Fundamental aspects of phase change slurries: Thermo-fluidic characteristics

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Abstract Thermal energy storage (TES) is an attention-gaining technology which is useful to improve the energy efficiency as well as to balance the energy supply and demand. Until recently, the latent heat TES (LHTES) technology has been promoted quite fast mainly due to the large heat storage/release capacity that takes place at nearly constant temperature. The phase change slurry (PCS) prepared by dispersing phase change materials (PCMs) into carrying fluid can serve not only as the energy storage media, but also as the heat transfer fluid (HTF). Compared with the conventional PCM which needs additional HTF, the PCS provides superior performance and has the great potential to upgrade the current TES systems. This paper reviews the latest investigations of the micro-encapsulated PCM (MPCM) and shape-stabilized PCM (SSPCM) slurries. A brief introduction of the preparation methods of the two types of the PCSs is summarized. And a comprehensive review of the flow and heat transfer characteristics of the PCSs, particularly in various tube-based geometries and heat exchangers, is conducted for a better understanding of the mechanism and further utilization of the next-generation TES systems.

Keywords Phase change slurry; Flow; Heat transfer; Thermal energy storage

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1 Introduction

With the rapid economic development and increasing energy demand, energy strategy has been one of the most important factors which relate to the social stability and national security. Presently, the large consumption of conventional fossil fuels results in serious negative effects, e.g., environmental pollution, global warming and shortage of energy reservoirs for the next generations. Energy-saving and emission control can effectively improve the energy efficiency and reduce the discharged pollutants. The development of renewable energy is also a viable solution to mitigate the increasing energy crisis. However, the renewable energy sources (e.g., solar) are often intermittent and season-oriented. This is a serious fact due to which commercialization of renewable energy is not yet comparable to its counterpart. Therefore, the most feasible route to address such issues is to utilize the energy storage technologies. Amongst them, TES technology has played a significant role in enhancing the energy efficiency of renewable energy sources. Consequently, the imbalance between energy supply and demand can be solved through the TES. In principle, the excessive energy can be stored at low energy load through the TES system and then be released at high energy load so that the problem of peak-valley difference for electric grid can be solved [1].

Phase-variant energy storage systems (i.e., LHTES driven by PCMs) are superior to other energy storage systems (i.e., sensible heat TES and thermochemical TES) [2] due to a large latent heat storage density and nearly isothermal characteristics during the phase change process, providing more stable temperature to the energy consumers. Although the heat storage density of the thermochemical TES is

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higher than that of the LHTES, the complex thermodynamics of chemical processes, high operational temperatures, intricate design parameters of the reactor and high project cost render the thermochemical systems less competitive. However, there are also some disadvantages of the PCMs limiting the extensive application of the LHTES. For example, the organic PCMs such as paraffin have low thermal conductivity and are flammable, and the inorganic PCMs such as high melting temperature metallic alloys and molten salts are corrosive to the container. Furthermore, the conventional PCMs usually need additional HTF such as water and oil to facilitate the energy charging and discharging processes, which complicates the system and operation of the TES.

PCS as a functional fluid, which can overcome the aforementioned problems, has been found to be much more attractive in the recent years [3]. The PCS mainly consists of the PCM and the carrying fluid which always retains the liquid state and helps to suspend the PCM particles. Inaba [4] reviewed the sensible and latent heat-type thermal fluids, and made a clear classification about the PCS based on the types of the PCM and carrying fluid: (1) 1-component slurry, such as slush hydrogen, slush nitrogen and ice slurry, in which there is only one component in the slurry; (2) Clathrate hydrate slurry (CHS), such as tetrabutylammonium bromide CHS (TBAB CHS), trimethylolethane CHS (TME CHS), and tetrabutylammonium fluoride CHS (TBAF CHS), in which the PCM is clathrate hydrate crystal and the carrying fluid is the corresponding solution; (3) Phase change emulsion (PCE), in which the small particles of insoluble PCM such as paraffin are uniformly distributed in the carrying fluid through the emulsifying agent; (4) Micro/nano-encapsulated PCM (M/NPCM) slurry, in which the PCM core is encapsulated by the polymer shell and then dispersed in the carrying fluid. The difference between the PCE and M/NPCM slurry is whether there is a shell embracing the PCM. (5) SSPCM slurry, in which the shape of the PCM is stabilized through the polymer matrix or other supporting materials to avoid the leakage in liquid state. These five types of the PCSs can be simply divided into two groups based on whether the PCM directly or indirectly contacts the carrying fluid. The PCM particles in the first three kinds of the PCSs can directly contact the carrying fluid. The PCM changes to carrying fluid when the PCM particles melt completely, which enhances the complexity of recycle because the preparation of the PCS is usually bundled with its application. In addition, the droplet form of PCM in the PCE above phase change temperature is not stable because the droplets of the PCM can easily make large clusters, which badly affects the homogeneity of the slurry. However, there is no such problem for the last two kinds of the PCSs. The shell of the M/NPCM and the supporting material of the SSPCM play important roles in isolating the PCM from the external environment so that the leakage and cluster-formation problems can be overcome. The corrosiveness of some PCMs, such as inorganic salt hydrates, to the metal can also be avoided through the shells or supporting materials. Therefore, the last two kinds of the PCSs, especially the MPCM slurry have attracted much more attention among different types of the PCSs over the last decade.

The PCS shows significantly excellent performance over the pure HTF and conventional PCM due to the following advantages. The PCS can be stored in the conventional tank, pumped through the pipelines and discharged directly without additional HTF due to the fluidity of the PCS. Meanwhile, the heat energy storage density of the PCS is apparently higher than that of the pure HTF because of the latent heat storage capability. Therefore, the PCSs are not only used as the HTF, but can also be used as the energy storage media. The PCS shows better performance than that of the single-phase fluid in energy transport. The pumping power can be reduced because the mass flow rate decreases when using the HTF with high energy storage density to transport the same amount of energy. Further, the large heat capacity of the PCS also contributes to the enhancement of heat transfer of the HTF, and the decrease of the PCS temperature compared with the conventional HTF is in favor of the cooling performance of the heat sinks and heat exchangers. In addition, the specific surface area of the PCM greatly increases in form of particles, which implies that the heat transfer between the PCM and the fluid is improved.

According to the advantages of the PCS and broad phase change temperatures of different PCMs, the PCS can be used in a variety of fields to improve the energy efficiency. For example, the slush hydrogen

was proposed as the cryogenic propellant in aeronautic and astronautic engineering [5]. It has been reported that the slush nitrogen was adopted in the high temperature superconducting system [6] and cryopreservation of cells [7], which showed better performance than the liquid nitrogen and was much more competitive. The ice slurry was widely engaged in cold energy storage due to the low temperature and high energy storage density. It showed excellent performance on the food cooling [8], air-conditioning system [9] and fire fighting techniques [10]. The phase change temperature of the CHS can be adjusted in the temperature range of 0—12℃ by changing the initial concentration of the solution, making it applicable for the air-conditioning system as a medium of secondary refrigeration [11]. The PCE was usually applied for cold energy storage in comfort-cooling applications [12] or as a cooling medium for multichip module [13].

In addition, the MPCM slurry as the most attractive PCS has been widely applied in the thermal energy storage and transportation systems due to the diversity of the PCMs as the core material. Kasza and Chen [14] proposed the concept of using the PCS in the waste heat recovery systems, and they presented a system model to analyze the energy saving potential of the PCS. The PCS worked between a heat source and a heat sink which were at constant temperatures, and decreasing the temperature difference between the source and sink was helpful to enhancing the usefulness of thermal energy. The results showed that the PCS could effectively decrease the temperature difference, and even when the PCS was not under the phase change process, the heat transfer temperature difference was also smaller because the micro-convection of particles improved the effective thermal conductivity of the slurry compared with the single-phase fluid. The large latent heat could further decrease the temperature difference. They found that the flow rate, pumping power consumption of the PCS and the volume of the storage tank were smaller than those of the single-phase fluid at the same temperature rise of the fluid. Wang and Niu [15] adopted the MPCM slurry in building engineering and designed a new cooled-ceiling (CC) system combined with the MPCM slurry storage tank. A mathematical model was built to analyze the energy efficiency of three different systems: CC with water, CC with the MPCM slurry and CC with ice storage. It was indicated that the system of CC with the MPCM slurry showed the most excellent performance in improving the energy efficiency. Also, the CC system with the MPCM slurry was cost-effective at low day/night electricity tariff ratios. Wu et al. [16] experimentally investigated the performance of the NPCM slurry applied for jet impingement and spray cooling. The volume fraction of the MPCM played an important role in the pressure drop and heat transfer coefficient of the NPCM slurry. There was a peak value of heat transfer coefficient when the inlet temperature was close to the peak melting temperature of the PCM as demonstrated by the DSC curve. The maximum enhancement of heat transfer coefficient of the NPCM slurry compared with that of water could achieve 50% and 70% for jet impingement and spray cooling, respectively. Chen et al. [17] employed the MPCM slurry as the cooling medium in the thermal management system of a proton exchange membrane fuel cell (PEMFC). The MPCM slurry demonstrated significantly large cooling potential compared with water. The large heat capacity of the MPCM slurry was helpful to reducing the weight, volume and pumping power of the coolant, leading to the reduced system size and increased output power of the PEMFC. Kong et al. [18] investigated the MPCM slurry as the HTF in a ground source heat pump (GSHP). The MPCM slurry had better thermal performance than water and was suitable to be applied in heating and cooling applications. The heat load-to-pumping power ratio of the MPCM slurry was about 34% higher than that of water, and the coefficient of performance of the GSHP system using the MPCM slurry was in the range of 3.2—4.0. Zhang et al. [19] employed the MPCM slurry loop for thermal management of batteries of electric vehicles. They compared the MPCM slurry loop with the conventional methods: direct cabin air blow and refrigerant circulation through the analysis of 1^{st} Law and 2^{nd} Law of thermodynamics. The results displayed that the method of direct cabin air blow would lead to much more heat load for the air-conditioning system than the other two methods if the cabin ventilation effect was not taken into account. The MPCM slurry loop brought the same heat load with the refrigerant circulation, but it showed higher exergy efficiency than the refrigerant circulation. Serale et al. [20] designed a solar energy storage system employed in the low-temperature application using n-eicosane/water+glycol MPCM

slurry as the HTF and storage media. Two prototypes with different loops were analyzed, and the details of the system including each component and thermo-physical properties of the MPCM slurry were introduced. They indicated that the designed system with the MPCM slurry could provide desirable enthalpy even at low temperatures.

It is apparent that the PCS has been extensively used in many fields of industry, and Figure 1 shows a collective illustration of the fundamental research and applications of the PCS. No matter whether the PCS is adopted as the HTF or as the energy storage medium, the flow and heat transfer characteristics of the PCS play a pivotal role in the performance of the system, which is apparently worthy of investigation. There are many different parameters affecting the thermo-fluidic of the PCS, such as solid volume fraction, particle diameter, melting temperature and so on. The different effects of these parameters on the performance of the PCS should be summarized. This paper mainly focuses on the MPCM slurry and SSPCM slurry, and presents a comprehensive literature review about the investigations of the flow and heat transfer characteristics, especially in tube and heat exchangers. The preparation methods of the MPCM and SSPCM are also briefly discussed.

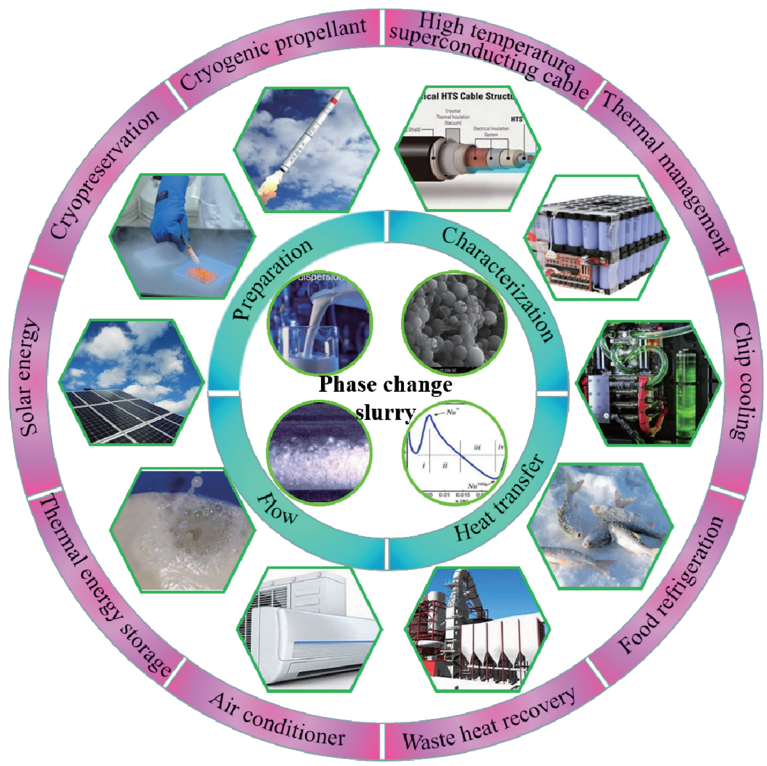


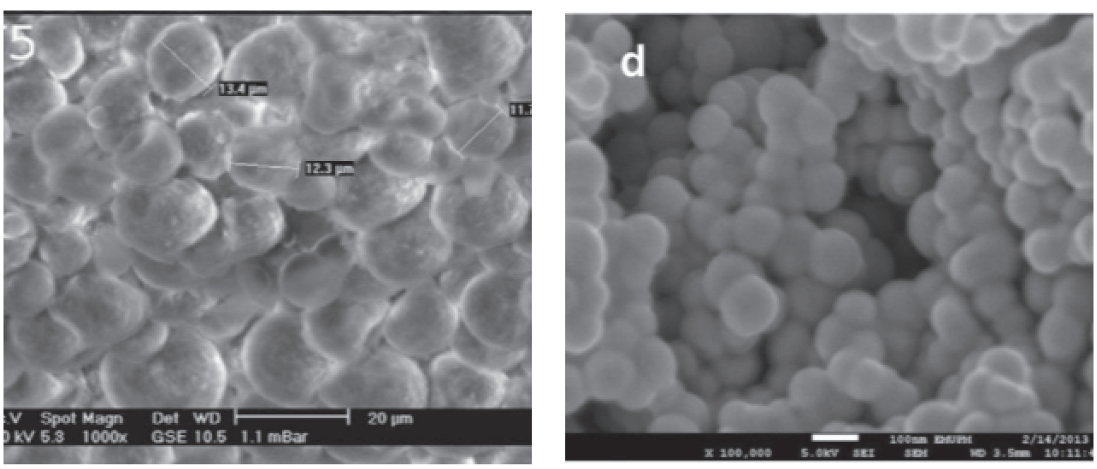
Figure 1 Applications and fundamental research of the PCS. The phase change slurries can be utilized as both the heat transfer fluid and energy storage medium due to the excellent heat transfer performance and large heat capacity. Different phase change slurries are widely applied in a variety of fields: cryogenic propellant (slush hydrogen), cryopreservation (slush nitrogen), air conditioner (ice slurry and clathrate hydrate slurry), chip cooling and solar energy (phase change emulsion and micro/nano-encapsulated phase change slurry), etc. The fundamental research on preparation, characterization, flow and heat transfer of the phase change slurries is therefore practically significant.

