and operational performance. This paper presents a review of research on MPCM slurries and their building applications. The research collects information on the currently available MPCM particles and shells, studies of the physical, structural and thermal stability, and rheological properties of MPCM slurries, and identification/determination of the critical parameters and dimensionless numbers relating to the MPCM slurries' heat transfer. The research suggests possible approaches for enhancing the heat transfer between a MPCM slurry and its surroundings, while several controversial phenomena and potential causes were also investigated. Furthermore, the research presents mathematical correlations established between different thermal and physical parameters relating to the MPCM slurries, and introduces a number of practical applications of the MPCM slurries in building thermal energy systems. Based on such extensive review and analyses, the research will help in identifying the current status, potential problems in existence, and future directions in research, development and practical application of MPCM slurries. It will also promote the development and application of cost-effective and energy-efficient PCM materials and thus contribute to achieving the UK and international targets in energy saving and carbon emission reductions in the building sector and beyond.

Keywords: ~~micro-encapsulated~~Micro-encapsulated phase change material (MPCM) slurries; ~~characterisation~~Characterization; ~~stability~~Stability; ~~rheology~~Rheology; ~~heat~~Heat transfer; ~~application~~Application

Nomenclature

α_0

thermal diffusivity(m^2/s)

A

constant

B

constant

C

specific heat ~~capacity(J/kg • K)~~capacity(J/kg K)

D

diameter of the duct or tube(m)

d_p

particle diameter(m)

e

velocity gradient(s~~$^{-1}$~~$^{-1}$)

f

ratio

F

undetermined function

h

convection heat transfer coefficient (J/m^2 ~~• K)~~K)

ΔH

fusion heat (J/m^3)

k_B

Boltzmann constant(J/K)

K

thermal ~~conductivity(W/m • K)~~conductivity(W/m K)

L

latent heat of Phase change(J/kg)

L_1

Inlet region length(m)

L_2

phase change region length(m)

m

constant

$\dot{m}$

mass flow rate (kg/s)

n_p

particale number concentration(m~~$^{-3}$~~$^{-3}$)

Nu

Nusselt number

Pe

Peclet number

Pr

Prandtl number

q

heat flux(W/m^2)

Re

Reynolds number

R

radius (m)

Ste

Stefan number

t

time (s)

$t_{\mathrm{b,o}}$

outlet temperature of the bulk slurry(K)

$t_{\mathrm{b,i}}$

inlet temperature of the bulk slurry(K)

T

Temperature (K)

T_l

lower phase change temperature limit (K)

T_u

upper phase change temperature limit (K)

Δt

temperature difference between the inlet and the outlet (K)

ΔT

~~temperature difference~~ temperature difference between phases(K)

u

velocity(m/s)

$\overrightarrow{U_1}$

velocity vector

w

weight ratio of the particles in the slurry

x^*

dimensionless distance from the inlet

Greek symbols

$\dot{\gamma}$

shear rate(s~~$^{-1}$~~$^{-1}$)

ε

fraction of MCPCM particles that undergo phase change

ρ

density(kg/m^3)

μ

dynamic viscosity(Pa•s)

τ

shear stressN/m^2

$\emptyset$

particle volumetric concentration

$\overrightarrow{\nabla\theta}$

vector of temperature gradient

Subscripts

0

	carrier fluid
b	bulk slurry
d	duct or tube
e	effective
p	particle
r	dimensionless
w	wall
$\dot{\gamma}$	based on shear rate
m	mean
x	dimensionless distance from the inlet
eff	effective

1 Introduction

Global energy consumption has grown enormously over the last few decades as a result of the economic growth, particularly in the developing world. This has caused severe impact to the environment, evidenced by the growing particulate and gas (CO2, SO_2, NO_x, etc.) emissions and measurable global temperature rise due to greenhouse gases, mainly CO_2. Development of renewable energy and energy efficiency technologies and exploitation of the new energy sources are recognised as the effective solutions to mitigate the energy shortage and environment problems. These involve: (1) increasing the use of 'clean' energy sources (e.g. nuclear and renewable energy sources); (2) developing viable technologies that can reduce the use of the fossil fuels and mitigate the environment deterioration (e.g. CO_2 capture and sequestration); (3) exploring new and clean energy sources (e.g. fusion); and (4) developing alternative (synthetic) fuels and large scale energy storages et al. Of these measures, enhancing energy efficiency of existing energy systems is thought to be the simplest and cheapest, and introducing a MPCM slurry into an existing system is ideally suited for this purpose. With relatively higher thermal capacity and lower temperature variation during the phase change(compared to single-phase fluid only), MPCM slurries with high performance are gaining growing applications in building energy systems. It is understood [1] that use of MPCM slurries as a replacement of water could increase the heat transport capacity of an energy system by ~~1 to 3~~ 1-3 times, providing that the appropriate materials and MPCM weight ratios are selected.

A MPCM slurry is a mixture of the micro-encapsulated PCM particles, water and one (or more) additive(s). This type of fluid has a number of distinguished features [1], namely, (1) having high thermal capacity during the phase change process; (2) acting as either the heat storage or heat transfer (transport) material; (3) conducting transfer of heat with relatively low temperature variation; (4) achieving a higher heat transfer rate during the phase change process; and (5) requiring a lower pump power owing to a lower mass flow required at the same heat transfer rate. A building energy system involves numerous heat transfer/transport processes, i.e., heat absorption in the heat generating devices, heat release in the heat emitting devices, heat transport through the pipelines, and heat store/discharge within the heat storages. A MPCM slurry can fulfil the three functions simultaneously, so this kind of slurry is one of the best solutions for enhancing the energy efficiency of building energy systems.

Compared to water the conventional heat transfer fluid in building energy systems, a MPCM slurry is a new, high performance fluid that can achieve enhanced heat transfer. Numerous researches into the fabrication, characterization and application of MPCM slurries have been reported. However, to the authors’ knowledge, a review study focusing on the slurries’ characterization and building application has not yet been carried out. To fill this gap, this paper will report a focused, review-based research into characterization and building application of the MPCM slurries. For this consideration, the research will help in identifying the current status, potential problems in existence; and future directions in relation to research, development and practical application of the MPCM slurries in buildings, and thus promote wide deployment of such an energy-efficient heat transfer fluid. The results of the research will contribute to achieving the UK and international targets for energy saving and carbon emission reduction in building sector and beyond.

2 Concept and characteristics of the MPCM slurries

2.1 The MPCM slurries

A PCM is a substance with latent heat of fusion, which will be melt when absorbing heat and frozen when releasing the heat, thus running the two phases cycling repeatedly. PCMs have significant variations in melting and freezing temperature, ranging from ~~-5°C~~–5 °C to ~~1500°C~~1500 °C [2]. Compared to a sensible heat storage phase material, e.g., masonry or water, a PCM could achieve ~~5-14~~5–14 times heat storage capacity at the same volumetric condition [3]. PCMs can be generally classified into three major categories: inorganic PCMs, organic PCMs, and eutectic PCMs. The inorganic group of PCMs is composed of salt hydrates and metals; the organic group is composed of paraffin and non-paraffin; while eutectics are the mixtures of inorganics and/or organics. These are briefly illustrated in Table 1.

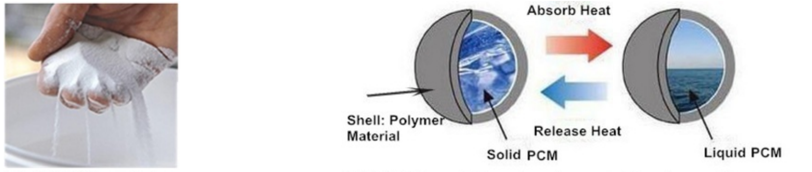
Table 1 ~~Characterisation~~Characterization of the three types of the PCMs [4].

alt-text: Table 1

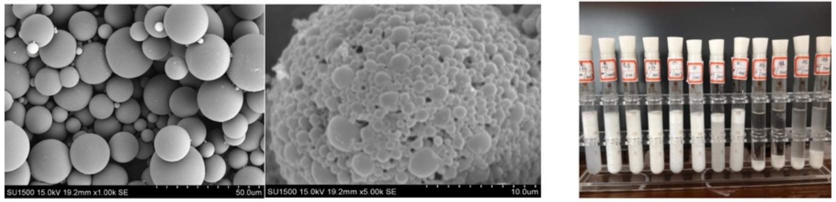
Classification	Advantages	Disadvantages
	1. Availability in a large temperature range	1. Low thermal conductivity (around 0.2 W/m K)
	2. High heat of fusion	2. Relative large volume change
Organic PCMs	3. No super-cooling	3. Flammability
	4. Chemically stable and recyclable	
	5. Good compatibility with other materials	
	1. High heat of fusion	1. Super-cooling
Inorganic PCMs	2. High thermal conductivity (around 0.5 W/m K)	2. Corrosion
	3. Low volume change	
	4. Availability in low cost	
Eutectics	1. Sharp melting temperature	Lack of currently available test data of thermo-physical properties
	2. High volumetric thermal storage density	

A PCM slurry is a multifunctional solid/liquid mixture comprising: (1) the liquid (e.g. water) that is a continuous single phase material within the operating range, dispersed PCM particles and the additive (s) that help dispersion of the particles. Such a slurry can store or transfer significant amount of thermal energy by means of latent heat of the PCM particles combined with sensible heats of both the liquid and PCM particles [5].

In recent years, a new way of dealing with PCMs has been developed in industries, such as BASF and EPS [6,7]. In this process, the PCM particles are encapsulated into the polymer shells with µm size order of magnitude. These encapsulated particles (see Fig. 1) are then mixed into a carrier fluid (e.g., water) with the selected additives (e.g., dimethylbenzene, anti-freezing fluid), thus forming a micro-encapsulated PCM (MPCM) slurry.



(a) MPCM particles (b) MPCM particles structure and its phase change



(c) SEM shotos (d) stability observation

Fig. 1 ~~Schematic of a MPCM particle and slurries,~~Schematic of a MPCM particle and slurries, (a) MPCM particles, (b) MPCM particles structure and its phase change, (c) SEM photos, (d) stability observation.

alt-text: Fig. 1.

The selected PCMs should have high latent heat, high thermal conductivity and also high specific heat; these three parameters are the most important indexes. The properties of the carrier fluid are also important as it plays a key role in conducting heat transfer and has a very high volume fraction within the slurry. Water, owing to its high conductivity and specific heat, is an excellent carrier fluid for the moderate temperature operation. However, other fluids, e.g., synthetic coolant, may be more appropriate to high temperature operation, during which the fluid may appear in the form of the gas state [8].