2 Micro/nano-encapsulated PCM slurry (M/NPCM slurry)

2.1 Preparation

The preparation of the MPCM slurries mainly includes how to encapsulate the PCM at the micro-scale. Many approaches have been proposed to produce the MPCM slurries. In recent years, the nano-encapsulated PCMs (NPCM) were also developed. The preparation methods of the MPCM and NPCM are classified together because the preparation mechanisms are nearly the same for them. There are mainly

three types of preparation methods: physical method, chemical method, and physio-chemical method. The chemical methods include *in-situ* polymerization, interfacial polymerization, suspension polymerization and emulsion polymerization. In the *in-situ* polymerization method [21], the reactive monomer and catalyst are added in the continuous phase, in which the monomer is soluble but the polymer is immiscible. The continuous phase here is usually the water which is immiscible with the PCM. The monomers polymerize in the continuous phase to form the pre-polymers. The sizes of the pre-polymers increase continuously and the pre-polymers will deposit on the surface of the dispersed particles or droplets which are the core materials. In the interfacial polymerization method [22], the core materials are first dispersed in a continuous phase which contains the first monomer of the shell material. Then, this solution is emulsified in an immiscible continuous phase, which could dissolve the second monomer, to form the O/W or W/O emulsion. The solution with the second monomer is added in the emulsion and the interfacial polymerization of the two types of monomers occurs on the surface of the core materials to form the shell. The difference between the *in-situ* polymerization and interfacial polymerization methods is that the polymerization of the monomer occurs only in the continuous phase for the *in-situ* polymerization, but it occurs on the interface of the two phases for the interfacial polymerization. The suspension polymerization method [23] is based on the free radical polymerization and suitable for the condition that the reactive monomer and the initiator are insoluble in the continuous phase. The oil phase containing the core material, monomer and initiator is suspended in the continuous phase and emulsified by adding surfactants. Then the free radical is released by the initiator because of a trigger such as heating. The radical polymerization occurs and forms the shell of the core material. The emulsion polymerization method [24] is similar to the suspension polymerization method. The difference is that the initiator here is soluble in the continuous phase. Therefore, the droplets in the formed emulsion only contain the core material and monomer. The MPCM and NPCM have been fabricated via the interfacial polymerization and *in-situ* polymerization methods. The corresponding scanning electron microscope (SEM) images are shown in Figure 2. It can be seen that the particles are smooth spheres with uniform diameters.



(a) (b)

Figure 2 SEM images of (a) MPCM [22] and (b) NPCM [21].

The physio-chemical methods include the complex coacervation method, simple coacervation method, sol-gel method and microfluidic method. In the complex coacervation method [25], the shell material contains two types of polymers with opposite charges. The core materials are dispersed into the solution containing the shell materials, and then the electrostatic interaction between the two types of polymers occurs due to the change of temperature or the PH value of the solution. The two types of polymers coalesce on the surface of the core materials to form the shell, and the phase separation occurs due to the reduction of the solubility. So, this method is also called the phase separation method. In the sol-gel method [26], a colloidal solution (sol) is first prepared through the polycondensation reaction of precursor

compounds and then it is added dropwise into the emulsion containing the core material. The colloidal solution is then converted to the oxide network (gel) on the surface of the core material as the shell. The emulsion should be stirred constantly to prevent the formation of continuous gel. There are also some other physio-chemical methods such as the simple coacervation method [27] and the microfluid method [28], which are not introduced here for brevity. The physical methods include the spray drying method [29], air suspension coating method [30], electrostatic method [31], vacuum impregnation method [32] and so on. Most of the physical methods are used in food and pharmaceutical fields and the spray drying method is usually adopted to encapsulate the PCM. In the spray drying method, the core materials are dispersed in a solution containing the shell material. Then, the mixture is sprayed at high temperature so that the solvent evaporates rapidly and the shell forms on the core material.

2.2 Flow and heat transfer characteristics

M/NPCM slurry has been found advantageous to modify the thermo-fluidic characteristics of fundamental flow regimes (laminar and turbulent flows), as well as to improve the performance of heat sinks and heat exchangers. This section has been systematically divided into experimental and theoretical studies.

2.2.1 Experiments in laminar regime

Goel et al. [33] investigated the heat transfer characteristics of the n-eicosane/water MPCM slurry in a circular tube with an inner diameter of 3.14 mm and a length of 0.3 m. The results showed that the dimensionless wall temperature of the tube was significantly decreased when using the MPCM slurry instead of the single-phase fluid. They found that the bulk Stefan number and inlet temperature played important roles in the heat transfer of the MPCM slurry. The low Stefan number, which can be achieved by increasing the solid volume fraction of the MPCM slurry or decreasing the diameter of the tube, depicted positive effect on the reduction of the wall temperature. Yamagishi et al. [34] conducted the laminar flow experiments of the octadecane/water MPCM slurry in a long tube with an inner diameter of 10.1 mm and a length of 8.0 m at constant heat flux. They measured the bulk temperature by collecting the MPCM slurries flowing through different heating lengths. The results showed that the pressure drop of the MPCM slurry was higher than that of water and increased with the increase of solid volume fraction. The heat transfer coefficient of the MPCM slurry in laminar flow was higher than that estimated by the empirical correlation under the condition of no melting, but smaller than that of the MPCM slurry with lower volume fraction which has been in turbulent flow at the same velocity, as shown in Figure 3. Inaba et al. [35] investigated the flow and heat transfer of a MPCM slurry containing different PCM particles. They found that the local Nusselt number of the MPCM slurry was higher than that of the single-phase

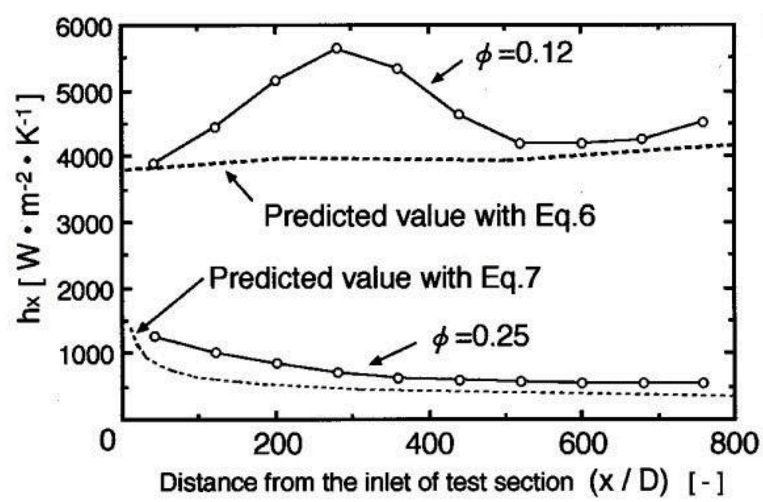


Figure 3 Local heat transfer coefficients of the MPCM slurry at volume fraction of 0.12 and 0.25. Re=7360—8650 (v=1.25 m/s) for volume fraction of 0.12. Re=1696—2183 (v=1.22 m/s) for volume fraction of 0.25 [34].

fluid (without PCM) because of the combined effects of latent heat and micro-convection of the particles. The results showed that the heat transfer enhancement of the MPCM slurry was more significant than the increase of friction factor in the laminar regime.

Rao et al. [36, 37] studied the flow behavior and heat transfer of n-octadecane/water MPCM slurry in the rectangular mini-channels. It was reported that the pressure drop of the MPCM slurry increased with the increase of the mass concentration. Also, the transition of Reynolds number from laminar to turbulent flow increased with the increase of the mass fraction, because the existing MPCM particles could suppress the generation of turbulence. Further, increasing the mass fraction of the MPCM could decrease the wall temperature and increase the Nusselt number at lower flow rates. At higher flow rates, the mass fraction had no effect on the heat transfer coefficient and Nusselt number, and the cooling performance of the MPCM slurry was close to or worse than that of water. Wang et al. [38, 39] investigated the hydraulic and heat transfer performance of the 1-bromohexadecane/water MPCM slurry in a horizontally circular tube with an inner diameter of 4 mm and a length of 1.46 m at constant heat flux. The results showed that the MPCM slurry could be considered as the Newtonian fluid even when the mass fraction was up to 27.6 wt%. The Fanning friction factors of the MPCM slurry in laminar flow were smaller than those estimated by the equation of 16/Re because of the entrance effect. The local heat transfer coefficients of the MPCM slurry were higher than those of water at the same velocity in laminar flow due to the latent heat and micro-convection of the particles. The heat transfer coefficient of the MPCM slurry increased with the mass fraction of the PCM. Chen et al. [40] investigated the heat transfer performance of the MPCM slurry in a circular tube. The heat transfer rate of the MPCM slurry increased significantly compared with that of water, and the dimensionless wall temperature could reduce about 30% as shown in Figure 4. The heat transfer enhancement ratio increased by enhancing the mass fraction of the MPCM slurry. The pumping power consumption of the MPCM slurry decreased significantly compared with that of water at the same heat transfer rate. Ho et al. [41] compared the heat transfer performance of the Al_2O_3/water nanofluid and n-eicosane/water MPCM slurry in a circular tube at constant heat flux. They found that both HTFs could increase the heat transfer coefficient and decrease the dimensionless wall temperature compared with water, but the MPCM slurry showed better heat transfer performance than that of nanofluid due to the larger heat storage capacity, especially only after the onset of the melting process of the PCM. However, in the pre-melting zone, the MPCM slurry could not outperform the nanofluid.

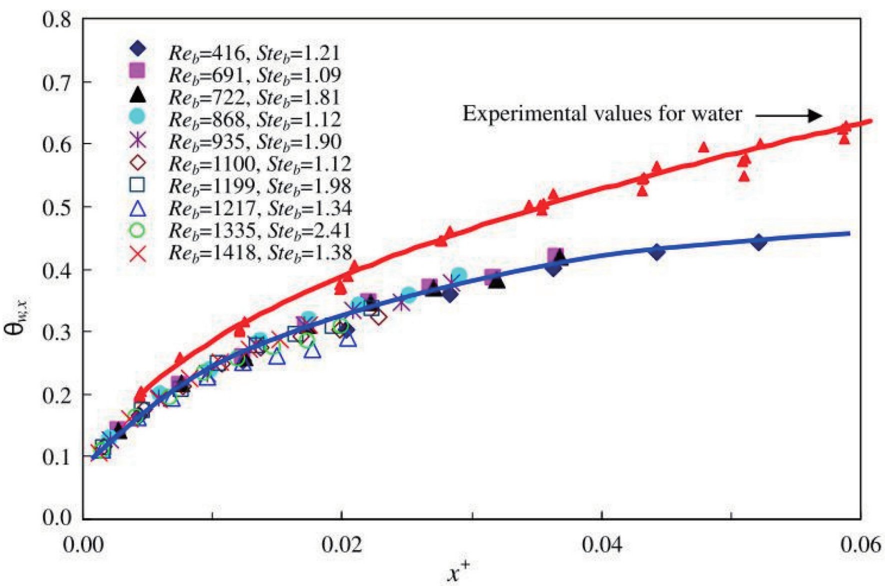


Figure 4 Dimensionless wall temperature versus dimensionless axial distance for the MPCM slurry with mass concentration of 15.8 wt% [40].

Delgado et al. [42, 43] studied the paraffin/water MPCM slurry in a circular tube with a diameter of 10

mm and a length of 1.82 mm. The heat transfer performance of the slurry was investigated with varying the mass fraction of paraffin from 14 wt% to 30 wt%. Generally, the average heat transfer coefficient of the MPCM slurry was higher than that of water, and particularly, the best heat transfer performance appeared at the mass fraction of 20 wt% because of the larger heat capacity than that of 10 wt% and lower viscosity than that of 30 wt%. And the ratio of transported heat to pumping power of the MPCM slurry was found higher than that of water. They also found that the average heat transfer coefficient of the MPCM slurry was higher when the operating condition was adjusted to make the phase change process occur in the heat transfer section. Huang et al. [44] prepared a novel magnetic n-octadecane/water MPCM slurry by dispersing the iron nanoparticles in the MPCM and investigated the heat transfer characteristics in a circular tube where the external magnetic field was imposed at different locations. The magnetic field caused the MPCM particles to move toward the tube wall, bringing a sudden reduction in the wall temperature. Besides, the local heat transfer coefficient was increased on the account of increasing magnetic field intensity. The effect of magnetic field on the heat transfer was much more apparent at lower mass flow rates and volume fractions.