2.2 Thermal and physical properties of the commercially available MPCM slurries including the core and shell materials of the MPCMs

2.2.1 Commercially available PCM materials and their thermal and physical properties

Tables 2 and 3 present a series of commercially available PCM materials, including the cores and shells. Table 2 addresses the core materials and their major thermal and physical properties, while Table 3 addresses the commonly used shell materials and their thermal and physical properties. The core materials can be generally classified into two groups: (1) the materials for cooling processing that have melting temperature in the range ~~0~~0–6 ~~to 6°C,~~ °C; (2) the ones for heating processing that have melting temperature in the range ~~50~~ 50–118 ~~to 118°C.~~°C.

Table 2 Thermal and physical properties of the commercially available PCM core materials.

alt-text: Table 2

Material	Supplier	Type	Melting temperature, Tm, °C	Latent heat of fusion, L, kJ/kg	Density, ρ, kg/m³	Thermal conductivity, k, W/m K	Specific heat, cp, kJ/kg K
RT 0	Rubitherm GmbH **[9]**	Organic	0	225			
PCM-HS01P	SAVENRG **[10]**	Inorganic	0	290	1010		
E0	PlusICE **[11]**	Eutectic	0	332	1000	0.58	4.19
PureTemp 1	PureTemp **[12]**	Organic	1	300	1000		2.32
A2	PlusICE **[11]**	Organic	2	200	765	0.21	2.2

A3	PlusICE **[11]**	Organic	3	200	765	0.21	2.2
RT 3 HC	Rubitherm GmbH **[9]**	Organic	3	250			
A4	PlusICE **[11]**	Organic	4	200	766	0.21	2.18
RT 5 HC	Rubitherm GmbH **[9]**	Organic	5	240			
PCM-0M06P	SAVENRG **[10]**	Organic	5.5	260	735		
RT 6	Rubitherm GmbH **[9]**	Organic	6	175			
A50	PlusICE **[11]**	Organic	50	218	810	0.18	2.15
PureTemp 48	PureTemp **[12]**	Organic	52	245	820		2.1
PureTemp 53	PureTemp **[12]**	Organic	53	225	990		2.36
RT 55	Rubitherm GmbH **[9]**	Organic	55	172			
Climsel C58	Climator **[13]**	Inorganic	58	288.5	1460	0.6	1.89
A60H	PlusICE **[11]**	Organic	60	212	800	0.18	2.15
PureTemp 60	PureTemp **[12]**	Organic	61	230	870		2.04
PureTemp 63	PureTemp **[12]**	Organic	63	199	840		1.99
PCM-OM65P	SAVENRG **[10]**	Organic	65	210	840		
PureTemp 68	PureTemp **[12]**	Organic	68	198	870		1.85
Climsel C70	Climator **[13]**	Inorganic	70	282.9	1400	0.6	3.6
RT 80 HC	Rubitherm GmbH **[9]**	Organic	79	240			
RT 82	Rubitherm GmbH **[9]**	Organic	82	176			
PCM-HS89P	SAVENRG **[10]**	Inorganic	89	180	1540		
RT 90 HC	Rubitherm GmbH **[9]**	Organic	90	200			
A95	PlusICE **[11]**	Organic	95	205	900	0.22	2.2
A118	PlusICE **[11]**	Organic	118	340	1450		2.7

Table 3 Thermal and physical properties of the major shell materials.

alt-text: Table 3

Literatures	materials	Density Kg/m3	Specific heat J kg^{-1} °C^{-1}	Thermal conductivity W m^{-1} s^{-1}	Decomposition temperature °C	Melting Point °C
[14–17]	Melamine formaldehyde	1490	1670	0.42	–	–
[18]	Polyvinyl acetate (PVAc)	1190	101.86	0.159	150	–
[18,19]	Polystyrene (PS)	1050	1220	0.111	347	240
[18]	Polyethyl methacrylate(PEMA)	1160	–	–	–	–
[20]	Polyurethane (PU, PUR)	1030	1700	0.14	–	200

[21–23]	Urea-formaldehyde(UF)	1490	1675	0.433	–	–
[18,24,25]	Polymethyl methacrylate(PMMA)	1190	1470	0.21	–	210

3 Physical, structural and thermal stability of the MPCM slurries

The stability of the MPCM slurries can be indicated from three sides: physical, structural and thermal aspects. The physical stability, referred as to ‘mechanical stability’ (or briefly as ‘stability’), concerns the stratification (creaming or sedimentation), flocculation, coalescence, Ostwald ripening, or phase inversion, while the structural/thermal stabilities are associated with the potential rupture of the microcapsules.

3.1 Physical stability

The physical stability of a MPCM slurry is very important to heat transfer and thermal energy store. A poor physical stability of a MPCM slurry, e.g., creaming or sedimentation, may reduce the heat transfer rate of a heat exchanger or lower the heat storing capacity of a heat storage tank. A MPCM slurry with a poor physical stability may require stirring during its operation in order to keep its performance steady throughout the process [26–37].

The physical stability of a MPCM slurry is a major concern during its development, production, and mixing-up processes. There are five major issues that need to be addressed [38]:

- **Creaming or sedimentation:** This is usually caused by the density difference between the dispersed and continuous-phase materials. In an oil/water mixture, creaming may be formed by the upward movement of the oil droplets which, owing to a lower density compared to water, will form a dense oil layer at the upper part of the emulsion. On the other hand, sedimentation is an opposite process that has a higher density solution deposited at the lower part of the emulsion.
- **Flocculation:** This is a process to agglomerate the specimen droplets within an emulsion, owing to the affinity characteristics of the droplets.
- **Coalescence:** This is a process to merge two or more dispersed droplets into a larger droplet.
- **Ostwald ripening:** This occurs in solid or liquid phases where the change of an inhomogeneous structure takes place over time. It includes small crystals or solution particles dissolving, followed by redeposition into larger crystals or solid particles.
- **Phase inversion:** This is a process in which the material in continuous phase converts itself into the dispersed phase and the material with dispersed phase converts itself into the continuous phase.

For the MPCM slurries, the major stability problem lies in creaming or sedimentation, while others (e.g., flocculation, coalescence, Ostwald ripening and phase inversion) could possibly be prevented by the shells of the PCM particles. Tadrosti et al. [38] indicated that there are numerous factors that have impacts on the slurries’ stability, including the particle size and its distribution, concentration, PH value, temperature, emulsifier, surfactants, and other additives et al. However, creaming or sedimentation is more likely to occur owing to the density difference between dispersed and continuous phase materials. A microcapsule has a polymer shell, which may be able to prevent the occurrence of the physical instability, apart from creaming or sedimentation.

Liu et al. [39] developed a MPCM slurry by adjusting the density of the carrier fluid to a similar level to that of the microcapsules. By using *n*-hexacosane as the core material and melamine resin as the shell material, the microcapsule with density of 0.9 g/ml was developed. Meanwhile, the solutions of the propanol/water mixture with densities of 0.8, 0.85, 0.9, 0.95 g/ml were also fabricated and used as the carrier fluid. Both the micro-capsules and carrier fluid were then mixed together at weight ratio of 40%. The experiments indicated that sedimentation occurred at the microcapsule’s density of 0.9 g/ml, while creaming occurred at the microcapsule’s density of 0.9 g/ml. This demonstrated that the microcapsules’ density should be controlled in the range between 0.9 g/ml and 0.95 g/ml. It was also found that the slurry with the overall density of 0.94 g/ml presented the most stable physical behaviour and this physical stability state can last for 48 h at the static state condition (Fig. 2).

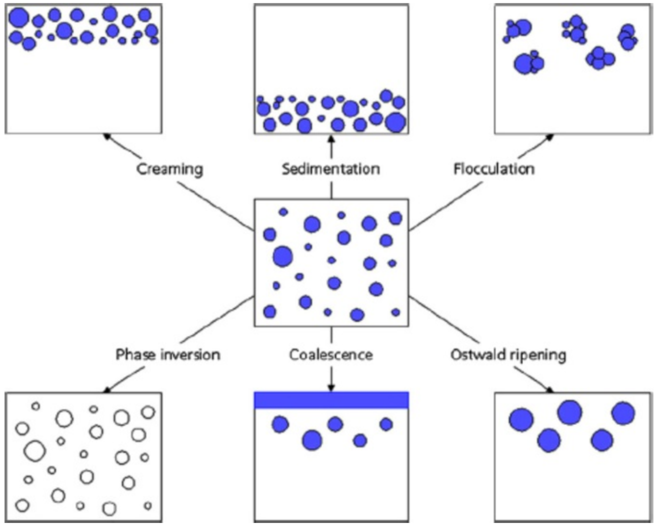


Fig. 2 Instability problems of slurries and emulsions [38].

alt-text: Fig. 2.

Delgado et al. [40] studied the physical stability of four slurries with concentrations of 14%, 20%, 30% and 42% respectively, indicating that the slurries can maintain stability for as long as 10,080 ~~minutes.~~ min. The major factors impacting on the physical stability of slurries are the density difference between the carrier fluid and solid particles, as well as the viscosity of the carrier fluid. Inclusion of an additive, e.g., surfactants, dispersing agents, or viscosity modifiers, could help improve the physical stability of slurries but meanwhile increase the viscosity of the carrier fluid, leading to increased flow resistance, greater pressure drop within the pipe line, and reduced turbulence that may reduce convective heat transfer of slurries. Reducing the density difference between the carrier fluid and solid particles could not only improve the physical stability of the slurry but also maintain a low fluid viscosity, and is thus regarded as a better method to enhance the stability of the slurry. The density of the micro-encapsulated particles depends on the materials of the shells and cores used, while the density of the carrier fluid could be adjusted by including a second fluid and regulating the mixture ratio between the primary and secondary fluids [39].

In summary, the creaming and (or) sedimentation are the major problems that reflect the physical instability of a MPCM slurry. The factors impacting on its physical stability include the size and distribution of the MPCM particles, the MPCM's weight ratio, temperature of the slurry, and emulsifier, surfactants, and other additives contained in the slurry. The most effective measure to prevent the creaming or sedimentation is to keep the MPCM particles and carrier fluid at the roughly equivalent densities, which can be achieved by selecting or adjusting the compositions of the two parts. Further, the reduced density difference between the MPCM particles and carrier fluid could also decrease the viscosity of the slurry, thus reducing the flow resistance of the slurry during the fluid movement. A MPCM slurry with a poor physical stability may require stirring during its operation in order to maintain performance.

3.2 Structural and thermal stability

Another problem remaining with MPCM slurries is the potential rupture of the microcapsules, which is can be caused by mechanical shear force or thermal cycle (i.e., alternative solidification and fusing). Yamagishi et al. studied [41] two types of MPCMs that use *n*-Tetradecane and *n*-Dodecane (with melting points of 5.5 °C and −13.5 °C respectively) as the encapsulate cores, which have equivalent diameter in the range 5 μm to 1000 μm. Those microcapsules of 5 μm were found to be more structurally stable, having no rupture observed under at least 5000 thermal cycles (solidification and fusing) and under the high shear action of a centrifugal pump.