Sabbah et al. [45] studied the heat transfer performance of the MPCM slurry flowing through a circular tube with an inner diameter of 4.3 mm and a length of 1016 mm. They found that the dimensionless wall temperature of the tube was reduced by about 40% when using the MPCM slurry instead of water. The local heat transfer coefficient of the MPCM slurry was higher than that of water at the same flow rate and increased with the increase of the mass concentration. The enhancement of average heat transfer coefficient was more apparent when the inlet temperature was close to the phase change temperature. Wang and Lin [46] worked on the n-octadecane/water MPCM slurry in a rectangular tube. The heat transfer performance of the MPCM slurry was better than that of water at larger dimensionless axial distances. They found that the wall temperature was reduced when using the small aspect ratio rectangular tube instead of the circular tube because of the smaller hydraulic diameter. Song et al. [47] proposed a novel eicosane based MPCM slurry using liquid metal (gallium) as the carrying fluid and investigated the heat transfer characteristics in a circular tube at constant heat flux. It was indicated that the MPCM slurry showed the Newtonian behavior. The pressure drop increased with the increase of solid volume fraction of the MPCM and it was higher than that of pure liquid gallium at the same velocity. In comparison with liquid gallium, the MPCM slurry resulted in reduced wall temperature and higher heat transfer coefficient at the same Reynolds number. Furthermore, the local heat transfer coefficient increased with the increase of solid volume fraction of the MPCM slurry and Reynolds number as shown in Figure 5. Liu et al. [48] prepared a paraffin based MPCM slurry using the water/alcohol as the carrying fluid and investigated the heat transfer performance of the MPCM slurry flowing through a circular tube immersed in a water bath with constant temperature. The results showed that the heat transfer coefficient and Nusselt number of the MPCM slurry were higher than those of the carrying fluid at the same Reynolds number, and enhanced with the increase of mass concentration of the MPCM.

2.2.2 Experiments in turbulent regime

Yamagishi et al. [34] also investigated the convective heat transfer of the MPCM slurry in turbulent flow. The measured bulk temperature of the MPCM slurry was close to the estimated value by the three-region model proposed by Choi et al. [49]. The local heat transfer coefficient of the MPCM slurry firstly increased when the PCM began to be melted and then decreased with the increase of melted PCM, so there was a maximum value for the local heat transfer coefficient and it was affected by the solid volume fraction of the MPCM, the Reynolds number and the heating rate. The heat transfer coefficient of the MPCM slurry was higher than that of slurry without phase change under the same condition due to the latent heat, but worse than that of water at the same velocity because of the large viscosity. Inaba et al. [35] extended their experiments to the turbulent flows to analyze the MPCM slurry containing plural types of MPCM particles. They found that the generation of turbulence in the MPCM slurry was suppressed by the MPCM particles in turbulent flow. The friction factor reduction ratio was more significant than the heat transfer enhancement ratio, demonstrating that the MPCM slurry was more suitable if employed as the heat

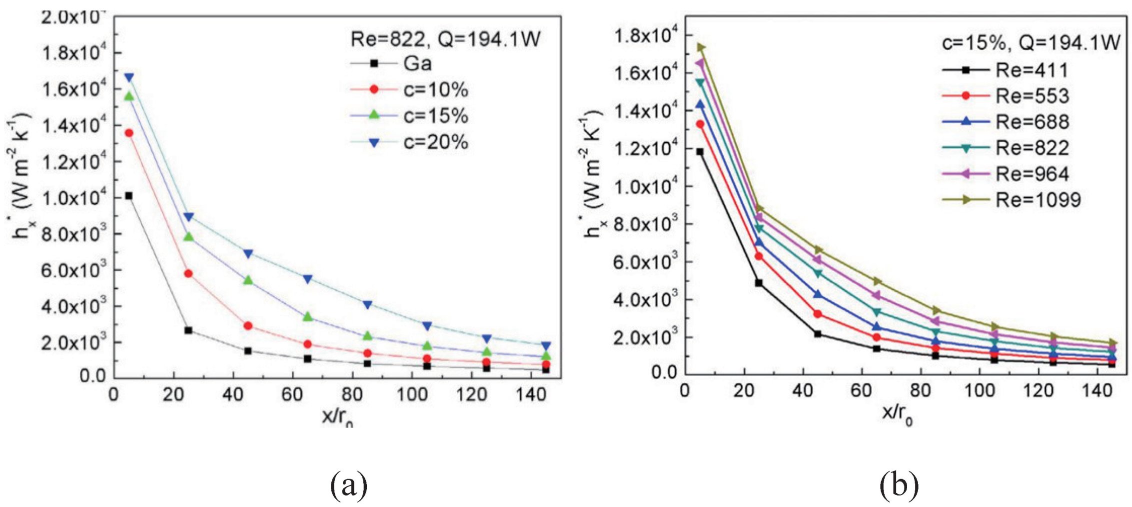


Figure 5 The local heat transfer coefficient of the MPCM slurry versus flow distance [47]. (a) At different solid volume fractions; (b) at different Reynolds numbers.

transport medium. Wang et al. [38, 39] conducted the experiments of the MPCM slurry under the low turbulent condition in a circular tube. They showed that the peak value of the local heat transfer coefficient appeared earlier at high heat flux. The Nusselt number of the MPCM slurry was higher than that of the single-phase fluid estimated by the empirical correlation. Alvarado et al. [50] conducted a comparative study to verify the effect of the MPCM slurry in various tubes, namely, regular tube (no extended fins) and enhanced surface tube (extended micro-fins). The heat transfer coefficients of the MPCM slurry in both tubes were lower than that of water at the same velocity due to the suppression effect of particles on turbulence, as shown in Figure 6. Meanwhile, the enhanced surface tube showed better heat transfer performance than a regular tube because of the helical micro-fins. Particularly, the effect of the enhanced surface tube was more significant at lower mass fractions. It further suggests that design guidelines of practical systems should consider the impact of the inner surface of flow channels as well as the role of the MPCM slurries.

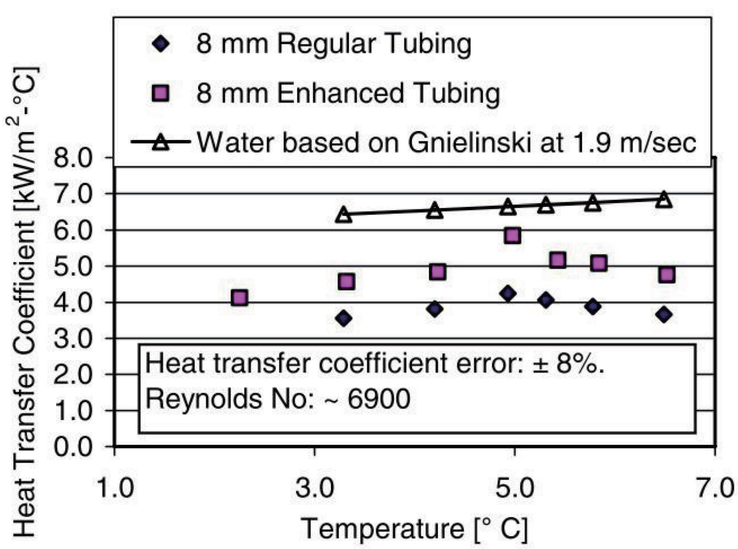
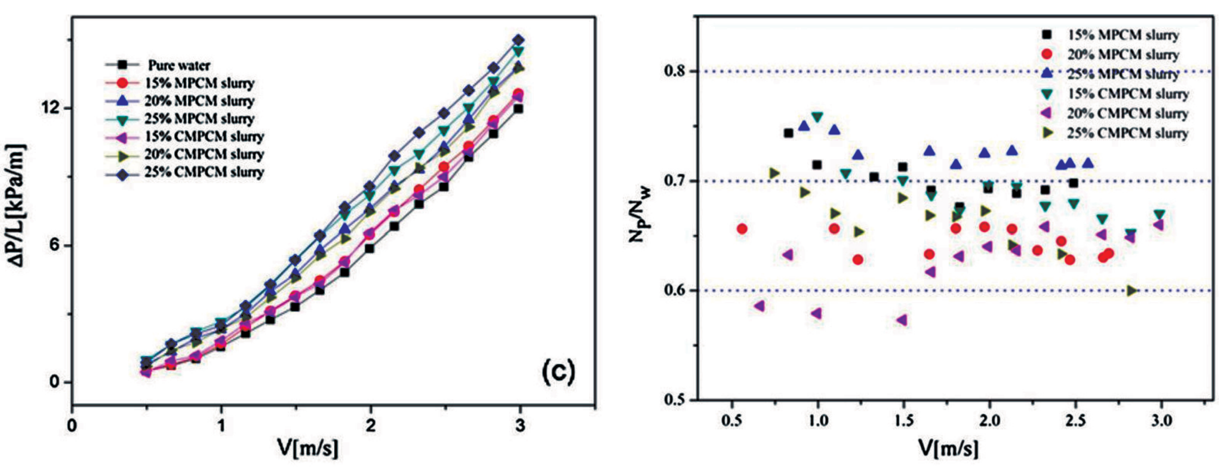


Figure 6 Heat transfer coefficient of the MPCM slurry with mass concentration of 7.0 wt% in different tubes [50].

Tumuluri et al. [51] studied the heat transfer characteristics of the multi-walled carbon nanotubes (MWCNT) nanofluid, octadecane/water MPCM slurry and MWCNT-MPCM blend in a circular tube. The results showed that the pressure drop of the MWCNT nanofluid was higher than that of water due to the

higher viscosity, and the pressure drop of the MPCM slurry was lower than that of water because of the drag reduction effect; whereas the MWCNT-MPCM blend was still in laminar flow at the same flow condition. The local heat transfer coefficient of the MPCM slurry increased during the melting process due to the increase of the effective specific heat capacity, and the heat transfer performance was more significantly affected by the flow rate than by the heat flux. They found that the heat transfer coefficient gradually decreased in the order of the MWCNT-MPCM blend, MPCM slurry, and MWCNT nanofluid at the same Reynolds number, and decreased in the order of MWCNT nanofluid, MPCM slurry, and MWCNT-MPCM blend at the same flow velocity. Taherian et al. [52] tested various PCM types and the durability of the MPCM slurry in a circular tube with an inner diameter of 11 mm and a length of 10.5 m. Even after thousands of cycles, the MPCM slurry was still durable. Moreover, they found that the heat flux and various PCM types (PCMs with similar mass fraction and latent heat) had few effects on the heat transfer performance of the MPCM slurry. The heat transfer coefficient decreased with the increase of mass fraction of the MPCM and increased with the increase of the flow rate.

Kong et al. [53] investigated the hydraulic and heat transfer performance of the butyl stearate/water MPCM slurry in the helical-coiled tube at constant heat flux. It was depicted that large viscosity of the MPCM slurry was the main reason for poor heat transfer performance compared with that of water at the same velocity. While, the increment in Nusselt number, especially during the melting process of the PCM, was beneficial to ensuring the better thermal performance. Further, the Nusselt number of the MPCM slurry increased with the increase of the mass fraction at the same Dean number. Also, there was an apparent secondary flow in terms of the variations of heat transfer coefficients at the outside and inside of the coiled tube. Therefore, the heat transfer of the coiled tube was improved due to the enhanced mixing effect of the fluid along the radial direction caused by the secondary flow compared with that of the straight tube. Li et al. [54] prepared a novel paraffin/graphene/water composite MPCM slurry. The graphene was added into the shell of the MPCM as a thermal conductivity enhancer. They tested that slurry in a circular tube with an inner diameter of 8.0 mm and a length of 1.2 m. The results showed that the pressure drop of the composite MPCM slurry was higher than that of the MPCM slurry without graphene at the same velocity and the pressure drops of both of them were higher than that of water, as shown in Figure 7(a). The fabricated slurries could reduce the pumping power consumption compared with water, as displayed in Figure 7(b), and the composite MPCM slurry with mass fraction of 20 wt% was recommended.



(a) (b)

Figure 7 (a) Pressure drop versus velocity for slurries at 88°C; (b) pumping consumption ratios of slurries to water [54].