Gschwander et ~~al~~al. [42] developed a structurally-stable MPCM slurry that can withstand the harsh mechanical impetus by a piping system. The slurry was exposed to a high shear stress condition generated by the pipes and pumps. After several-weeks continuous operation, the capsules within the slurry were visually inspected using the scanning electron microscopy (SEM). It was found that the stability of the micro-capsules is negatively affected by the pumps' shear rate. Among a few pumps tested, the centrifugal pump was found to be able to circulate the MPCM slurry for a relatively longer period, during which the destruction or crack of the microcapsule shells were not observed. It was also found that a smaller capsule diameter and a larger shell thickness benefited to the slurries' structural stability.

Alvarado et ~~al~~al. [26] investigated the structural durability of several sets of MPCM particles, with the size in the range ~~2~~ 2–150 μm. The experiment indicated that small microcapsules (2–10 μm) had the least degree of damage; those small microcapsules were detected with no physical damage after experiencing 1200 cycles through the circulation pump.

Kim and Cho [44] studied the rupture phenomena of the microcapsules that were possibly caused by material expansion during the phase change. Volatile cyclohexane was mixed with the phase change material; these were then encapsulated into the polymer cells. During the heating process, the cyclohexane was evaporated, thereby leaving some room for the phase change material to expand and the shells to keep intact.

In order to evaluate the thermal stability of the PCM capsules during the phase transition, the morphological evolution was investigated using a polarized optical microscope at a temperature scanning rate of ~~5 °C/min~~5 °C/min within ~~25–60 °C~~25–60 °C [23]. It was observed, the capsules were completely coalesced when the shell content was relatively low, e.g., ~~2.1 wt%,~~2.1 wt%, which was mainly caused by the leakage of the melt paraffin core from the cracked shell. When the shell content was increased to ~~16.7 wt%,~~16.7 wt%, the capsules were partially coalesced with the identifiable spherical contour appeared. When the shell content was increased to ~~28.0 wt%,~~28.0 wt%, the capsules were intact while the solid powder form was retained after many melting/crystallization cycles.

Zhang et ~~al~~al. [16] investigated the effect of the stirring rate and styrene-malefic anhydride copolymer content on the thermal stability of a MPCM slurry. It was found that the thermal stability of the microcapsules increased largely with the increase of the stirring rates. When increasing the stirring rate, more evenly distributed emulsion droplets were developed, leading to a narrow diameter range in both the emulsion and microcapsules that had more even shell thickness. At the slurry concentration of ~~5 wt%~~5 wt% and stirring rate of ~~9,000 rpm,~~9000 rpm, the temperature of the microcapsules reached the highest level, i.e., approximately ~~197°C.~~197 °C. It was also found that the thermal stability of the microcapsules increased slightly with the increase of emulsifier content. When increasing the emulsifier content, more evenly distributed emulsion droplets were formulated, leading to a narrow diameter range in both the emulsions and microcapsules that had a more even shell thickness. The nano-capsules with ~~2.3 wt.%~~2.3 wt% was found to have the highest thermal stability temperature, which is approximately ~~195 °C.~~195 °C.

Fan et ~~al~~al. [43] indicated that the cyclohexane content in the oil phase (carrier fluid) had a high effect onto the morphology, thermal stability and permeability of the post-treated microcapsules. The microcapsules were initially heated at ~~100 °C~~100 °C until a fixed weight ratio was achieved, and then further heated at ~~160 °C~~160 °C for the duration of ~~30 min.~~30 min. This led to the formation of a reserved expanding space that allowed the cyclohexane to completely escape from the microcapsules, thus effectively enhancing the thermal stability of the microcapsules.

In summary, the rupture of the microcapsules within a MPCM slurry was mainly affected by the type and rotation speed of the pump, diameter of the microcapsules, and the volume and weight ratio between the PCM core and its shell. The phenomena of the microcapsules rupture can be mitigated by using a low-speed centrifugal pump, selecting the small sized PCM cores and large thickness shells, as well as slightly smaller core-to-shell weight ratio. Further, the shell diameter should be made slightly larger to allow the PCM core material to expand during the heating operation, thus presenting the potential rupture of the shell owing to the core material volume growth.

4 Rheological properties

4.1 Overview of the previous studies

Yang et ~~al~~al. [18] studied the rheological properties of microencapsulated tetradecane in a few MPCM slurries. There are three types of shell materials available, namely, poly vinyl acetate (PVAc), polystyrene (PS), polymethyl methacrylate (PMMA) and polyethyl methacrylate (PEMA). The viscosities of slurries with the these shell materials were measured using the NDJ-1 rotating viscosity meter at ~~5°C~~5 °C and ~~25°C,~~25 °C, giving the results shown in Fig. 3. It was found that the viscosities of the slurries were not affected by the shell materials but largely dependent upon the operational temperature; a higher temperature led to a lower viscosity. Fig. 4 shows that the viscosity of the slurry increased gradually with the increase of tetradecane concentration in a PMMA-encapsulated tetradecane slurry, while a sharp rise occurred at the MPCM weight ratio of 40%. In terms of deionized water, its viscosity was in the range 0.93 mPa ~~mPa.s~~ s and 1.01 mPa ~~mPa.s,~~ s, while the temperature varied from 5 to ~~25°C~~25 °C and the weight ratio of the tetradecane within the slurry was as high as 35%. However, when its weight ratio reached 40%, the viscosity of the slurry became significantly higher, being about 20 times that of water. As increased slurry viscosity will require increased pump power, the magnitude of the viscosity should be appropriately controlled although a high viscosity may lead to increased heat transfer between the slurry and surroundings.

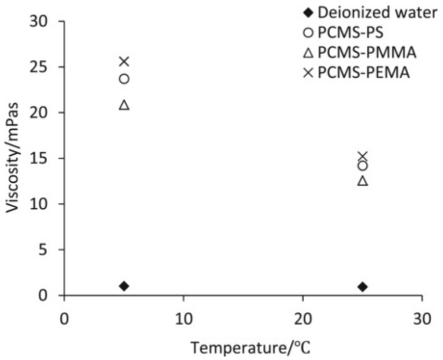


Fig. 3 Effect of shell material on viscosities slurries Data source: Table 6 of literature [18]

alt-text: Fig. 3.

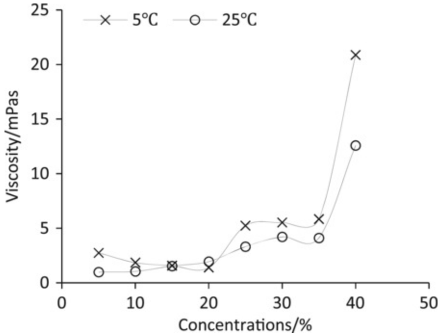


Fig. 4 Effect of concentration on of MPCM viscosities of MPCM(PMMA).~~ Table 7 [18]~~

alt-text: Fig. 4.

Data source: Table 7 of literature [18].

Yamagishi et al. [41] measured the viscosities of the *n*-tetradecane and *n*-dodecane based MPCM slurries using a cylindrical Couette viscometer. It was found that the apparent viscosity was largely dependent upon the temperature of the slurry, size of the microcapsules and the weight ratio of the MPCM. When some additives, e.g., surfactant agents, were added, the slurry changed from a non-Newtonian to a Newtonian fluid.

Wang et ~~al~~al. [28] studied the rheological behaviour of a MPCM slurry, which contained such particles with $C_{16}H_{33}Br$ as the cores and amino plastics as the shells. The core-to-shell ratio was controlled to a level of 7:1 in weight, while the thickness of the shell wall was approximately ~~0.3μm.~~0.3 μm. The diameters of the micro-encapsulated particles were measured using a particle characterization system, namely, Malvern Masterzer 2000 made by Malvern Instrument Ltd, giving an average volumetric diameter of ~~10.112μm.~~10.112 μm. It was found that a slurry with the MPCM weight ratio of 27.6% or below behaved as a Newtonian fluid, in which the shear stress increased linearly with the shear rate of the slurry under the two operational temperatures, i.e., ~~10°C~~10 °C and ~~20°C.~~20 °C. The reason for this lay in the use of the plastic shells which had a frictional interaction with the carrier fluid. However, it was also found that the rheological behaviour of the slurry was not affected by the phase transition of the MPCM particles.

By using a Kinexus Ultra Rheometer, Zhang et ~~al~~al. [45] studied the rheological behaviour of the MPCM slurries that had the MPCM weight ratio in the range ~~10% to 35%.~~ 10–35%. It was found that slurry with the MPCM weight ratio of 25% or below behaved as a Newtonian fluid, while slurry with the MPCM weight ratio in the range ~~25% to 35%~~ 25–35% behaved as a non-Newtonian fluid which had a shear rate greater than ~~200s~~200 s~~^{1}~~$^{-1}$. The rheological behaviour was not affected by the PCM phase changing as the shells of the microcapsules, in contact with the fluid, were the determining factor on the rheological behaviour. Furthermore, the viscosity of the slurries increased with the size of the PCM microcapsules.

Rao et al. [46] studied the flow characteristics of *n*-octadecane based slurries with the MPCM weight ratio in the range 5–20%, when these were flowing through horizontally-laid mini-channels. Under laminar flow condition, the friction factor of the slurries was found to increase with the MPCM weight ratio. Compared to the friction fraction of water, a slight increase was observed in a low-weight-ratio (5%) slurry. Nevertheless, when the weight ratio was 10% or higher, the increment in friction factor was more notable. The increment in MPCM weight ratio of the slurries tended to suppress the generation of turbulence within the flow. When the weight ratio was less than 15%, no obvious transition from laminar to turbulent flow was observed, as the critical transition only occurred when the Reynolds number (Re) was greater than 2000. At a certain MPCM weight ratio, the pressure drop of the MPCM slurry across the mini-channels increased with the increase of the flow speed of the MPCM slurry.

Alvarado et ~~al~~al. [26] investigated the flow characteristics of tetradecane-based slurry with MPCM weight ratio in the range ~~5% to 17.7%.~~ 5-17.7%. Relative viscosity was found to be irrelevant to the temperature of the slurry at all weight ratio conditions, which was somehow against the classical viscosity theory. The slurry behaved as a Newtonian fluid when the mass fraction was below 17.7%, while the pressure drop of the slurry increased slightly with the increase of MPCM weight ratio. In some cases, the pressure drop of the slurry was even lower than that of water, which was possibly due to the rupture of the microcapsules and leakage of the core material off the shells.

Chen et ~~al~~al. [47] indicated that the pump power of the slurry system was lower than that of the water based system of the same heat output. The reduction is caused by the reduced flow speed (by around two thirds). In this case, the water flow was at the turbulent condition while the slurry flow was at the laminar condition, owing to its lower speed and higher viscosity.

Chen et al. developed [48] a slurry containing the 5 µm sized *n*-eicosane particles and water. This slurry, with a melting temperature of 36.4 °C, was made with tow weight ratios, i.e., 10% and 20%. The dedicated viscosity measurement indicated that the slurry behaved as a Newtonian fluid.

Yamagishi et ~~al~~al. [27] investigated a slurry made of the octaddecane based MPCM particles and water. The cores of the particles were the laboratory-made octaddecane with the sizes in the range ~~2µm~~2 µm to ~~10µm,~~10 µm, and average diameter of 6.3 ~~µm,~~ µm, while the shells of the particles were a polymer with thickness of around 0.1 ~~µm.~~ µm. Fig. 5 showed the relationship between the temperature and apparent viscosity of the MPCM slurry at the MPCM volume ratio (φ) of 0.15, whereas the shear rate of the slurry was measured at 100 s~~^{1}~~$^{-1}$.

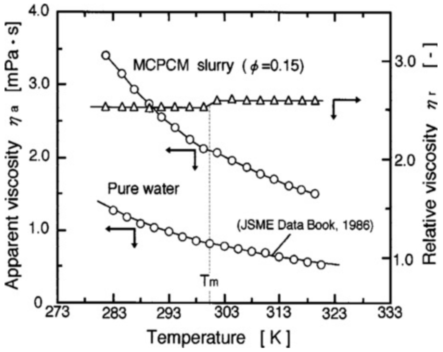


Fig. 5 Effect of temperature on apparent and relative viscosity for MPCM slurry. Results of Couette viscometer measurement for the shear of 100 sy1 and the gap size of 1.27 mm. **[27]**.

alt-text: Fig. 5.

The relative viscosity, which is defined as the ratio of the apparent viscosity of the slurry to the viscosity of pure water, remained approximately constant. The correlation between the apparent viscosity and temperature of the slurry was highly dependent upon the viscosity of pure water. At the melting temperature of octadecane (MPCM core material), a nominal change of around 3% in relative viscosity was detected owing to the volume change of the MPCM particles. However, this change was not clearly reflected in the pressure drop measurement and thus, no significant change in the pressure drop of the melting MPCM slurry was detected. In Fig. 6, it is interestingly to see that the pressure drops of the slurry at the MPCM volume ratio of 0.3 were lower than that of pure water; both were at the same flow velocity in the range ~~2~~2–2.5 ~~to 2.5m/s.~~ m/s. The reason for this was viscosity: the higher viscosity led to laminar flow. A similar phenomenon on the impact of the slurry viscosity to the flow state was also reported in previous researches [49,50].

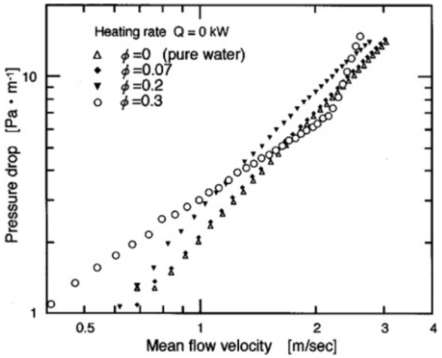


Fig. 6 Pressure drop vs. Mean flow velocity for pure water and MPCM capsules at 298 K. [27].

alt-text: Fig. 6.

4.2 The mathematic and dimensional analysis

There are numerous factors impacting on the rheology of the MPCM slurries, namely, the properties of the MPCM particles and carrying fluid, shear stress, timing and so on. In order to carry out the dimensional analysis, the following assumptions are made:

- **(a)** The MPCM particles were rigid and spherical;
- **(b)** All the particles had the same diameter throughout the slurry, ignoring the slight variation in their sizes;
- **(c)** The surfactant additives had no effect on the rheology of the carrying fluid;
- **(d)** The phase change transition had no effect on the rheology of the slurry.

On this basis, Krieger et ~~al~~al. [51,52] and Jomha et ~~al~~al. [53] carried out a series of dimensional analyses, which are detailed below:

The correlation between the slurry’s viscosity and relevant parameters was of the form:

$$\mu_b = f\left(R_p, \rho_p, n_p, \mu_0, \rho_0, k_B \bullet T, \dot{\gamma}\,\mathrm{or}\,\tau, t\right) \quad (1)$$

Using a dimensionless treatment, Eq. (1) can be simplified to:

$$\mu_r = f\left(\phi, \rho_r, Pe_{\dot{\gamma}}, Re_{\dot{\gamma}}, t_r\right) \quad (2)$$

where

$$\mu_r = \frac{\mu_B}{\mu_0} \quad (3)$$

$$\phi = \frac{4\pi}{3} n_p R_p^3 \quad (4)$$

$$\rho_r = \frac{\rho_p}{\rho_0} \quad (5)$$

$$Pe_{\dot{\gamma}} = \frac{6\pi \mu_0 R_p^3 \dot{\gamma}}{kT} \quad (6)$$

$$Re_{\dot{\gamma}} = \frac{\rho_0 R_p^2 \dot{\gamma}}{\mu_0} \quad (7)$$

$$t_r = \frac{tk_BT}{\mu_0 R_p^3} \tag{8}$$

For the neutrally buoyant systems at the steady state operational condition, ρ_r and t_r can be ignored and thus, Eq. (2) can be further simplified:

$$\mu_r = f\left(\phi, Pe_{\dot{\gamma}}, Re_{\dot{\gamma}}\right) \tag{9}$$

If the MPCM particles have a size (radius: Rp) of around 1 ~~µm,~~ µm, the Reynolds number (Reɣ) will approach zero. In this case, the Eq. (9) can be further simplified:

$$\mu_r = \mathrm{f}\left(\phi, Pe_{\dot{\gamma}}\right) \tag{10}$$

In terms of a non-Brownian system which has a very large Peclet number ($Pe_{\dot{\gamma}} \to \infty$), as shown in Fig. 5, the slurry will behave as the shear thickening or Newtonian flow. In this case, the impact of $Pe_{\dot{\gamma}}$ and $\mathrm{Re}_{\dot{\gamma}}$ to μ_r will become minimal **[54-56]**, thus,

$$\mu_r = f(\phi) \tag{11}$$

It is seen from Eq. (11) that at a certain MPCM weight ratio (with φ a constant), the viscosity of the slurry is a constant, indicating that the slurry is a Newtonian fluid.

When $\mathrm{Re}_{ɣ}$ is less than 10~~^{3}~~$^{-3}$ and $\mathrm{Pe}_{ɣ}$ is greater than 10^3, both $\mathrm{Re}_{ɣ}$ and $\mathrm{Pe}_{ɣ}$ can be removed from the Eqs. (10 and 11). This situation will only take place in a very narrow range of shear stress; in which the slurry may behave as a Newtonian fluid, as shown in Fig. 7.

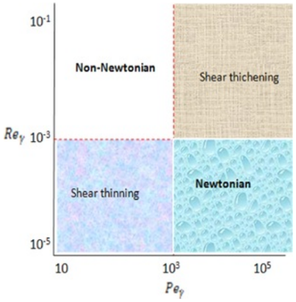


Fig. 7 Zones of slurries rheology in principle.

alt-text: Fig. 7.

4.3 Models for the slurry viscosity prediction

Numerous models have been developed for calculating the viscosity of slurries. Eq. (12) is such an empirical model, termed the ‘Vand model’ [57], and has been widely adopted by researchers [35,58,59]. This model is well suited to slurries with MPCM volume ratio of less than 37%.

$$\frac{\mu_b}{\mu_0} = \left(1 - \phi - A\phi^2\right)^{-2.5} \tag{12}$$

The constant A, being a factor reflecting the size, shape and type of the MPCM particles, can be determined by experiment. Vand et ~~al~~al. [57] yielded a value for A of 1.16 referring to glass sphere of ~~0.013cm~~0.013 cm in diameter; Mulligan et ~~al~~al. [59] indicated that the A-value was 3.4 when the MPCM particles within the slurry were in the range ~~10~~10–30 ~~– 30µm~~ µm in diameter; while Yamagishi et ~~al~~al. [27] gave a A-value of 3.7 for the octadecane based slurry with an average diameter of ~~6.3µm.~~6.3 µm. Wang et ~~al~~al. investigated [28] the viscosities of bromohexadecane($C_{16}H_{33}Br$)-based slurry, which had an average diameter of ~~10.112µm~~10.112 µm and weight ratio in the range ~~5~~5–27.6 ~~to 27.6 wt.%,~~ wt%, yielding a value for A of 4.45.

4.4 Summary

The velocity profile of a laminar non-Newtonian flow is significantly different from that of a Newtonian flow [60]. As the flow state of the slurry is directly associated with the heat transfer between the slurry and surrounding, the characteristics of the Newtonian or non-Newtonian flows need to be carefully investigated and identified. Based on the above review-based research, the following conclusions can be drawn:

(1) There are numerous factors impacting on the rheology of a MPCM slurry, including the thermal-physical properties of the micro-encapsulated particles and carrying fluid, the shear stress and operational time et al. The empirical model(Vand model), represented by Eq. (12), can calculate the viscosity of the slurries. This model, adopted by many researchers, is well suited to slurries with the MPCM volume ratio of less than 37%;

(2) In order to create a Newtonian flow condition, the slurries with high shear rate are more suitable, especially when the MPCM's volume ratio exceeds 37%;

(3) Phase change transition at the phase change temperature had insignificant impact to the relative viscosity of the MPCM slurry;

(4) The pressure drop of a slurry was lower than that of a pure water at a wide range of flow speeds and concentrations. This is because the increased slurry viscosity can create a laminar flow condition, but this condition can reduce the heat transfer rate between the slurry and surronding.

It is also suggested that further researches should focus on the following issues:

(1) As the constant factor ~~'A'~~'A' shown in Eq. (12) is highly relevant to the size, shape and type of the MPCM particles, the inter-relationship among these parameters should be further investigated;

(2) The impact of the surfactant additives on the rheologic properties of the slurry should be studied further.

(3) How to keep a relatively lower pressure drop within the slurry flow is a critical issue for further study.