2.2.3 Numerical investigations of flow and heat transfer characteristics in laminar regime

Due to the limit of experiments, it is hard to obtain more information, such as the temperature and solid volume fraction distributions about the PCS. And this problem can be overcome through the numerical simulation, which could provide more comprehensive understanding about the flow and heat transfer of the

PCS. Charunyakorn et al. [55] proposed a numerical model considering laminar flow of the MPCM slurry in a circular tube at constant heat flux. In the energy equation, the heat generation (or absorption) during the phase change process of the PCM was supposed to be a heat source. The reduction in Stefan number and increment in solid volume fraction of the MPCM slurry simultaneously enhanced the Nusselt number, depicting better heat transfer and effectively sustaining the fluid temperature. Zhang and Faghri [56] used the temperature transforming model, in which the phase change process occurred in a temperature range, instead of the quasisteady model [55]. The results showed that numerical results agreed well with the experimental results [33] with the consideration of microcapsule' crust and sub-cooling of the inlet temperature compared with the phase change temperature. Also, the heat transfer enhancement of the MPCM slurry was found to be reduced when the phase change temperature range was enlarged. Alisetti and Roy [57] adopted different effective specific heat functions, such as sine curve, left and right triangle functions, in the numerical model built for the PCS flowing through a circular tube at constant wall temperature. These functions had slight effect on the mean Nusselt number of the PCS in the same phase change temperature range. The supercooling degree of the inlet temperature greatly influenced the heat transfer of the PCS, and consequently, the mean Nusselt number increased with the decrease of the supercooling degree. Roy and Avanic [58] carried out the laminar flow heat transfer of the PCS in a circular tube. The effective specific heat model, in which the latent heat was considered as the temperature-dependent effective specific heat of the PCM, was adopted in the energy equation. They found that the most important parameter affecting the heat transfer of the PCS was the Stefan number. The dimensionless wall temperature of the tube decreased with the decrease of the Stefan number. Hu and Zhang [59] and Zhang et al. [60] adopted different functions, such as sine curve and rectangular, to describe the variation of effective specific heat of the PCM during the phase change process. The results showed that the Nusselt number was significantly affected by the specific heat functions. And increasing the solid volume fraction of the MPCM or decreasing the Stefan number could improve the heat transfer performance of the MPCM slurry. The heat transfer enhancement of the MPCM slurry decreased with the increase of the supercooling degree of inlet temperature and the phase change temperature range. The MPCM slurry with larger particles showed better heat transfer performance. They found that the heat transfer enhancement of the MPCM slurry was more significant in the thermal fully developed region than that in the thermal developing region. Bai and Lu [61, 62] proposed a numerical model, which not only considered the heat transfer between the MPCM slurry and the tube wall but also the heat transfer between the carrying fluid and the MPCM particles. The model was solved by the finite difference method and the dual reciprocity boundary element method. Increasing the particle size, volume fraction of the MPCM and Reynolds number or decreasing the Stefan number could further reduce the wall temperature.

Ho et al. [63] and Ho [64] used a mixture continuum model to investigate the heat transfer of the PCS in a circular tube under constant heat flux, and different parameters were conducted in the simulation. The PCS greatly contributed to suppressing the dimensionless wall temperature. Besides, the axial conduction along the tube cannot be simply neglected, especially at a high ratio of the wall thickness to the inner diameter, or a high ratio of wall-to-fluid thermal conductivity. The axial conduction effect was more apparent at low Peclet number. Wang and Zhang [65] investigated the laminar flow heat transfer of the MPCM slurry in a circular tube with the external convection boundary condition. The dimensionless wall temperature increased with the increases of the Biot number and the Stefan number, and decreased with the increase of the solid volume fraction of the MPCM. Zhao et al. [66] studied the heat transfer performance of the MPCM slurry in a circular tube at constant wall temperature. Different parameters were investigated and they found that the Stefan number, solid volume fraction and the particle-to-tube radius showed more significant effect on the heat transfer enhancement than the initial subcooling degree, phase change temperature range and the Reynolds number. The enhancement of the heat transfer increased when increasing the solid volume fraction and particle-to-tube radius or decreasing the Stefan number. They concluded that the effect of the particle size on the improvement of heat transfer was mainly caused by the micro-convection of the particles. Ravi et al. [67] investigated the heat transfer of the MPCM

slurry in laminar flow in an internally finned tube under constant heat flux and constant wall temperature. The results showed that the Stefan number, fin height and thermal conductivity of the fin played important roles in the heat transfer performance of the MPCM slurry. The Nusselt number of the MPCM slurry increased when increasing the height ratio (ratio of fin height to the tube radius) and the fin thermal conductivity. Zeng et al. [68] adopted the enthalpy model to investigate the laminar flow heat transfer characteristics of the MPCM slurry in the thermal fully developed region in a circular tube at constant heat flux. They divided the variation of the Nusselt number with the dimensionless axial distance into four stages, as shown in Figure 8: (1) The local Nusselt number increased with the melting of the PCM. The wall temperature achieved the phase change temperature and the bulk temperature was still below the phase change temperature, so the temperature difference between the wall and the slurry gradually decreased. (2) The local Nusselt number decreased with the melting of the PCM. The bulk temperature of the slurry achieved the phase change temperature and increased slowly, so the temperature difference between the wall and the slurry increased gradually. (3) The local Nusselt number increased along the dimensionless axial distance. The bulk temperature of the MPCM slurry was above the phase change

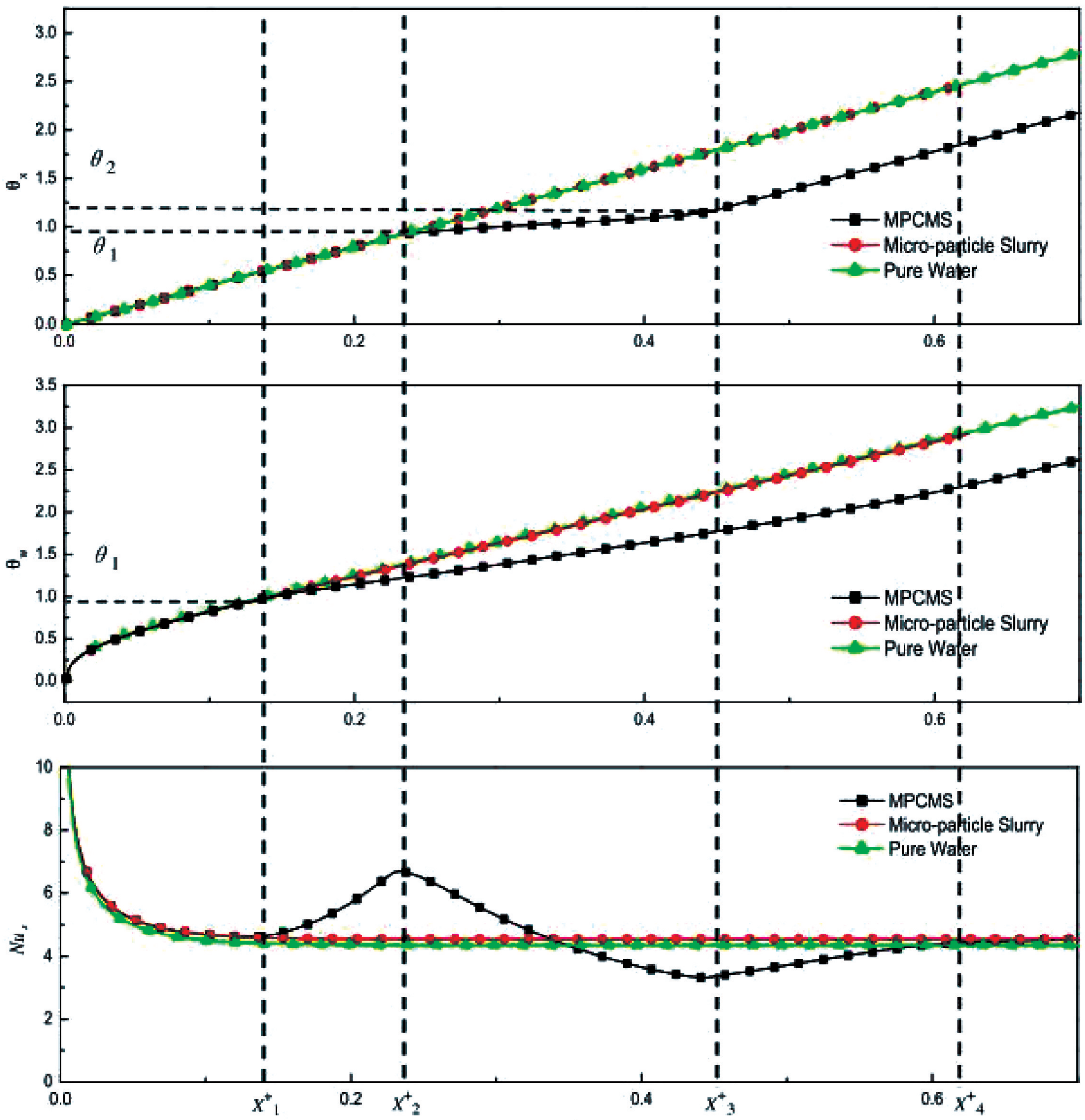


Figure 8 The dimensionless bulk temperature θ_x, dimensionless wall temperature θ_w and local Nusselt number Nu_x of the MPCM slurry along the dimensionless axial distance [68].

temperature and increased quickly. The temperature difference between the wall and the slurry decreased in this stage. (4) The local Nusselt number no longer changed when the central temperature of the MPCM slurry was above the phase change temperature. The results showed that the dimensionless wall temperature was reduced due to the latent heat of the PCM. They found that the variation of local Nusselt number was significantly affected by the Stefan number and the dimensionless phase change temperature range. The dimensionless wall temperature decreased with the increase of the solid volume fraction, particle size and Reynolds number.

Kousksou et al. [69] investigated the heat transfer of the MPCM slurry during a cooling process taking into account the effect of stochastic crystallization on the supercooling breakdown. However, the probability of crystallization needed further investigation. The results showed that the wall temperature of the tube increased with the increase of the solid volume fraction of the MPCM or with the decrease of the Stefan number. The particle size also had slight effect on the wall temperature due to its effect on the effective thermal conductivity of the MPCM slurry. Sabbah et al. [70] investigated the laminar flow heat transfer of the MPCM slurry in the circular tube at constant heat flux. The results showed that the development of the thermal boundary layer of the MPCM slurry was impeded due to the phase change of the PCM and the thickness of the thermal boundary layer was related to the location of the melting interface. They found that the heat transfer coefficient of the MPCM slurry gradually decreased when the melting interface moved from the wall bank to the center of the tube. While, the heat transfer coefficient of the MPCM slurry increased with the increase of the slope of Peclet number. Chen et al. [71] conducted the numerical investigation of the laminar flow heat transfer of the MPCM slurry in a circular tube at constant heat flux. The results showed that the wall temperature was constant during the phase change process. It was indicated that the Stefan number and mass fraction showed more significant effects on the heat transfer of the MPCM slurry than the phase change temperature range and Reynolds number. The heat transfer coefficient of the MPCM slurry increased with the decrease of the phase change temperature range. Scott et al. [72] proposed a homogenous model to investigate the laminar flow heat transfer characteristics of the MPCM slurry flowing upward in a vertical tube at constant heat flux. They defined the bulk temperature of the MPCM slurry based on the bulk specific enthalpy to avoid the effect of sharp variation of effective specific heat with temperature during the phase change process. The numerical results agreed well with the experimental results based on the wall temperature. They found that the wall temperature of the tube using the MPCM slurry was close to or even higher than that of water at certain heating powers. Kurnia et al. [73] investigated the flow and heat transfer of the MPCM slurry in coiled square tube with different configurations such as conical spiral, in-plane spiral and helical spiral under constant wall temperature. The results showed that the heat transfer rate was enhanced with the increase of the volume fraction of the MPCM. The secondary flow of the MPCM slurry was also changed due to the variation of solid volume fraction. They found that the in-plane spiral tube showed the best heat transfer performance among the different configurations. But the overall performance of the MPCM slurry was worse than that of water when taking into account the pumping power consumption. Lenert et al. [74] studied the laminar flow heat transfer of the MPCM slurry through a parallel plate channel, where particles concentrate near the bottom wall that was at constant heat flux, while the top wall was adiabatic. The homogeneous flow was first calculated to validate the model and the variation of the local Nusselt number was found similar to that reported by Zeng et al. [68]. Then the MPCM particles concentrating near the heated wall at different heights were studied. The results showed that the Nusselt number increased with the enhancement of the mass fraction and latent heat of the MPCM. In addition, decreasing the phase change temperature range, channel height and heat flux also had positive effect on the enhancement of the heat transfer performance of the MPCM slurry. They found that the MPCM slurry showed better heat transfer performance when the MPCM particles concentrated within 30% of the channel height.

Song et al. [75] investigated the heat transfer of the MPCM slurry using the liquid metal as the carrying fluid in a circular tube at constant heat flux. The heat transfer performance of the MPCM slurry was

reported to be enhanced upon increasing the Reynolds number and mass fraction or decreasing the Stefan number, phase change temperature range and initial supercooling degree. The Stefan number and the mass fraction were the most influential parameters. In addition, the MPCM slurry using the liquid metal as the carrying fluid provided better performance than that of water as the carrying fluid. Song et al. [76] also conducted the investigation of 1-bromo-hexdecane/water MPCM slurry in a circular tube with twisted tape inserts to study the laminar flow heat transfer characteristics. And the heat transfer performance of the MPCM slurry in the tube with twisted tape inserts was better than that of the MPCM slurry in a smooth tube or that of water in a tube with twisted tape inserts. Besides, the friction factor increased when increasing the Reynolds number or decreasing the twisted ratio. The Nusselt number of the MPCM slurry increased with the decrease of the Stefan number and twisted ratio. The performance ratio which indicated the ratio of the Nusselt number enhancement to friction factor enhancement was significantly dependent on the Reynolds number. Seyf et al. [77] investigated the laminar flow heat transfer of the NPCM slurry flowing through an isothermal unconfined square cylinder in a parallel plate channel under the adiabatic condition. By increasing the Reynolds number and solid volume fraction, the heat transfer coefficient and shear stress over the cylinder block were also increased. While, decreasing the phase change temperature range could enhance the heat transfer of the NPCM slurry as shown in Figure 9. However, the effect of the phase change temperature range was less than that of the volume fraction and Reynolds number.

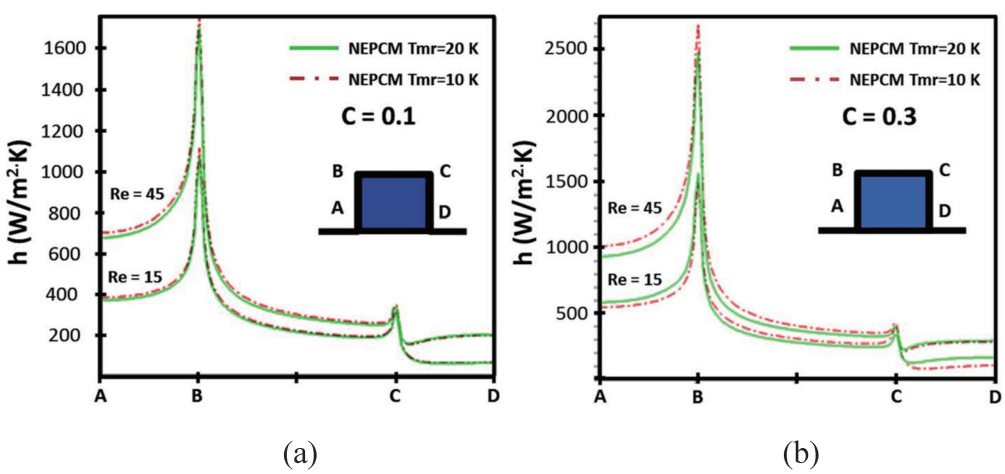


Figure 9 Local heat transfer coefficient for different melting ranges at the solid volume fraction of 10% (a) and 30% (b) [77].

Lu et al. [78] applied a 2D numerical model on the NPCM slurry flowing through a backward-facing step. The top wall and upstream bottom wall were adiabatic and the downstream bottom wall was at constant heat flux. The heat transfer coefficient of the NPCM slurry has been shown to be significantly higher than that of water, and correspondingly, the pressure drop was also increased. Moreover, the increments in solid volume fraction and Reynolds number improved the heat transfer performance of the NPCM slurry. The heat transfer coefficient of the NPCM slurry first increased with the increase of the heat flux and then changed slightly with the heat flux when the heat flux achieved a certain value. Khakpour and Seyed-Yagoobi [79] implemented the volume-of-fluid (VOF) model on the evaporation of the liquid film containing MPCM slurry flowing through a heated plate. The variation of solid volume fraction caused by the evaporation of liquid film was taken into account. Using the MPCM slurry instead of water could effectively suppress the decline of film thickness due to the enhanced Peclet number. The heat transfer coefficient of the MPCM slurry was higher than that of water, and it increased with the increases of solid volume fraction and mass flow rate. It was indicated that the MPCM slurry showed large potential to delay the dry-out of liquid film. Rhafiki et al. [80] used the heat source model to describe the phase change of the MPCM slurry in a circular tube under constant heat flux. The water and NH_4Cl-H_2O aqueous solution were adopted as the PCMs in the numerical simulation, respectively. The wall

temperature of the tube has been effectively regulated by means of MPCM slurry. Furthermore, the wall temperature was affected by the heat flux, Stefan number, solid volume fraction, Reynolds number and particle diameter. They found that the binary mixture (ice-water-NH_4Cl) showed better heat transfer performance than water as the PCM. And the heat transfer coefficient of the binary mixture based MPCM slurry was related to the initial mass fraction of the binary mixture. Liu et al. [81] investigated the MPCM slurry in a rectangular tube at constant heat flux. The results showed that the Stefan number and the mass fraction were the most important parameters affecting the heat transfer performance of the MPCM slurry. Decreasing the thickness of the shell of the MPCM particle could also boost up the heat transfer performance of the MPCM slurry. In addition, the heat transfer of the MPCM slurry was improved when increasing the aspect ratio of the rectangular tube.

2.2.4 Numerical investigations of flow and heat transfer characteristics in turbulent regime

Roy and Avanic [82] used the effective specific heat capacity model to investigate the heat transfer characteristics of the PCS in a circular tube at constant heat flux. The numerical model was validated through the experiments. The results showed that the wall temperature of the tube decreased when using the PCS compared with the pure carrying fluid. The reduction of the wall temperature increased upon decreasing the Stefan number, phase change temperature range and the supercooling degree. Ma et al. [83] adopted the Eulerian-Eulerian model and the kinetic theory of granular flow to investigate the MPCM slurry in a circular tube at constant heat flux. Owing to the increase of frictional loss, the pressure drop of the MPCM slurry increased with the decrease of the particle diameter at the same velocity and solid volume fraction. Also, the heat transfer coefficient of the MPCM slurry increased when decreasing the particle diameter. Particularly, the particle diameter in the range of 10—100 μm was recommended because of the relatively good heat transfer performance and relatively small increase of the pressure drop. There was an apparent temperature difference between the MPCM particle and the carrying fluid at larger particle diameters caused by the weakened heat transfer between the solid phase and liquid phase. In addition, a ratio of the transported heat to the pumping power consumption was established as the performance index to evaluate the energy transport characteristics of the MPCM slurry. The results showed that the performance index increased with the increase of the heat flux and decreased with the increase of the Reynolds number, as shown in Figure 10. The energy transport performance of the MPCM slurry was better than that of water at small heat flux and high Reynolds number. Languri et al. [84] studied the flow and heat transfer characteristics of the MPCM slurry in a helically coiled tube at constant heat flux. The Nusselt number of the MPCM slurry was reported to be decreased with the increase of the mass

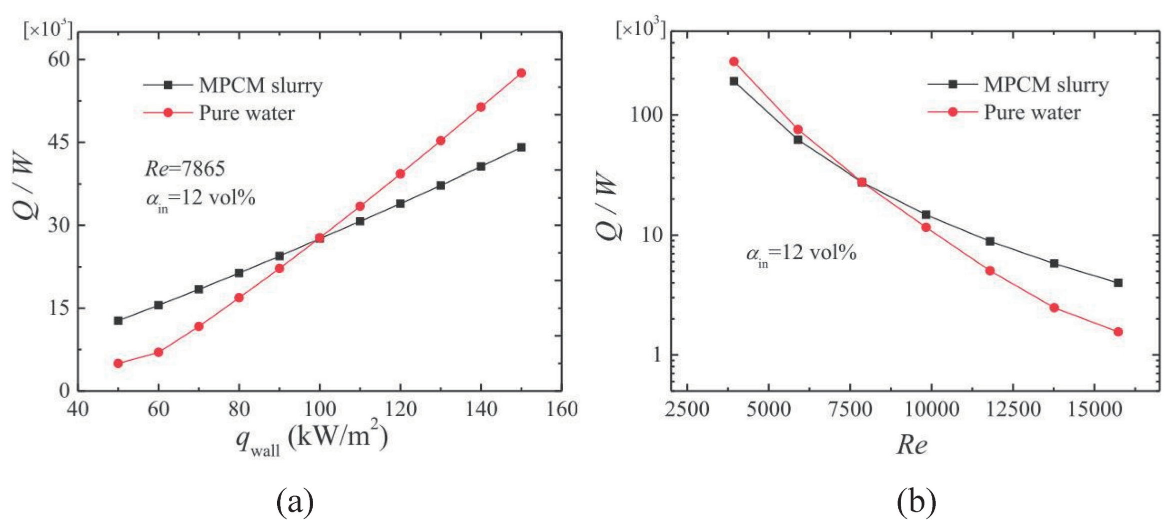


Figure 10 Ratio of the transported heat to the pumping power consumption [83]. (a) At different heat fluxes at Re=7865; (b) at different Reynolds numbers at heat flux of 100 kW/m^2.

fraction due to the increased viscosity. The outer Nusselt number was higher than the inner Nusselt number, especially at lower mass fractions, which was attributed to the effect of the curvature of the helically coiled tube.

2.2.5 Flow and heat transfer characteristics in microchannel

Hao and Tao [85] proposed a two-phase model which took into account the interaction between two phases to investigate the laminar flow heat transfer of the PCS in a microchannel under the conditions of constant heat flux and constant wall temperature. There was an apparent temperature difference between the particles and the carrying fluid during the phase change process, and the heat transfer performance of the PCS was significantly enhanced during this process. The heat transfer coefficient increased along the flow direction to a peak value and then decreased along the microchannel. Xing et al. [86] also used a two-phase non-thermal equilibrium model to study the heat transfer performance of the PCS in a microchannel at constant heat flux. In this study, two kinds of ratios were introduced: the ratio of heat transfer rate of the PCS to that of the single-phase fluid as the effectiveness factor to evaluate the heat transfer enhancement, and the ratio of heat transfer rate to the pumping power between the PCS and the single-phase fluid as the performance index. The results showed that there was an optimum heat flux to achieve the maximum effectiveness factor and performance index at the same Reynolds number and solid volume fraction. The effectiveness factor and performance index decreased with the increase of the Reynolds number in the range of 100—600, therefore the low Reynolds number was recommended to obtain better heat transfer enhancement under the laminar condition. Tao et al. [87] used the similar model to investigate the heat transfer performance of the PCS with high solid volume fraction in the microchannel at low Reynolds numbers (<50). They also found that there was an optimum heat flux to obtain the best effectiveness factor and performance index. However, there was a peak value for the effectiveness factor when changing the Reynolds number, which indicated that the Reynolds number also needed to be optimized. In addition, the decrease of the particle diameter leads to the enhancement of heat transfer of the PCS. Kuravi et al. [88, 89] numerically and experimentally investigated the heat transfer performance of the MPCM and NPCM slurries in a manifold microchannel at constant heat flux. The experimental results showed that the heat transfer performance of the MPCM slurry was worse than that of water at the same mass flow rate due to the large particle diameter and low thermal conductivity of the MPCM slurry. They adopted the NPCM slurry in the numerical model and found thermal conductivity playing an important role in the heat transfer of the PCS. In the microchannel with a larger hydraulic diameter, the heat transfer performance of the water-based NPCM slurry was worse than that of water, whereas the performance of the polyalphaolefin (PAO)-based NPCM slurry was better than that of PAO. Besides, the heat transfer coefficient of the water-based NPCM slurry was always higher than that of water at different mass concentrations in the microchannel with a smaller hydraulic diameter. The heat transfer coefficient of the NPCM slurry increased with the increase of the mass fraction.

Alquaity et al. [90, 91] adopted the discrete phase model (DPM) and homogeneous model to investigate the flow and heat transfer of the NPCM slurry. They found that the pressure drop of the NPCM slurry was close to the pure single-phase fluid when using the DPM, which indicated that the DPM failed to predict the flow behavior of the NPCM slurry. Then the homogeneous model was used to study the NPCM slurry flowing through a microchannel at constant heat flux on the bottom wall. The results showed that there was an optimum heat flux to mass flow rate ratio to achieve the maximum effectiveness ratio, performance index and the Merit number. These three parameters increased with the increase of the solid volume fraction of the NPCM. Kondle et al. [92] numerically investigated the heat transfer of the PCS in the microchannel under three different boundary conditions: constant heat flux with constant peripheral temperature (H1), constant heat flux with variable peripheral temperature (H2) and constant wall temperature (T). It was indicated that the heat transfer performance of the PCS under H1 condition was better than that under H2 and T conditions due to the effect of wall temperature on the temperature gradient of the PCS. The Nusselt number of the PCS was higher than that of the single-phase fluid and the variation during the phase change process was similar for the H1 and H2 conditions. The Nusselt number

first increased at the beginning of the melting process and then decreased at the end of the melting process. They also numerically investigated the flow and heat transfer of the PCS flowing through a microchannel with staggered circular pins and square pins [93]. The results showed that the pressure drop of the HTF in a microchannel with circular pins was lower than that with square pins, and the Nusselt number of the HTF was larger when using circular pins. The Nusselt number was enhanced using the PCS instead of the single-phase fluid and the enhancement was more apparent under the constant heat flux condition than that under the constant wall temperature condition. Petrovic et al. [94] numerically compared the flow and heat transfer performances of water, NPCM slurry and Cu-water nanofluid in laminar flow in a circular tube at constant heat flux. The results showed that the NPCM slurry with low phase change temperature had better heat transfer performance than that with high phase change temperature. The heat transfer coefficient of the NPCM slurry with low phase change temperature was higher than that of water when the solid volume fraction of the slurry was higher (3 vol%), and it was similar to that of water when the solid volume fraction of the slurry was lower (1 vol%). The nanofluid showed better heat transfer performance than the NPCM slurry and water at the same Reynolds number or pumping power due to the enhanced thermal conductivity. Wang et al. [95] experimentally investigated the laminar flow heat transfer characteristics of the MPCM slurry at different solid volume fractions (≤2%) in a microchannel of 0.35 mm×0.35 mm×0.44 mm (width×depth×length) at constant heat flux on the bottom. The pressure drop of the MPCM slurry was concluded to be higher than that of water at the same Reynolds number and increased with the increase of the solid volume fraction, as well as decreased with the increase of the temperature. Further, the Nusselt number of the MPCM slurry was also higher than that of water due to the micro-convection of the particle and the effect of particle motion on the thermal boundary layer. It was indicated that high heat flux was needed for the MPCM slurry with high solid volume fraction to ensure the melting of the PCM for better heat transfer performance. Roberts et al. [96] experimentally investigated the flow and heat transfer performance of the MPCM slurry with and without shell in a circular microchannel at constant heat flux. It was found that the heat transfer coefficient of the MPCM slurry was higher than that of water at the same Reynolds number and increased when increasing the mass fraction and flow rate. Because the thermal conductivity was improved by the metal shell, the MPCM slurry showed better heat transfer performance than the non-coated PCM slurry, as shown in Figure 11.