5 Forced heat transfer

5.1 Main parameters in relation to phase change

The previous studies indicated that the main parameters impacting on a MPCM slurry's heat transfer are numerous. These include Stephan number(*Ste*), MPCM weight (volume) ratio, the slurry's heat capacity(C_p), the microcapsules' size (d_p), Peclet number (*Pe*), Reynolds number (Re), as well as Prandtl number (*Pr*). Definitions of these parameters are presented below:

5.1.1 Stefan number

~~The Stefan~~ The Stefan number [1], Ste, is defined as the ratio ~~of the~~ of the sensible ~~heat to latent~~ heat to latent heat, which is expressed as follow:

$$Ste = \frac{C\Delta T}{L} \tag{13}$$

This dimensionless parameter was named after Josef Stefan [62] who developed a method for calculating the phase change rate of water. On this basis, Charunyakorn et ~~al~~al. [58] defined a generalized Stefan number applicable to MPCM slurry heat transfer in a circular tube, as below:

$$Ste = \frac{C_b\left|T_W - T_m\right|}{\emptyset L\left(\rho_p/\rho_b\right)} = \frac{C_b\left|q_W R_d/K_b\right|}{\emptyset L\left(\rho_p/\rho_b\right)} \tag{14}$$

Further research carried out by Chen et ~~al~~al. [48] indicated that the term $C_b\left|T_W - T_m\right|$ cannot reflect the sensible heat occurred in the heat transfer process. To resolve this deficiency, a modified Stefan number, Ste_b, was proposed by Chen et ~~al~~al. [48], as below:

$$Ste = \frac{C_b\left(t_{b,0} - t_{b,i}\right) - L}{L} = \frac{q_w}{\dot{m}L} - 1 \tag{15}$$

This equation can reflect the effect of the phase change on the convectional heat transfer.

5.1.2 Peclet number

The Peclet number of the MPCM slurries is defined as [63]:

$$Pe_b = Re_b \Pr_b = \frac{\rho_b C_b R_d u}{K_b} \tag{16}$$

5.1.3 Heat capacity

The effective heat capacity reflecting the phase change of a slurry can be expressed as [64,65]:

$$C_e = C + \varepsilon w L \Delta t \tag{17}$$

5.1.4 Thermal conductivity

Thermal conductivity of the static dilute slurry, K_b, can be derived from Maxwell's equation [66], as below:

$$K_b = \frac{2K_0 + K_p + 2w\left(K_p + K_0\right)}{2K_0 + K_p - w\left(K_p - K_0\right)} \tag{18}$$

Owing to the interaction between the MPCM particles and carrier fluid, the effective conductivity of a slurry flow is actually higher than that predicted by Eq. (18). Leal et ~~al~~al. [67] studied the enhancement of the thermal conductivity of the diluted slurry that has a very low Peclet number. As a result, the following correlation between the conductivity of the slurry and water was developed, as below:

$$\frac{K_e}{K_0} = 1 + 3.0\emptyset {Pe_p}^{1.5} \tag{19}$$

$$Pe_p = \frac{e{d_p}^2}{\alpha_0} \tag{20}$$

Avinoam and Acrivos [68] applied a similar model to the diluted slurry flow at a very high particle Peclet number, thus yielding the following correlation:

$$\frac{K_e}{K_0} = 1 + A\emptyset {Pe_p}^{1/11} \tag{21}$$

where A is a constant that can be determined by experiment. Sohn and Chen [69] conducted experiments at the moderate Peclet numbers and proposed a new correlation, as below:

$$\frac{K_e}{K_b} = F(C, \bullet\bullet\bullet){Pe_p}^m \tag{22}$$

Based on the results discussed above, a general correlation was proposed by Charunyaorn [58], as below:

$$\frac{K_e}{K_b} = f = 1 + B\emptyset {Pe_p}^m \tag{23}$$

where B and m are two constants depending upon Peclet number of the MPCM particles. For a lower Peclet number, the values of B and m are given as 3.0 and 1.5 respectively. For a high Peclet number, m can be calculated from Eq. (23), thus giving a value of 1/11. For a moderate Peclet number, the experimental results derived from ref. [58] are used to evaluate B and m, giving the values of 1.8 and 0.18 respectively. In view of the Peclet number curve, the value of the Peclet number from low to moderate region transition was approximately 0.67. At the point from moderate to high region transition, it is around 250 [69], while the B value is determined as 3.0. The full correlations governing the entire flow regions are shown in Fig. 2. As a result, the effective thermal conductivity of the MPCM slurries, K_e, can be outlined as follow:

$$\begin{cases} \frac{K_e}{K_b} = f = 1 + B\emptyset {Pe_p}^m \\ B = 3.0, m = 1.5, Pe_p \le 0.67 \\ B = 1.8, m = 0.18, 0.67 \le Pe_p \le 250 \\ B = 3.0, m = 1/11, Pe_p \le 250 \end{cases} \tag{24}$$

5.2 Analysis of the parameters associated with the MPCM slurry heat transfer

5.2.1 Analytical tables

Table 4 provides a collocation of the parameters and the dimensionless numbers that have impact on the MPCM's slurry's heat transfer under the laminar flow condition. The analysis of these parameters indicated that the heat transfer between the slurry and surrounding can be enhanced by increasing the MPCM weight ratio, heat capacity, latent heat, size of the MPCM particles, velocity, Reynolds number, Prandtl number, and Peclet number, or by decreasing the inlet sub-cooling temperature, range of the phase change temperature, as well as Stefan number.

Table 4 The collocation of the parameters impacting on the heat transfer of a MPCM slurry at the laminar flow condition.

alt-text: Table 4

Slurries constants/ parameters/ dimensionless numbers	~~Increase(↑)~~ Increase (↑) or ~~decrease(↓)~~decrease (↓)	Heat transfer enhancement	Reason for enhancing heat transfer	References
Heat capacity function	↑	Yes	Carrying more heat energy	[29,30,33,75,76]
Concentration	↑	Yes	Increasing the bulk latent heat	[28–30,32,34,35,39,47,72,75,77–80]
Particles size	↑ (in the range of1–1000 µm)	Yes	Increasing particle diffusion	[29,30,33–35,75,79]
Flow rate or Velocity	↑	Yes	Enhancing turbulence	**[32]**
Reynolds number	↑	Yes	Enhancing turbulence	[28,31,34,49,72,75,77–79,81–83]
Prandtl number	↑	Yes	Combined effort of ingredient parameters	**[78]**
Stephan number	↓	Yes	Combined effort of ingredient parameters	[29,30,34,35,69,74,75,78,79,81–83]
Peclet number	↑	Yes	Combined effort of ingredient parameters	**[29]**
Phase change temperature range, M_r	↓	Yes	Phase change enthalpy	**[30,34,39,74,79]**
Inlet subcooling M_s	↓	Yes		**[30,34,39,75]**
Heat flux	↓	Yes		**[28,39,70,72]**
$\overline{U_1} \bullet \overline{\nabla\theta}$	↑	Yes	Not an independent factor, related to Prandtl number	**[76]**
Physical stability			no observable effect	**[35]**

Table 5 provides a collocation of the parameters and the dimensionless number that have impact on a MPCM slurry’s heat transfer at the turbulent flow condition. Similar to the laminar flow, the heat transfer between the slurry and surrounding at the turbulent flow condition can be enhanced by increasing MPCM particles’ weight ratio, heat capacity, latent heat, velocity, Reynolds number, Prandtl number, and Peclet number, or by decreasing the inlet sub-cooling temperature, range of the phase change temperature, as well as Stefan number.

Table 5 The collocation of the parameters impacting on heat transfer of a MPCM slurry at the turbulent flow condition.

alt-text: Table 5

Slurries constants/ parameters/ dimensionless numbers	~~Increase(↑)~~ Increase (↑) or ~~decrease(↓)~~decrease (↓)	Heat transfer enhancement	Reason for enhancing heat transfer	References
Heat capacity function	↑	Yes	Carrying more heat energy	[85]
Concentration	↑	Yes	Increasing the bulk latent heat	[26–28,71,78,84]
Flow rate or Velocity	↑	Yes	Enhancing turbulence	[71,81]
Reynolds number	↑	Yes	Enhancing turbulence	[27,28,78,84,85]
Prandtl number	↑	Yes	Combined effort of ingredient parameters	[78]
Stephan number	↓	Yes	Combined effort of ingredient parameters	[73,78,85]
Phase change temperature range, M	↓	Yes	Phase change enthalpy	[85]

Inlet subcooling M_s	↓	Yes		[85]
Heat flux	↓	Yes		[27,28,71,84]

5.2.2 The dominant parameters indicating the impact of the phase change on heat transfer

Charunyakorn et ~~al~~al. [29] numerically investigated the heat transfer characteristics of the MPCM slurry flow in a circular duct. The energy equation was developed by taking into account the heat absorption (or release) due to the phase change and the conductivity enhancement induced by the movement of the particles. The heat source or heat generation function in the energy equation was derived from analysing the freezing or melting process occurred in a sphere. The correlation for the effective conductivity of the slurry was obtained based on available analytical and experimental results. The governing parameters include the MPCM particle weight (volume) ratio, Stefan number of the fluid bulk, duct/particles radius ratio, the particle/fluid thermal conductivity ratio, and Peclet number. For low temperature applications, it was found that the dominant parameters are the Stefan number of the fluid bulk and MPCM weight (volume) ratio. The numerical solutions show that heat flux of the slurry was around ~~2-4~~2–4 times higher than that of the single phase flow.

Goel et al. [35] conducted an experimental study using a suspension of *n*-eicosane microcapsules within water in order to evaluate the heat transfer characteristics of the phase change material based suspension. Experiments were carried out for the laminar, hydro-dynamically fully developed flows in a circular duct with a constant wall heat flux. The primary parameters in the study were the Stefan number and the MPCM volume ratio. In addition, a few more experiments were carried out to evaluate the effect of the particle diameter and degree of homogeneity of the suspension. The most dominant parameter impacting on the heat transfer was found to be the Stefan number. The effect of the MPCM volume ratio was found to be insignificant by itself, though its impact was imposed indirectly through the Stefan number. Increase in the particle diameter by a factor of 2.5 was found to further reduce the wall temperature rise by 15%. The degree of homogeneity of the suspension was observed to have no effect to the wall temperatures.

Roy et ~~al~~al. [73] studied the turbulent heat transfer numerically. In their model the phase change effect was directly incorporated into the thermal equation. The numerical solutions fitted well with the published experimental results. The most influential parameter in the heat transfer was Stefan number. The heat transfer coefficient increased with the decrease of Stefan number and thus, the MPCM slurry achieved a much lower wall temperature than water did.

Zeng et ~~al~~al. [79] experimentally and numerically investigated the convective heat transfer characteristics of a MPCM slurry flowing across a circular tube. The enhanced convective heat transfer mechanism of the MPCM slurry, especially in the fully developed flow range, was analyzed by using the enthalpy model. Three kinds of fluid, i.e., pure water, micro-particle slurry and MPCM slurry, were numerically investigated. It was found that in the phase change heat transfer region, Stefan and Mr numbers are the most significant parameters impacting on the variation of Nusselt number and the dimensionless wall temperature. The parameters, Re_b, d_p and c, also had impact on the Nusselt number and the dimensionless wall temperature, though these are independent of the phase change process.

Based on the above review-based researches, it is clear that the most dominant parameter that reflects the impact of phase change on heat transfer is the Stefan number, while Re and Pr are also the important parameters in characterising the heat transfer process, though these are irrelevant to the phase change. The impacts of other parameters, i.e., the particles weight (volume) ratio, particle size, heat capacity, latent heat, velocity, inlet sub-cooling temperature, and phase change temperature range, can be represented by a number of parameters including Re, Pr, Ste, and Pe.

5.3 Heat transfer enhancement mechanism

5.3.1 Thermal conductivity enhancement by the particles' micro-convection

Ahuja [86] studied the approaches of enhancing heat transfer within the polystyrene suspension under the laminar flow condition, while Eckstein et ~~al~~al. [84] investigated the self-diffusion coefficients of MPCM particles. To assess the impact of the shear-enhanced thermal conductivity on the heat transfer, Sohn and Chen [88] carried out theoretical investigation into the heat transfer coefficient of laminar pipe Newtonian flow with a shear-dependent thermal conductivity, indicating that the significant enhancement in the heat transfer coefficient could be achieved under this flow condition. Table 6 presents the enhancement ratios of the thermal conductivity and heat transfer coefficient derived from the above theoretical analyses [88]. However, no experimental data are yet available to validate these theoretical predictions.

Table 6 Theoretical Enhancement Ratios for Thermal Conductivity and Heat transfer Coefficients in Slurry Flow in Pipes without Phase Change.

alt-text: Table 6.

Velocity, m/s	Particle Diameter,mm	Thermal conductivity enhancement ratios[a]		Laminar thermal enhancement[b]		Laminar fully developed[b]	
		Tube D=3 mm	Tube D=10 mm	Tube D=3 mm	Tube D=10 mm	Tube D=3 mm	Tube D=10 mm

0.1	0.1	–	–	–	–	–	–
	0.3	<2	–	<1.6	–	<2	–
	1	5.5	3.0	3.1	2.1	5.5	3.0
1	0.1	<2	–	<1.6	–	<2	–
	0.3	5.2	2.8	3.0	2.0	5.2	2.8
	1	17	9.5	6.7	4.5	17	9.5
10	0.1	5.5	3.0	3.1	2.1	5.5	3.0
	0.3	16	9	6.5	4.3	16	9
	1	55	30	14	10	55	30

[C] Based on the assumption that the particle diameters are small relative to the laminar sublayer and that the slurry behaves as a single-phase fluid of similar bulk properties. See Eq. (3)

[a] Based on the theory of Ref. [89] and the extrapolation of the data of literature **[69]**.

[b] Based on sources cited in footnote a and the theory of Ref. [88].

Section 5.1.4 provides an equation (i.e., Eq. (23)) for calculating an effective thermal conductivity, which was developed by Charunyaorn [29]. Apart from the above possible enhancement mechanisms, a few more factors, e.g., particle-to-particle collisions, particle behaviour in a turbulent flow, and the particle depletion layer near a wall, can also have an impact on the slurry's thermal conductivity and heat transfer.

Ahuja [86,90] carried out an experimental study on how to enhance the heat transfer coefficient of a MPCM slurry. The measurement data were used to compute the effective thermal conductivity by applying the theoretical correlation between the thermal conductivity and heat transfer coefficient for the 'Graetz' problem. Although the data indicated that enhancement in heat transfer was achievable, Sohn and Chen [88] pointed out that Ahuja's results [86] only related to the shear-rate dependent thermal conduction, which was hence radius-dependent, while the theoretical results only related to the situation of uniform flow. In this case, the two sets of results were inconsistent and incomparable.

It was noted that most theoretical and experimental studies have put the focus on laminar flows with simple flow channel geometries, while the established theories can approve the enhancement in heat transfer. However, these results were only applied to diluted suspensions and cannot be extended to slurries with a high MPCM weight (volume) ratio. In this case, in-depth and extensive studies are needed to cover a wider range conditions to, including the flow state, MPCM ratio in a slurry, phase change temperature, as well as piping set-up.

5.3.2 Heat transfer at the turbulent flow condition

Heat transfer performance of a MPCM slurry in the turbulent flow condition is more complex and difficult to predict than in laminar flow condition. For turbulent flow, migration of the MPCM particles within the boundary layer or shear zone adhering to the piping wall surface (see Fig. 8) would help to disrup the laminar sub-layer, thus significantly enhancing the heat transfer between the slurry and surrounding. Fig. 8 is a schematic indicating how a single phase turbulent flow can enhance heat transfer of the MPCM slurry.

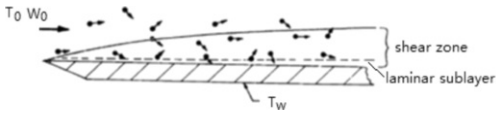


Fig. 8 Simplified Model of Turbulent Slurry Flow over a Surface [91].

alt-text: Fig. 8

For single-phase turbulent flows, dependence of the heat transfer coefficient on the physical properties of the slurry can be presented using the well-known Sieder-Tate equations, as below:

$$Nu = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{1/3} \quad \textbf{(25)}$$

$$h \propto \mathrm{K}^{2/3} \mathrm{C}_p{}^{1/3} U^{0.8} \mu^{-0.467} \tag{26}$$

In other words, the heat transfer coefficient (*h*) is proportional to the2/3 power of the thermal conductivity (*K*), and 1/3 power of the specific heat (C_p). Concentrated suspensions, which have the MPCM particle as small as the turbulent eddy and the laminar sub-layer thickness, could possibly behave as a single-phase fluid. In this case, the heat transfer coefficient would increase with the increase of the effective slurry thermal conductivity (k_{eff}). This conductivity (k_{eff}), as the replacement of 'k' shown in Eq. (26), could reflect the impact of the local shear rate (in particular, the shear rate in the laminar sub-layer) on the heat transfer. However, this model is not applicable to the suspensions with the larger sized MPCM particles, e.g., those with the diameters larger than the laminar sub-layer thickness.

For slurry with both larger or smaller sized MPCM particles, measurement data are needed to verify the theoretical predictions, or develop empirical or semi-empirical correlations in cases where theoretical predictions are not available or unrealistic. At present, the measurement data for the turbulent slurry flow are unfortunately unavailable.

5.3.3 Enhancement of the phase change related heat transfer

Chen [92] reports on a preliminary study of the heat transfer enhancement mechanism for phase-change-occurring laminar slurries. It was argued that since the heat transfer coefficient increases as the 1/3 power of the specific heat for either laminar flow or turbulent flow (see **Eq.** (26)), and the latent heat of the phase-change medium can be viewed as a form of specific heat with a Delta-function behaviour, the use of a fusible suspension with melting point within the range of the imposed thermal-system temperature difference would increase the heat transfer coefficient. It was further shown that for laminar boundary layers with thermal equilibrium between the two phases of a MPCM slurry, the enhancement ratio of the heat transfer coefficient is given by:

$$\frac{h_b}{h_0} = 0.023\mathrm{Re}^{0.8}\left(\emptyset\frac{\Delta H}{C_p T}+1\right)^{\frac{1}{3}} \tag{27}$$

This equation indicates that slurries containing a phase change material have the potential to significantly enhance the heat transfer rate, whether or not it is under laminar or turbulent flow condition. To verify this prediction, an experimental study into the suspension composing of the paraffin particles and water and with the temperature difference in the range ~~10°C~~10 °C to ~~20°Cwas~~20 °C was carried out, indicating that a 3-fold enhancement in heat transfer coefficient could be achieved.

5.3.4 Contradicting phenomena and relevant causes analyses

Among the numerous researches made on the MPCM slurries heat transfer enhancement, a few contradictory observations were reported. Alvarado et ~~al~~al. [26] indicated that the heat transfer coefficient of the slurry increased during the phase change process, while the heat transfer coefficient increased with flow velocity. However, the heat transfer coefficient of the water was higher than that of MPCM slurry and the possible reason for this lay in the suppression of the flow turbulence by the higher viscosity of the slurry.

Yamagish et ~~al~~al. [27] fabricated the slurry and experimentally investigated its turbulent convective heat transfer behaviour. It was found the local heat transfer coefficient across the circular tube decreased with the increase of microcapsules concentration in the slurry at a certain velocity, which is conflict with the conclusion presented in Table 5.

Wang et al. [78] also obtained a lower heat transfer coefficient at a higher MPCM weight ratio in the turbulent convective heat transfer study, which contradicts to the common understanding of the MPCM slurries. Hasan et al. [80] investigated the hydrodynamic and thermal characteristics of a MPCM slurry flowing across the micro channels of CFMCHE. The MPCM made use of *n*-octadecane as the microcapsules and polymethylmethacrylate(PMMA) as the shell material; both were bound together to form the microcapsules and suspended in water at a weight ratio of 0–20%. The simulation results indicated that use of the MPCM suspensions as a cooling fluid led to enhanced cooling effectiveness as well as an increased pressure drop. From heat transfer point of view, the cooling effectiveness enhancement was superior to the pressure loss increase. However, an energy analysis of two opposing effects is needed.

A possible reason that caused the controversial observations lied in the complexity of the heat transfer process occurring in the MPCM slurries. This process, as indicated in Table 5, was affected by many factors, including density, thermal conductivity, heat capacity, latent heat, concentration, viscosity, micro-capsules size, velocity, Reynolds number, Prandtl number, Stephan number, Peclet number et al. Different combinations in the operational parameters were high likely to turn out controversial heat transfer phenomena. Another reason could possibly be the unclear understanding of the coupled effect of the MPCM particles phase changing and convective heat transfer.

5.3.5 Summary of ~~Heat~~heat transfer ~~Enhancement~~enhancement

In summary, enhancement of the heat transfer capacity of MPCM slurries could be effectively achieved, whether or not the slurries involve the phase change. This enhancement could become significant when a phase change take place.

The mechanisms responsible for the enhancement were numerous; these include particle rotation in a shear flow, particle migration in the laminar and turbulent flow, and good use of the MPCM's latent heat for increasing the heat transfer. The existing data, however, were found to be quite incomplete for laminar flows and almost non-existent for turbulent flows, the latter are the most commonly seen in engineering practice. For any of the above cases, no proven correlations are available for the use in the design of a slurry based energy system.

Considering the great potential of increasing heat transfer in thermal systems and the lack of understanding of the heat transfer mechanisms of the MPCM slurries, in-depth and systematic studies of MPCM slurry heat transfer enhancement are required.

Overall, the MPCM slurry can enhance the heat transfer in some operational conditions, but definitely not in any. The operational conditions of the MPCM slurries need to be identified to ensure enhanced heat transfer of the MPCM slurries to take place, thus creating a better performance over a single phase fluid (e.g. water).