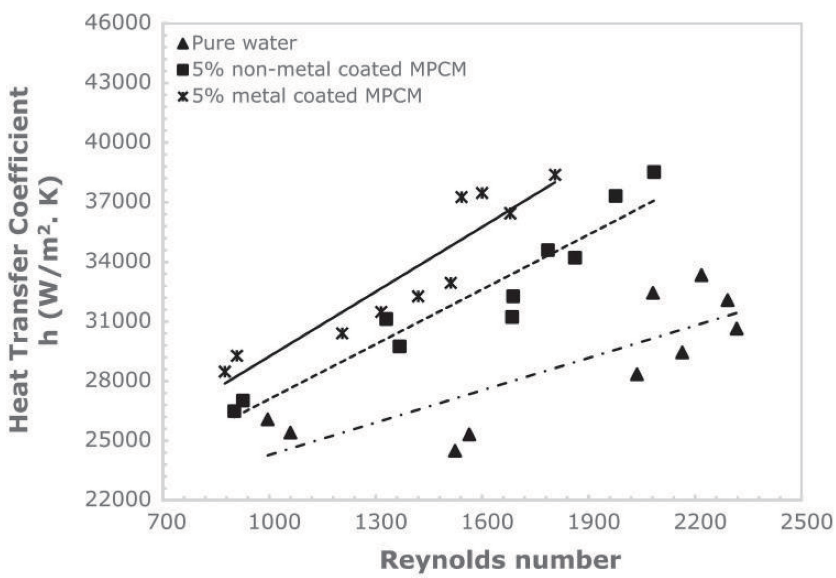


Figure 11 Heat transfer coefficient versus Reynolds number for water, non-metal coated and metal coated MPCM slurries [96].

2.2.6 Natural convection heat transfer characteristics

Inaba et al. [97, 98] used a 2D single-phase fluid model to investigate the heat storage and natural

convection heat transfer characteristics of the MPCM slurry in a horizontally rectangular enclosure heated from the bottom and cooled at the top under constant temperature. The results showed that the heat storage time of the MPCM slurry increased due to the increase of the heat capacity. With involvement of the latent heat, the heat transfer coefficient of the MPCM slurry was higher than that of the slurry without phase change. Increasing the Rayleigh number had positive effect on the Nusselt number and there was a peak value of the local Nusselt number during the phase change process. The heat transfer coefficient of the MPCM slurry increased with the increase of the mass fraction at lower mass fractions and decreased with the increase of the mass fraction at higher mass fractions because of the increased viscosity. In addition, the onset point of the natural convection of the MPCM slurry shifted to earlier time when decreasing the mass fraction of the MPCM. Besides, increasing the height of the enclosure at a fixed width led to the increase of the heat storage time and the decrease of the heat transfer coefficient of the MPCM slurry. Diaconu et al. [99, 100] experimentally investigated the heat storage and heat transfer characteristics of the MPCM slurry in a cylindrical tank. A helically coiled tube containing water was immersed in the tank to heat the MPCM slurry. The results showed that the natural convection heat transfer coefficient of the MPCM slurry was 5 times that of the water at the same temperature in the phase change interval of 2—6℃. Zhang et al. [101, 102] experimentally studied the heat storage and natural convection heat transfer of the MPCM slurry in rectangular enclosure heated at bottom. Increasing the mass fraction of the MPCM and the height of the enclosure led to the increase of the heat storage time. The maximum local heat transfer coefficient occurred during the phase change process, and increasing the mass fraction enhanced the Nusselt number of the MPCM slurry at the same Rayleigh number. The heat transfer coefficient of the MPCM slurry increased with the increase of the temperature difference between the bottom and the top plates, and then decreased with the increase of the temperature difference, which was dependent on the phase change of the PCM.

Sabbah et al. [103] numerically investigated the natural convection heat transfer of the MPCM slurry in a rectangular cavity heated and cooled from the left and right sides at constant temperature. The results showed that the heat transfer coefficient of the MPCM slurry was significantly higher than that of water due to the higher volumetric thermal expansion of the MPCM particles changing from solid to liquid and the latent heat of the PCM. Increasing the mass fraction led to the increment of heat transfer coefficient of the MPCM slurry at lower fractions, but the heat transfer coefficient decreased with the increase of the mass fraction at higher fractions due to the sharply increased viscosity. Wang et al. [104] conducted the experiments of natural convection of the MPCM slurry, in which the hot water flowed through a circular tube horizontally immersed into the MPCM slurry. The results showed that the heat storage capacity increased and the temperature rise was effectively suppressed with the increase of the mass fraction of the MPCM. But the heat transfer coefficient of the MPCM slurry was lower than that of water and decreased with the increase of the mass fraction due to the large viscosity. They divided the natural convection process into three regimes: the pure conduction, quasi-steady and decay periods, as shown in Figure 12. The quasi-steady period was prolonged due to the effect of phase change when increasing the mass fraction of the MPCM. In addition, they found that the natural convection heat transfer performance of the MPCM slurry was improved when the temperature or flow rate of the HTF in the tube was increased.

2.2.7 Flow and heat transfer characteristics in heat exchanger and heat sink

The PCS are usually adopted in the heat exchanger and heat sink to improve the heat transfer performance utilizing the larger heat storage capacity compared with the conventional single-phase fluid. Hasan [105] numerically investigated the flow and heat transfer characteristics of the MPCM slurry as the coolant in a counter flow microchannel heat exchanger. The effectiveness of the heat exchanger was defined as the ratio of actual heat transfer to the maximum possible transfer heat, and the overall performance of the heat exchanger was the ratio of effectiveness to the pressure drop. The results showed that the effectiveness of the MPCM slurry was higher than that of pure fluid and increased with the increase of the solid volume fraction of the MPCM. However, the overall performance of the heat exchanger was lower than that of pure fluid and decreased with the increase of the solid volume fraction due to the significant

increase of the pressure drop. Lower velocity was demonstrated as the possible option to make full use of the latent heat of the PCM. Wu et al. [106] experimentally investigated the heat transfer performance of the polyalphaolefin (PAO) based nano-PCS in which the PCM particles were with or without shell in a microchannel heat exchanger. The results showed that the pressure drop of the nano-PCS with shell was lower than that of the nano-PCS without shell; however, the heat transfer coefficients of the two types of slurries were similar. Importantly, the heat transfer coefficient of the nano-PCS was higher than that of pure PAO at the same flow rate and increased with the increase of the mass fraction. The thermal performances of the two types of slurries changed little after thousands of thermal cycles, and it was indicated that the shell used to avoid the coalescence of particles was not necessary. Kong et al. [107] experimentally studied the flow and heat transfer characteristics of the MPCM slurry in a coil heat exchanger with double tubes. The water flowed through the outer tube and the MPCM slurry flowed through the inner tube with a corrugated surface to enhance the heat transfer performance. The results showed that the pressure drop, overall heat transfer coefficient and the effectiveness of the MPCM slurry were higher than those of water and increased with the increase of the mass fraction of the MPCM at the same flow rate, as shown in Figure 13(a). But the performance efficiency coefficient (PEC) of the MPCM slurry, which took into account the pressure drop, increased with the decrease of the mass fraction, as can be seen in Figure 13(b).

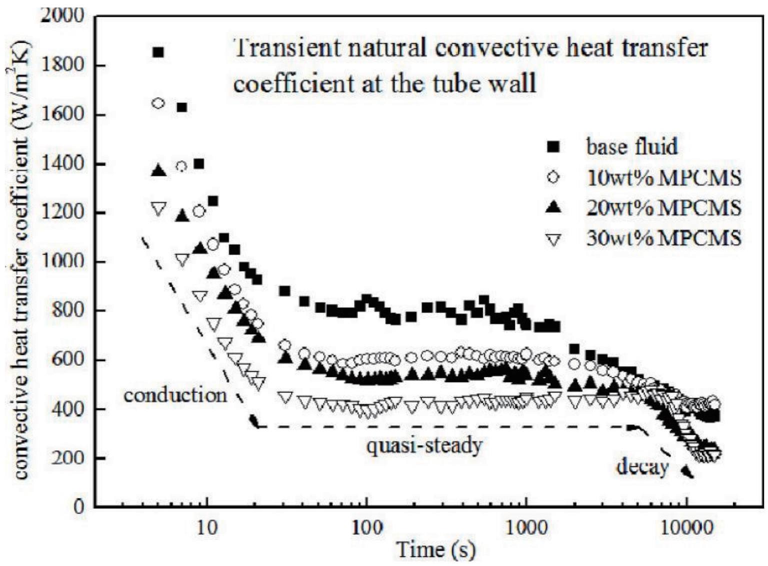


Figure 12 Effect of mass fraction on the natural convection heat transfer coefficient of the MPCM slurry at the external of the tube [104].

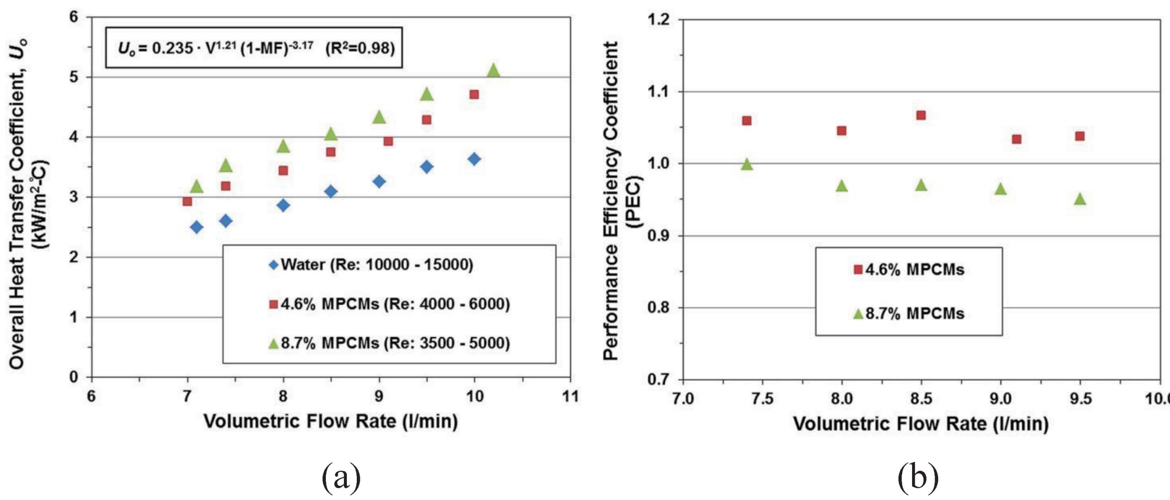


Figure 13 (a) Overall heat transfer coefficients for the MPCM slurries and water; (b) PECs for the MPCM slurries with different mass fractions [107].

Sabbah et al. [108] numerically investigated the hydraulic and heat transfer performance of the MPCM slurry in a rectangular microchannel heat sink under constant heat flux at the bottom wall. It was indicated

that the MPCM slurry with lower mass fractions showed better heat transfer performance than that of water, and the heat transfer enhancement increased when increasing the mass fraction. But the enhancement index, which represented the ratio of bottom wall temperature reduction factor to the pumping power increase factor, was higher at lower mass fractions of the MPCM because the viscosity of the slurry significantly increased with the mass fraction. Further, the wall temperature decreased when using the MPCM slurry instead of water, and also, the pumping power was reduced for the same heat sink temperature compared with that of water. Ho et al. [109—111] experimentally investigated the cooling performance of the MPCM slurry and nanofluid in a minichannel heat sink. The results showed that the MPCM slurry had better heat transfer performance and higher temperature control effectiveness than water, especially at low Reynolds numbers. Increasing the flow rate and the latent-sensible heat ratio (mass fraction to the Stefan number) led to the decrease of the heat transfer effectiveness of the MPCM slurry. It was indicated that the flow rate was the most important parameter affecting the heat transfer performance of the MPCM slurry and nanofluid. Adding the nanoparticles into the MPCM slurry could further enhance the heat transfer performance compared with water. Meanwhile, the friction factor was significantly increased due to the addition of MPCM particles and nanoparticles. Seyf et al. [112] numerically studied the hydraulic and heat transfer performance of the PAO based NPCM slurry in a microtube heat sink. The results indicated that the thermal performance of the NPCM slurry was better that that of pure PAO, which was further enhanced with the increase of the mass fraction, the Reynolds number and the melting temperature range of the PCM. In addition, the MPCM slurry could effectively reduce the maximum temperature difference of the wall and the entropy generation rate. Rajabifar [113] conducted the numerical simulations of the NPCM slurry and nanofluid, acting as the coolants and flowing through a double layer microchannel heat sink. With the NPCM slurry and the nanofluid, the cooling performance of the heat sink was enhanced compared with that of water, but the increase of the pumping power could not be avoided. They recommended the feasible operating conditions by optimizing the solid volume fractions of fluids during flow, such as 4 vol% of the nanofluid in the upper layer and 20 vol% of the NPCM slurry in the bottom layer. Rajabifar et al. [114, 115] numerically investigated the performance of the NPCM slurry flowing in a microchannel heat sink with pin fin at constant temperature on the bottom wall. The results showed that the Nusselt number of the NPCM slurry was higher than that of water and increased with the solid volume fraction. The variation of the tip clearance effectively made the NPCM slurry achieve a higher Nusselt number with a lower pumping power. Deng et al. [116] used the fin model and porous model to analyze the cooling performance of the MPCM slurry in a microchannel heat sink at constant heat flux on the bottom wall. They found that the overall Nusselt number was overestimated using the fin model due to the over-simplification, then the porous model was used to investigate the heat transfer performance of the MPCM slurry. The heat transfer coefficient of the MPCM slurry first increased when increasing the porosity of the heat sink and then decreased with the porosity, as shown in Figure 14. The Nusselt number decreased with the increase of the particle diameter, but the overall heat transfer coefficient increased with the increase of the particle diameter. The heat transfer enhancement was improved, and the temperature rise of the HTF decreased by increasing the solid volume fraction.

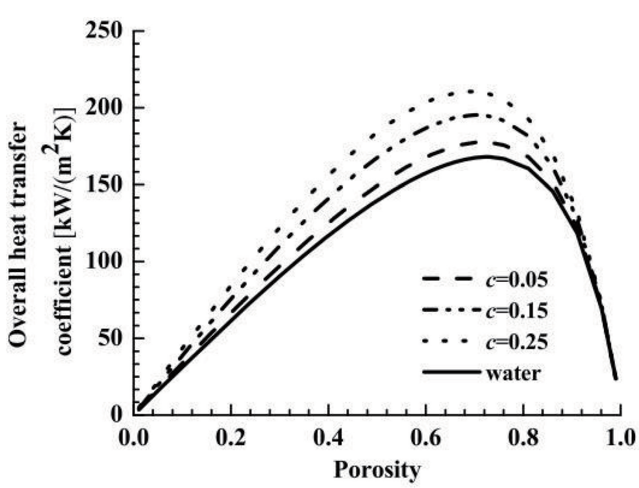


Figure 14 Overall heat transfer coefficient varies with porosity [116].

3 Shape stabilized PCM slurry (SSPCM slurry)

3.1 Preparation

Apart from the promising features of PCMs, the leakage threat on phase change completion is one of the engineering problems that should be controlled/minimized. Utilizing the porous scaffolds into which the PCM can be effectively adsorbed/absorbed is the most viable approach of recent and current era. These scaffolds are often termed as supporting materials, which can be classified into two types: polymeric, e.g., polymethyl methacrylate (PMMA), high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low density polyethylene (LLDPE); and inorganic, e.g., activated carbon, mesoporous calcium silicate and expanded graphite. Alkan and Sari [117] prepared the fatty acids based composite PCM using the PMMA as the supporting material, which retained the shape of the PCM in liquid phase. The micrographs of the prepared SSPCM are displayed in Figure 15, where a kind of well-coalesced structure with a unified appearance can be seen. Şentürk et al. [118] used different biodegradable polymers such as cellulose, agarose and chitosan as the supporting materials and polyethylene glycol (PEG) as the PCM to prepare the SSPCM through the solution casting method. The maximum mass ratio of the PCM to supporting material to prevent the leakage of the PCM was also quantified. Chen and Wolcott [119] adopted the HDPE, LDPE and LLDPE as the structural matrix to support the paraffin, separately, using a parallel co-rotating twin screw extruder. It was indicated that the HDPE based SSPCM had little leakage compared with the LDPE or LLDPE based SSPCMs. Other polymers, such as styrene maleic anhydrate copolymer [120] and polyaniline [121], could also be used as the supporting materials for the SSPCM. As for the inorganic scaffolds, Khadiran et al. [122] employed the activated carbon to prepare a shape stabilized nanocomposite PCM through the one-step impregnation method. The thermal conductivity of the composite increased and no significant leakage of the PCM was observed. Qian et al. [123] adopted the PEG as the PCM and mesoporous calcium silicate as the supporting material to prepare composite PCM through a direct impregnation process. Different measurements showed that the composite PCM had excellent chemical compatibility and reliability. Kim et al. [124] prepared the SSPCM by impregnating the octadecane into the expanded graphite by a kneader mixing method. In addition, there were some other inorganic materials, such as the porous building materials [125] and titanium dioxide [126], adopted as the supporting materials.

3.2 Flow and heat transfer characteristics of the SSPCM slurry

Royon et al. [127, 128] prepared the SSPCM using the water as the PCM and a tri-dimensional network of polymer as the supporting material. They dispersed the SSPCM particles in oil to form the SSPCM slurry, and experimentally and numerically investigated the heat transfer of the SSPCM slurry in an agitated tank with constant external temperature. The results showed that the SSPCM slurry had similar properties to that of ice slurry. The heat capacity increased due to the addition of the PCM. And a limited suprecooling phenomenon was observed with the decrease of the particle diameter. It was indicated that the simplified model was able to estimate the freezing time of the PCM during the crystallization process. There was an apparent plateau for the temperature variation of the SSPCM slurry due to the solidification of water. The duration of the plateau increased with the increase of the mass fraction. Ionescu et al. [129] experimentally investigated the heat transfer performance of the ice/oil SSPCM slurry, during the melting and solidification processes, flowing through a rectangular channel in laminar and transitional flows. They found that the heat transfer performance of the SSPCM slurry was significantly improved compared with pure oil. The heat transfer coefficient of the SSPCM slurry was higher than that of oil and increased with the increase of the mass fraction of the SSPCM. Royon and Guiffant [130] proposed a model for ice/oil SSPCM slurry considering the turbulent regime in a circular tube at constant wall temperature, which was set below the phase change temperature. An apparent plateau was found for the dimensionless bulk

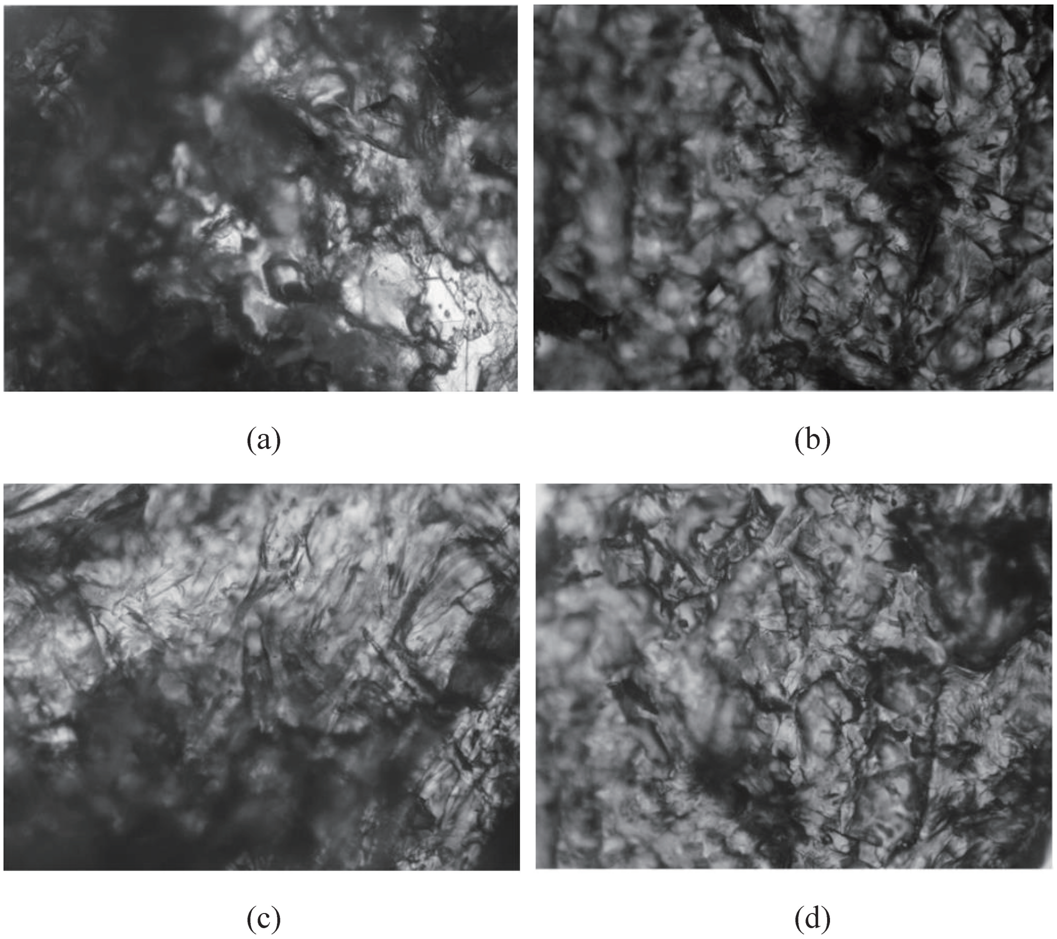


Figure 15 Micrographs of fatty acid/PMMA (80/20 wt%) SSPCM [117]. (a) Stearic acid/PMMA; (b) palmitic acid/PMMA; (c) myristic acid/PMMA; (d) lauric acid/PMMA.

temperature of the slurry due to the phase change of the PCM. The results showed that the length of the plateau increased when increasing the mass fraction or decreasing the Stefan number. It was further indicated that the minimum length of the tube to make all the particles freeze completely increased with the increases of the mass fraction, the Reynolds number and the wall temperature. They also prepared a paraffin based SSPCM slurry using the styrene-butadiene-styrene block copolymer as the supporting material and investigated the phase change process of the slurry in an agitated bath [131]. The results showed that the complete melting time increased with the increase of the particle diameter. Royon et al. [132] experimentally investigated the flow behavior of the SSPCM slurry in a circular tube. The results showed that the pressure drop of the SSPCM slurry increased when increasing the flow rate and decreased when increasing the temperature. The pumping power was significantly reduced compared with that of chilled water for the same transported heat, as can be seen in Figure 16. Boujaddaini et al. [133] numerically studied the heat transfer characteristics of the SSPCM slurry in the laminar regime in a vertically rectangular channel at constant wall temperature using the Eulerian-mixture model. It was indicated that the heat transfer coefficient of the SSPCM slurry increased with the increase of the Reynolds number and the mass fraction of the SSPCM. The heat transfer performance of the SSPCM slurry was significantly higher than that of water.

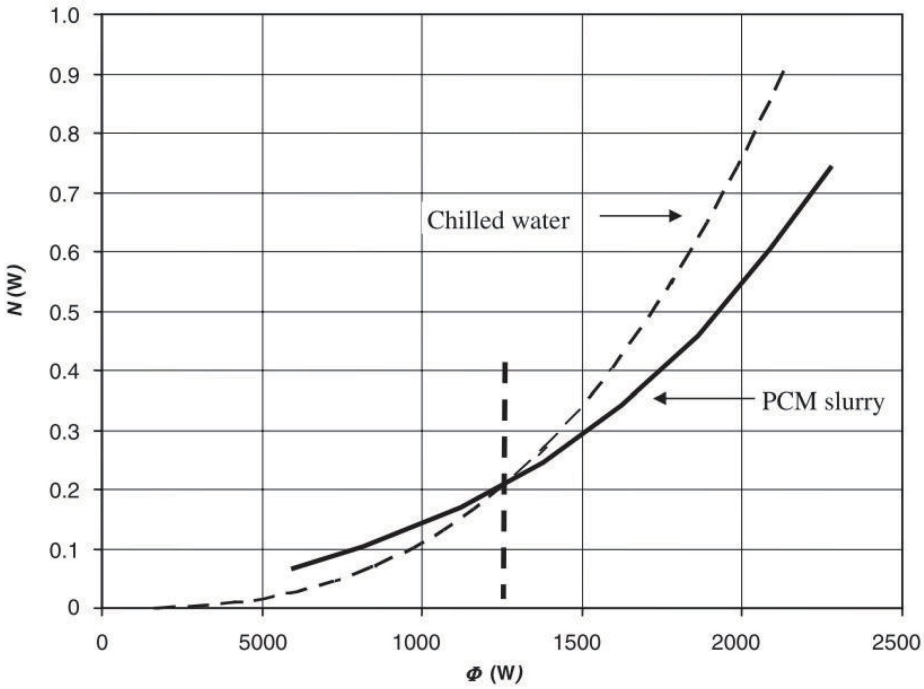


Figure 16 Pumping power consumptions N vary with the heat transportation rate Φ for chilled water and the SSPCM slurry [132].

4 Conclusion

A brief introduction of the preparation methods and a comprehensive summery of the flow and heat transfer characteristics of the M/NPCM and the SSPCM slurries have been carried out in the present study. The preparations of the M/NPCM slurry and SSPCM slurry have been found to be still at lab-scales, and the methods for large-scale production are necessary to facilitate further investigation and applications. The PCS usually showed different hydraulic and heat transfer characteristics from the pure single-phase fluid due to the involvement of the latent heat of the PCM. Meanwhile, the PCS can be considered as the Newtonian fluid if lower mass fractions of the PCMs are used. It can behave as homogenous fluid for smaller particles of the PCMs, and the flow pattern changes with the variation of the flow rate, solid volume fraction and particle size. The pressure drop of the PCS is higher than that of pure carrying fluid in the same flow regime due to the presence of solid particles. The pressure drop of the PCS increases when increasing the Reynolds number and the mass fraction. Because of the large heat capacity of the PCS, the pumping power consumption of the PCS is significantly reduced compared with that of pure carrying fluid at the same transported heat. The parameters mainly affecting the heat transfer characteristics of the PCS include the mass fraction of the PCM, the Stefan number, the Reynolds number, melting temperature range, supercooling degree of the inlet temperature, etc. The most important parameters are the Stefan number and the mass fraction of the PCM. The heat transfer performance of the PCS in laminar flow is usually better than that of pure carrying fluid due to the effect of the latent heat, which can be further enhanced by decreasing the Stefan number, phase change temperature range and supercooling degree or increasing the mass fraction and the Reynolds number. The effect of particle size cannot be predicted accurately because of the controversial results. Therefore, further investigation is still needed to clarify the performances of the PCSs compared with the pure carrying fluid and optimize the operating condition to make full use of the PCM. Besides, the stability of the PCS for a long-time storage is a practical problem which needs thoughtful actions in the future.

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References

[1] Alva G, Liu L, Huang X, et al. Thermal energy storage materials and systems for solar energy applications. Renew Sust Energ Rev, 2017, 68(Part 1): 693—706.