5.4 Correlations for the forced convection heat transfer

The dimensionless correlations are required for design purposes to predict the convection heat transfer of a MPCM slurry in a horizontal circular pipe. Because of the presence of microencapsulated PCM particles in the water, correlations for a single-phase flow failed to predict the heat transfer behaviours of the MPCM slurries, and hence new correlations are urgently required. Several empirical correlations have been reported to predict the heat transfer characteristics of a solid/liquid complex flow in pipes without phase change. Salamone et ~~al~~al. [93] investigated the heat transfer of a suspension, fabricated by dispersed solid particles of copper, carbon, chalk, and silica with various size ranges from 1.5 to 56 μm in the water and with the volume ratio ranging from 2.3% to 10.7% in a horizontal tube. As a result, the following correlation was derived:

$$Nu = 0.131Re^{0.62}\Pr^{0.72}\left(\frac{K_p}{K_0}\right)^{0.05}\left(\frac{D}{d_p}\right)^{0.05}\left(\frac{C_p}{C_0}\right)^{0.35} \quad \textbf{(28)}$$

for $14,000 \le Re \le 140,000, \quad 3.4 \le \Pr \le 12.7, \quad 0.53 \le K_p/K_0 \le 12.7, 282 \le \mathrm{D}/d_p \le 10,500, 0.09 \le C_p/C_0 \le 0.22$

Harada et ~~al~~al. [94] investigated the heat transfer of the water/glass-bead slurry in horizontal pipe, which had particle diameters ranging from 0.06 to 1.0 mm and a MPCM volume ratio in the range ~~0 to 10%.~~ 0-10%. The experimental data obtained were not in agreement with the Salamone and Newman correlation [93], mainly owing to the various MPCM particles applied in this process. However, on the basis of the Sieder-Tate equation, the following correlation could be derived:

$$Nu = 1.6 \times 10^{-2}Re^{0.88}\Pr^{1/3}\left(\frac{\mu_0}{\mu_W}\right)^{0.14} \quad \textbf{(29)}$$

It was claimed that the heat transfer and slurry flow were subject to the following conditions:

$$8000 \le Re \le 50,000$$
$$0.01 \le \dot{m} \le 0.1$$
$$0.0024 \le d_p/D \le 0.071$$

Under this condition, the accuracy of the correlation was measured as around ±15%. On the basis of the experimental data, Ozbelge and Somer [95] developed a correlation for the dilute liquid/solid flow and heat transfer in a horizontal tube, given by:

$$Nu = 0.202Re^{0.6}\Pr^{0.675}\left(\frac{D}{d_p}\right)^{0.092}\left(\frac{\mu_0}{\mu_W}\right)^{-1.95} \quad \textbf{(30)}$$

Under the following operational conditions, i.e., $27,000 \le Re \le 120,000, \quad 2.1 \le \Pr \le 3.4, 1.17 \le \frac{\mu_0}{\mu_W} \le 1.83, 282 \le \frac{D}{d\,p} \le 512, 0.5\% \le w \le 3\%,$ the accuracy of the correlation was measured as ~~0-20%.~~0-20%.

For a laminar flow, a linear model was proposed based on the regression analysis of heat transfer coefficient data [78]. The coefficients of the proposed model were determined by the least square method, which yields the following correlation equation that can give the best fit with the present experimental data.

Under the following claimed operational conditions: i.e., 6 $0 \le Re_m \le 2200, \quad 12 \le \Pr_m \le 73, 0.05 \le w \le 0.276$, the heat transfer correlation can be expressed as:

$$Nu = 0.8148 \times 10^{-4}Re_m^{\,0.4593}\Pr_m^{0.4836}Ste^{0.1277}\left(\frac{L_1 + L_2}{D}\right)^{0.3059} \quad \textbf{(31)}$$

As shown in Eq. (31), the heat transfer correlation equation of the slurry in the phase change region has negative power to the Stefan number and phase change region length, and positive power to the Reynolds number and Prandtl number. Comparison between the experimental data and the simulation results derived from Eq. (31) indicated that the deviation of the correlation was ~~± 10%.~~ ±10%. Shah and London [96] proposed a correlation for the pure water based laminar flow, given by:

$$Nu_x = 5.364\left[1+\left(\frac{220x^*}{\pi}\right)^{-10/9}\right]^{3/10} - 1.0 \tag{32}$$

where $x^* = (x/D)/(Re_{xb}\mathrm{Pr}_{xb})$. Based on the experimental data obtained for different power inputs, flow conditions and MPCM particle weight ratios, a new correlation was eventually developed. This correlation was in accordance with the Shan and London model (in Eq. (20)), applicable to the laminar single-phase MPCM slurry flows in the developing region under a constant heat flux, and can be expressed as[28]:

$$\frac{Nu_{MPCM}}{Nu_{ShanandLondon}} = C \tag{33}$$

where C is a constant in relation to the slurry's MPCM weight ratio, as shown in the Table 7.

Table 7 Value of C [28].

alt-text: Table 7

Weight ratio (%)	C
5	1.336
10	1.341
15.8	1.418

For the turbulent MPCM slurry flow, dimensionless analysis was also conducted by Wang et ~~al [78]~~al. [78] in the derivation of heat transfer correlation for 2100 $\leq Re \leq 3500$, $13 \leq \mathrm{Pr} \leq 15, 0.05 \leq w_p \leq 0.1$, thus yielding the following correlation:

$$Nu = 4.8527 \times 10^{-4} Re_m{}^{0.7733} \mathrm{Pr}_m^{2.7941} Ste^{0.3159} \left(\frac{L_1 + L_2}{D}\right)^{-0.333} \left(\frac{\mu_m}{\mu_w}\right)^{-2.4349} \tag{34}$$

This equation involved the average Reynolds number ($\mathrm{Re_m}$), average Prandtl number ($\mathrm{Pr_m}$), the phase change region length [(L_1+L_2)/D)], as well as the dimensionless group (μ_m/μ_w) which is a correction factor representing the effect of wall temperature on the heat transfer coefficient.

Table 8 provides comparison of the dimensionless correlations. It indicates, among the correlations Eqs. (28–30) proposed for suspensions with solid particles(without PCM particles), Eq. (28) involves the most dimensionless numbers/parameters providing the most dedicated operational conditions, and covers the widest Reynolds number range. Also it should be noted that they are all developed for turbulent flow. Comparatively Eqs. (31 and 33) were developed for laminar flow for suspensions with PCM particles, while Eq. (34) is subject to slight turbulent flow and involves the most dimensionless numbers/parameters.

Table 8 Comparison of dimensionless correlations.

alt-text: Table 8

Suspensions	Dimensionless correlations	Dimensionless numbers or parameters involved	Operational conditions
Without PCM	Eq. (28)	$Re, \mathrm{Pr}, \frac{K_p}{K_0}, \frac{D}{d_p}, \frac{C_p}{C_0}$	$14,000 \leq Re \leq 140,000, 3.4 \leq \mathrm{Pr} \leq 12.7,$ $0.53 \leq \frac{K_p}{K_0} \leq 12.7, \quad 282 \leq \frac{\mathrm{D}}{d_p} \leq 10,500,$ $0.09 \leq C_p/C_0 \leq 0.22$
	Eq. (29)	$Re, \mathrm{Pr}, \frac{\mu_0}{\mu_w}$	$8000 \leq Re \leq 50,000$

			$0.01 \le \dot{m} \le 0.1$ $0.0024 \le d_p/D \le 0.071$
	Eq. (30)	$Re, \Pr, \frac{D}{d_p}, \frac{\mu_0}{\mu_w}$	$27,000 \le Re \le 120,000$ ，$2.1 \le \Pr \le 3.4$ $1.17 \le \frac{\mu_0}{\mu_W} \le 1.83$ ，$282 \le \frac{D}{d\,p} \le 512$ $0.5\% \le w \le 3\%$
With PCM	Eq. (31)	$Re_m, \Pr_m, Ste, \frac{L_1+L_2}{D}$	$60 \le Re_m \le 2200$ ，$12 \le \Pr_m \le 73$ $0.05 \le w \le 0.276$
	Eq. (33)	$Re_{xb}, \Pr_{xb}, C$	N.A.
	Eq. (34)	$Re_m, \Pr_m, Ste, \frac{L_1+L_2}{D}, \frac{\mu_m}{\mu_w}$	$2100 \le Re \le 3500$, $13 \le \Pr \le 15$, $0.05 \le w_p \le 0.1$ ，

6 Current status of the MPCM slurries application in building energy systems

The building sector is one of the major sectors involving significant energy use. In Europe, the buildings are responsible for around 40% of the total energy consumption [97] and 36% of total carbon emission [98]. Considerable efforts have been made by the researchers and scientists on finding solutions in reducing energy consumption and finding low carbon sources of energy. In 2007, the European Union set out the energy goals for 2020 buildings [99] which are to (1) increase energy efficiency to achieve a reduction of 20% of total energy use (below 2005 levels); (2) increase the use of renewable energy contributing to 20% of total energy use (11.5% above 2005 contribution), and (3) reduce 20% greenhouse gases relative to 1990 emissions (14% below 2005 emission).

MPCM slurries can be used as a heat transfer (or heat/cold storage) fluid in buildings, e.g. in heating, ventilation & air conditioning (HVAC) systems, domestic hot water (DHW) systems, solar thermal systems. Effective and appropriate applications of the MPCM slurries in buildings can help reduce the buildings' energy consumption, and the associated carbon emission. Numerous such application cases were recently reported and below are some of the selected cases.

Wang et ~~al~~al. [100] studied a MEPCM slurry based thermal energy storage (TES), which is applied to several low energy buildings. Hexadecane ($C_{16}H_{34}$) is chosen as a core material (phase change material encapsulated) because of its low super cooling and high latent heat. Some technical issues relating to the phase change material applications were addressed and associated problem-solving approaches were proposed. It was suggested that MPCM is a better solution for building applications, which could mitigate the difficulties remaining with the common PCM materials, e.g., volume change, low thermal conductivity and incongruent melting. Further, routes for material development for dealing with the super cooling and matching the required melting temperature were also proposed.

Li et ~~al~~al. [101] studied a hybrid cooling system for the use in an office. This system was comprised of three parts: chilled ceiling system, evaporative cooling system and MEPCM slurry storage tank. The encapsulated Hexadecane ($C_{16}H_{34}$) particles were mixed with pure water to produce the MEPCM slurry, which stored the cooling energy produced by the evaporative cooling system in order for the system to be able to operate at any time when the wet bulb temperature reaches the set point in one day time. The feasibility and effectiveness of such a system for use in five cities in China were investigated, with each city representing a typical climatic condition of China. It was concluded that the proposed hybrid system is appropriate to dry climate with high diurnal temperature swings.

Zhang at al [102] and Wang et ~~al~~al. [103] made use of a MPCM slurry consisting of encapsulated Hexadecane ($C_{16}H_{34}$) PCM particles and pure water in a chilled ceiling(CC) cooling system. The ceiling panels were installed in offices rooms to remove sensible heat. Air was supplied at minimum ventilation rate at low level by a conventional air handling unit (AHU), The chiller was operated at night to generate the cold energy that was stored in the MPCM slurry. Three different chilled ceiling systems, namely (1) CC with a MPCM slurry storage; (2) CC with an ice storage (Case 2); and (3) CC with no thermal storage (Case 3), were investigated at the Hong Kong climate. It was concluded that the CC in combination with the MPCM-slurry-based storage is the most energy efficient system among the three options.

Huang et ~~al~~al. [104] tested the performance of a MPCM slurry for use in a thermal storage cylinder in a residential solar system. The cylinder was filled with a MPCM slurry with melting temperature of ~~65°C~~65 °C and three different volume ratios. A heat exchanging loop was included in the system to investigate the performance of the system at different fluid inlet temperatures and the flow rates. It was found that the MPCM slurry with a volume ratio of 50% is inappropriate to this application due to low rates of heat transfer resulting to suppression of natural convection and mixing in the store, while the changes in sizes, position and type of the heat exchanger, as well as the MPCM volume ratio in the slurry could provide the significantly improved thermal performance of the system.

A MPCM slurry based thermal storage system was integrated into an existing 2500 RT (about ~~8792.5kW)~~8792.5 kW) electrical turbo-chiller, thus forming a hybrid unit for the use in cooling of Narita Airport space in Tokyo, Japan [105,106]. This combination aims to enhance the cooling performance of the system which had the reduced cooling capacity following a change in refrigerant for environment benefit. During the process, n-Paraffin waxes were selected as the PCM, while the slurry was a mixture of water and microcapsules with mean diameter of 2 ~~microns,~~ µm, melting temperature of ~~8°C~~8 °C and the latent heat of 75.9 kJ/kg. The storage tank, ~~24.7m~~24.7 m in height and ~~7.4m~~7.4 m in diameter, was used to store cold energy at night. The MPCM slurry at ~~11.5°C~~11.5 °C was transported into the storage tank by using a conventional centrifugal pump, and cooled in a flat-plate heat exchanger by a refrigerant at ~~3.5°C,~~3.5 °C, thus leading to the change of the phase of the slurry and ~~4°C~~4 °C drop in the slurry's temperature. The cold energy stored in the slurry was then released during day time. Through the heat exchange, coolant at ~~5.1°C~~5.1 °C was obtained and this was pumped to the load side for cooling. The COPs of the chiller and the whole system during the cold storing process were 5.4 and 3.2, respectively, which were lower than the COP values (5.9 and 4.4) of the same units when no cold storage was implemented. Compared to the traditional cold storage system that made use of the external melting ice, the MPCM slurry based system had around 60% less thermal storage capacity, while its operational cost was 32% lower.

Griffiths et ~~al~~al. [107] investigated the performance of a MPCM slurry as a heat transfer fluid in a test chamber equipped with a chilled ceiling panel. The schematic of the testing rig is shown in Fig. 9. The MPCM, produced by BASF, had microcapsules diameter of 2–8 ~~µm~~ µm and a melting temperature of ~~18°C,~~18 °C, which is close to the working temperature of chilled ceiling (i.e., ~~16~~16–18 ~~–18 °C).~~ °C). The performance of such a MPCM slurry system was investigated with reference to the chilled water based system. To maintain the test chamber at a constant temperature of ~~19°C,~~19 °C, a flow rate of ~~0.7l/s~~0.7 l/s was required when water was utilized as the heat transfer fluid, while only ~~0.25L/s~~0.25 L/s was required for the slurry with the MPCM weight ratio of 40%. Throughout more than four-months of continuous operation, it was proved that the slurry with 40% of MPCM weight ratio was a better performing heat transfer fluid than water for the use in the chilled ceiling panels. During the trial, no deposition of microcapsules in pipe or the degradation of the slurry was detected, while the pump power of the system was reduced owing to the reduced flow rate. However, it was recommended that the control algorithm of the system should be updated when using the slurry instead of water as the heat transfer fluid.

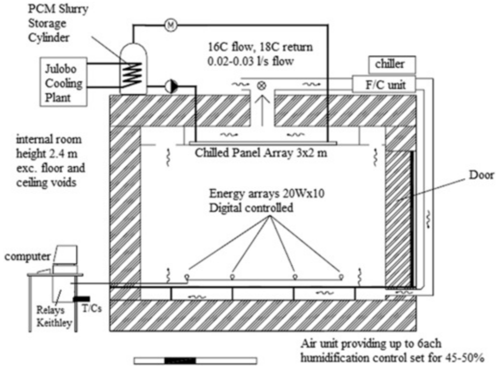


Fig. 9 The schematic of the testing rig.

alt-text: Fig. 9

Qiu et ~~al~~al. [108,109] carried out a theoretical and experimental investigation into the energy performance of a novel MPCM slurry based PV/T heat and power system. This involved (1) development and validation of a dedicated mathematical model and computer program; (2) simulation of the energy performance of the MPCM slurry based PV/T system; and (3) investigation of the impacts of the slurry flow state, MPCM weight (volume) ratio, Reynolds number and slurry serpentine size on the energy performance of the PV/T system. It was found that the established model, based on the Hottel-Whillier assumption, is able to predict the energy performance of the MPCM slurry based PV/T system at a very good accuracy, with the average error level in the range ~~0.3 to 0.4%.~~ 0.3–0.4%. Analyses of the simulation results indicated that laminar flow is not a favourite flow condition in terms of the energy efficiency of the PV/T module. Instead, turbulent flow is a desired flow condition that has potential to enhance the energy performance of PV/T module. Under the turbulent flow condition, increasing the MPCM weight ratio led to the reduced PV cells' temperature and increased thermal, electrical and overall efficiency of the PV/T module, as well as increased flow resistance. As a result, the net efficiency of the PV/T module reached the peak level at the MPCM weight ratio of 5% at a specified Reynolds number of ~~3,350.~~3350. With all other parameters fixed, increasing the diameter of the serpentine piping led to an increased slurry mass flow rate, decreased PV cells' temperature and consequently, increased thermal, electrical, overall and net efficiencies of the PV/T module. Overall, the MPCM slurry based PV/T module is a new, highly efficient solar thermal and power configuration.

7 Challenges for applying an MPCM based thermal system

The major challenges that may arise when applying the MPCM based thermal system are presented here as below.

(1) One of the major obstacles for the engineering application of an MPCM based system is the high cost of encapsulation. This increases the overall cost of the system.

(2) The correct choice of PCM, shell material, encapsulation method and its size varies with the application.

(3) Precise prediction of moving solid–liquid boundary during the phase change process is still a major problem to be resolved. The rate of movement of this boundary is not known a priori. [110]

(4) For MPCM Slurries, the conventional heat transfer correlations cannot be used due to phase change effect on the slurry. An in-depth knowledge of heat transfer enhancement mechanism and PCM phase change rate prediction are essential while applying the MPCM slurries based thermal system.

(5) Other considerable challenges are sub-cooling of the MPCM. The inorganic PCMs are observed to be more prone for these challenges. Although this problem can be alleviated by addition of suitable materials, the impact due to addition of these materials on the latent heat storage capacity and phase change temperature of the PCM is evident.

8 Conclusions

The physical stability of a MPCM slurry is critically important to enable it to act as a heat transport fluid or a thermal storage material. The main reason for slurry instability is the density difference between the solid MPCM particles and the carrier fluid. An effective measure to achieve physical stability of a MPCM slurry is to increase its viscosity, which, however, also causes the increased flow resistance. Further, the increase in viscosity will suppress flow turbulence of the slurry, which will lead to the reduced heat transfer rate. It is still a challenge to remain a good physical stability and meanwhile keep a reasonably low viscosity, in order to achieve the good heat transfer between the slurry and its surroundings.

Rupture of the micro-capsules shells will lead to the leakage of the encapsulated phase change material, thus resulting in the coalescence of the PCM particles. It is too expensive to replace the micro-encapsulated PCM particles frequently, so avoiding the fast rupture of the shells is a challenge in the MPCM slurry application. Shell rupture mainly results from mechanical shear stress, caused by the operation of the pump. The type of the pump and its rotation speed, diameter of the MPCM particles, and weight ratio between the shell and the encapsulated particles are three major factors impacting on shell rupture. By using a low speed centrifugal pump, keeping the microcapsule diameter below 10 µm and increasing the shell-to-microcapsule weight ratio to above 28%, the microcapsules can have a relatively long life span without rupture.

Viscosity of a MPCM slurry is a key parameter used in calculation of heat transfer rate and flow resistance. A semi-experimental correlationEq. (12)) for computing the slurry viscosity has been developed. However, the coefficient factor A within the correlation remains uncertain. More elaborate experiments are required to establish the relationship between the factor A and the size, shape and type of the microcapsule particles.

The heat transfer performance of a MPCM slurry could be enhanced by several measures: (1) increasing the thermal conductivity of the slurries by enhancing the heat convection of the MPCM particles; (2) breaking up the laminar sub-layer within the shear zone; and (3) increasing the heat capacity of the slurry by enhancing the phase change of the PCM material. It was observed that compared to water, MPCM slurry as a heat transport fluid may lead to a reduced heat transfer rate under a certain operational condition. This is an unusual phenomenon which may result from the inconsistent operational conditions and incomplete understanding of the multi-phase fluid in terms of fluid flow, heat transfer and phase change. To assess the performance of the MPCM slurry against a single phase fluid, a criteria equation should be developed. The analysis of the equation will be able to sort out the conditions for the favourite use of the MPCM slurry. It should be particularly addressed that only under the specific operational conditions, the MPCM slurry can behave as a better performing heat transport fluid over ~~water~~water.

It was found by comparison between the dimensionless correlations, Eq. (28) was proposed for suspensions with solid particles(without PCM particles), involving the most dimensionless numbers/parameters, providing the most dedicated operational conditions, and covering the widest Reynolds number range. Eq. (34) was developed for slight turbulent flow of MPCM suspensions, and subject to the most dimensionless numbers/parameters. The established dimensionless correlations for the MPCM slurry heat transfer were based on the limited experiment data and few MPCM types, and thus cannot be applied to wide range of practical engineering projects. Although the Stefan number is defined as a term indicating the phase change performance of a slurry, its definition is unclear and somehow inconsistent in different literatures. This parameter is therefore unable to predict the overall performance of the MPCM slurries. In order to disclose the effect of the MPCM particles phase change on the convectional heat transfer of the slurry, more experimentation and more reliable correlations are required.

Although there are a few reported cases on the MPCM slurry application in building energy systems, a wide range of applications of the MPCM slurries in building sector have yet to be developed. This is largely owing to the immature nature of the MPCM slurry research, in terms of physical and chemical stability and heat transfer mechanism, as well as building services adaptability, and the perceived risk associated with novel systems.

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[61,87].

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Queries and Answers

Query:

Please provide the citation of footnote "c" in Table 6.

Answer: The following sentence should be erased:"cBased on the assumption that the particle diameters are small relative to the laminar sublayer and that the slurry behaves as a single-phase fluid of similar bulk properties. See Eq. (3)"

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