[2] Ibrahim N I, Al-Sulaiman F A, Rahman S, et al. Heat transfer enhancement of phase change materials for thermal energy storage applications: A critical review. Renew Sust Energ Rev, 2017, 74(Supplement C): 26—50.

[3] Delgado M, Lázaro A, Mazo J, et al. Review on phase change material emulsions and microencapsulated phase change material slurries: Materials, heat transfer studies and applications. Renew Sust Energ Rev, 2012, 16(1): 253—273.

[4] Inaba H. New challenge in advanced thermal energy transportation using functionally thermal fluids. Int J Therm Sci, 2000, 39(9): 991—1003.

[5] Carney R R. "Slush hydrogen" production and handling as a fuel for space projects. Advances in Cryogenic Engineering: Proceedings of the 1963 Cryogenic Engineering Conference University of Colorado College of Engineering and National Bureau of Standards Boulder Laboratories Boulder, Colorado August 19—21. 1963.

[6] Momotari H, Uryu T, Sato S, et al. Over-current characteristics of HTS tapes in slush nitrogen. Meetings of Cryogenics and Superconductivity, 2009.

[7] Talevi R, Barbato V, Fiorentino I, et al. Successful slush nitrogen vitrification of human ovarian tissue. Fertil Steril, 2016, 105(6): 1523—1531. e1.

[8] Rodríguez Ó, Barros-Velázquez J, Piñeiro C, et al. Effects of storage in slurry ice on the microbial, chemical and sensory quality and on the shelf life of farmed turbot (Psetta maxima). Food Chem, 2006, 95(2): 270—278.

[9] Wang M J and Kusumoto N. Ice slurry based thermal storage in multifunctional buildings. Heat Mass Transfer, 2001, 37(6): 597—604.

[10] Davies T W. Slurry ice as a heat transfer fluid with a large number of application domains. Int J Refrig, 2005, 28(1): 108—114.

[11] Douzet J, Kwaterski M, Lallemand A, et al. Prototyping of a real size air-conditioning system using a tetra-<i>n</i>-butylammonium bromide semiclathrate hydrate slurry as secondary two-phase refrigerant-Experimental investigations and modelling. Int J Refrig, 2013, 36(6): 1616—1631.

[12] Huang L, Petermann M, and Doetsch C. Evaluation of paraffin/water emulsion as a phase change slurry for cooling applications. Energy, 2009, 34(9): 1145—1155.

[13] Cho K and Choi M. Experimental study on the application of paraffin slurry to high density electronic package cooling. Heat Mass Transfer, 2000, 36(1): 29—36.

[14] Kasza K E and Chen M M. Improvement of the performance of solar energy or waste heat utilization systems by using phase-change slurry as an enhanced heat-transfer storage fluid. J Sol Energ Eng, 1985, 107(3): 229—236.

[15] Wang X and Niu J. Performance of cooled-ceiling operating with MPCM slurry. Energ Convers Manage, 2009, 50(3): 583—591.

[16] Wu W, Bostanci H, Chow L C, et al. Jet impingement and spray cooling using slurry of nanoencapsulated phase change materials. Int J Heat Mass Tran, 2011, 54(13): 2715—2723.

[17] Chen S, Wang X, Li W, et al. Experimental study on cooling performance of microencapsulated phase change suspension in a PEMFC. Int J Hydrogen Energ, 2017, 42(50): 30004—30012.

[18] Kong M, Alvarado J L, Thies C, et al. Field evaluation of microencapsulated phase change material slurry in ground source heat pump systems. Energy, 2017, 122(Supplement C): 691—700.

[19] Zhang X, Kong X, Li G, et al. Thermodynamic assessment of active cooling/heating methods for lithium-ion batteries of electric vehicles in extreme conditions. Energy, 2014, 64(Supplement C): 1092—1101.

[20] Serale G, Fabrizio E, and Perino M. Design of a low-temperature solar heating system based on a slurry Phase Change Material (PCS). Energ Buildings, 2015, 106(Supplement C): 44—58.

[21] Tumirah K, Hussein M Z, Zulkarnain Z, et al. Nano-encapsulated organic phase change material based on copolymer nanocomposites for thermal energy storage. Energy, 2014, 66(Supplement C): 881—890.

[22] Salaün F, Bedek G, Devaux E, et al. Microencapsulation of a cooling agent by interfacial polymerization: Influence of the parameters of

encapsulation on poly(urethane—urea) microparticles characteristics. J Membr Sci, 2011, 370(1): 23—33.

[23] Wang H, Luo J, Yang Y, et al. Fabrication and characterization of microcapsulated phase change materials with an additional function of thermochromic performance. Sol Energy, 2016, 139(Supplement C): 591—598.

[24] Giro-Paloma J, Konuklu Y, and Fernández A I. Preparation and exhaustive characterization of paraffin or palmitic acid microcapsules as novel phase change material. Sol Energy, 2015, 112: 300—309.

[25] Konuklu Y, Unal M, and Paksoy H O. Microencapsulation of caprylic acid with different wall materials as phase change material for thermal energy storage. Sol Energy Mater Sol Cells, 2014, 120: 536—542.

[26] Tahan Latibari S, Mehrali M, Mehrali M, et al. Synthesis, characterization and thermal properties of nanoencapsulated phase change materials via sol—gel method. Energy, 2013, 61(Supplement C): 664—672.

[27] Lazko J, Popineau Y, and Legrand J. Soy glycinin microcapsules by simple coacervation method. Colloids Surf B Biointerfaces, 2004, 37(1): 1—8.

[28] Fu Z, Su L, Li J, et al. Elastic silicone encapsulation of n-hexadecyl bromide by microfluidic approach as novel microencapsulated phase change materials. Thermochim Acta, 2014, 590: 24—29.

[29] Hawlader M N A, Uddin M S, and Khin M M. Microencapsulated PCM thermal-energy storage system. Appl Energ, 2003, 74(1): 195—202.

[30] Werner S R L, Jones J R, Paterson A H J, et al. Air-suspension particle coating in the food industry: Part I — state of the art. Powder Technol, 2007, 171(1): 25—33.

[31] De W L, Dabo D, Lidelöw S, et al. MSWI bottom ash used as basement at two pilot-scale roads: comparison of leachate chemistry and reactive transport modeling. Waste Manage, 2011, 31(2): 267—280.

[32] Memon S A, Cui H, Lo T Y, et al. Development of structural—functional integrated concrete with macro-encapsulated PCM for thermal energy storage. Appl Energ, 2015, 150: 245—257.

[33] Goel M, Roy S K, and Sengupta S. Laminar forced convection heat transfer in microcapsulated phase change material suspensions. Int J Heat Mass Tran, 1994, 37(4): 593—604.

[34] Yamagishi Y, Takeuchi H, Pyatenko A T, et al. Characteristics of microencapsulated PCM slurry as a heat - transfer fluid. AICHE J, 1999, 45(4): 696—707.

[35] Inaba H, Kim M-J, and Horibe A. Melting heat transfer characteristics of microencapsulated phase change material slurries with plural microcapsules having different diameters. J Heat Transfer, 2003, 126(4): 558—565.

[36] Rao Y, Dammel F, Stephan P, et al. Flow frictional characteristics of microencapsulated phase change material suspensions flowing through rectangular minichannels. Sci China, Ser E, 2006, 49(4): 445—456.

[37] Rao Y, Dammel F, Stephan P, et al. Convective heat transfer characteristics of microencapsulated phase change material suspensions in minichannels. Heat Mass Transfer, 2007, 44(2): 175—186.

[38] Wang X, Niu J, Li Y, et al. Flow and heat transfer behaviors of phase change material slurries in a horizontal circular tube. Int J Heat Mass Tran, 2007, 50(13): 2480—2491.

[39] Wang X, Niu J, Li Y, et al. Heat transfer of microencapsulated PCM slurry flow in a circular tube. AICHE J, 2008, 54(4): 1110—1120.

[40] Chen B, Wang X, Zeng R, et al. An experimental study of convective heat transfer with microencapsulated phase change material suspension: Laminar flow in a circular tube under constant heat flux. Exp Therm Fluid Sci, 2008, 32(8): 1638—1646.

[41] Ho C J, Huang J B, Tsai P S, et al. Water-based suspensions of Al2O3 nanoparticles and MEPCM particles on convection effectiveness in a circular tube. Int J Therm Sci, 2011, 50(5): 736—748.

[42] Delgado M, Lázaro A, Mazo J, et al. Experimental analysis of a microencapsulated PCM slurry as thermal storage system and as heat transfer fluid in laminar flow. Appl Therm Eng, 2012, 36(Supplement C): 370—377.

[43] Delgado M, Lázaro A, Peñalosa C, et al. Experimental analysis of the influence of microcapsule mass fraction on the thermal and rheological behavior of a PCM slurry. Appl Therm Eng, 2014, 63(1): 11—22.

[44] Huang Y, Xuan Y, and Li Q. Experimental investigation on convective heat transfer of magnetic phase change microcapsule suspension. Appl Therm Eng, 2012, 47(Supplement C): 10—17.

[45] Sabbah R, Seyedyagoobi J, and Alhallaj S. Heat transfer characteristics of liquid flow with micro-encapsulated phase change material: experimental study. J Heat Transfer, 2012, 134(4): 044501.

[46] Wang L and Lin G. Experimental study on the convective heat transfer behavior of microencapsulated phase change material suspensions in rectangular tube of small aspect ratio. Heat Mass Transfer, 2012, 48(1): 83—91.

[47] Song S, Shen W, Wang J, et al. Experimental study on laminar convective heat transfer of microencapsulated phase change material slurry using liquid metal with low melting point as carrying fluid. Int J Heat Mass Tran, 2014, 73(Supplement C): 21—28.

[48] Liu C, Ma Z, Wang J, et al. Experimental research on flow and heat transfer characteristics of latent functional thermal fluid with microencapsulated phase change materials. Int J Heat Mass Tran, 2017, 115(Part A): 737—742.

[49] Choi E, Cho Y I, and Lorsch H G. Forced convection heat transfer with phase-change-material slurries: Turbulent flow in a circular tube. Int J Heat Mass Tran, 1994, 37(2): 207—215.

[50] Alvarado J L, Marsh C, Sohn C, et al. Thermal performance of microencapsulated phase change material slurry in turbulent flow under constant heat flux. Int J Heat Mass Tran, 2007, 50(9): 1938—1952.

[51] Tumuluri K, Alvarado J L, Taherian H, et al. Thermal performance of a novel heat transfer fluid containing multiwalled carbon nanotubes and microencapsulated phase change materials. Int J Heat Mass Tran, 2011, 54(25): 5554—5567.

[52] Taherian H, Alvarado J L, Tumuluri K, et al. Fluid flow and heat transfer characteristics of microencapsulated phase change material slurry in turbulent flow. J Heat Transfer, 2014, 136(6): 061704-061704-7.

[53] Kong M, Alvarado J L, Terrell W, et al. Performance characteristics of microencapsulated phase change material slurry in a helically coiled tube. Int J Heat Mass Tran, 2016, 101(Supplement C): 901—914.

[54] Li L, Zou D, Ma X, et al. Preparation and flow resistance characteristics of novel microcapsule slurries for engine cooling system. Energ Convers Manage, 2017, 135(Supplement C): 170—177.

[55] Charunyakorn P, Sengupta S, and Roy S K. Forced convection heat transfer in microencapsulated phase change material slurries: flow in circular ducts. Int J Heat Mass Tran, 1991, 34(3): 819—833.

[56] Zhang Y and Faghri A. Analysis of forced convection heat transfer in microencapsulated phase change material suspensions. J Thermophys Heat Transfer, 1995, 9(4): 727—732.

[57] Alisetti E L and Roy S K. Forced convection heat transfer to phase change aaterial slurries in circular ducts. J Thermophys Heat Transfer, 1999, 14(1): 115—118.

[58] Roy S K and Avanic B L. Laminar forced convection heat transfer with phase change material suspensions. Int Commun Heat Mass, 2001, 28(7): 895—904.

[59] Hu X and Zhang Y. Novel insight and numerical analysis of convective heat transfer enhancement with microencapsulated phase change material slurries: laminar flow in a circular tube with constant heat flux. Int J Heat Mass Tran, 2002, 45(15): 3163—3172.

[60] Zhang Y, Hu X, and Wang X. Theoretical analysis of convective heat transfer enhancement of microencapsulated phase change material slurries. Heat Mass Transfer, 2003, 40(1): 59—66.

[61] Bai F W and Lu W Q. Numerical analysis of laminar forced convection heat transfer in microencapsulated phase change material suspensions. J Enhance Heat Transf, 2003, 10(3): 311—322.

[62] Lu W Q and Bai F W. A new model for analyzing laminar forced convective enhanced heat transfer in latent functionally thermal fluid. Chin Sci Bull, 2004, 49(14): 1457—1464.

[63] Ho C J, Lin J F, and Chiu S Y. Heat transfer of solid-liquid phase-change material suspensions in circular pipes: effects of wall conduction. Numer Heat Transfer, 2004, 45(2): 171—190.

[64] Ho C J. A continuum model for transport phenomena in convective flow of solid—liquid phase change material suspensions. Appl Math Model, 2005, 29(9): 805—817.

[65] Wang S and Zhang Y. Forced-convection heat transfer of microencapsulated phase-change material suspensions flow in a circular tube subject to external convective heating. J Enhance Heat Transf, 2008, 15(2): 171—181.

[66] Zhao Z N, Rui H, and Shi Y Q. Parametric analysis of enhanced heat transfer for laminar flow of microencapsulated phase change suspension in a circular tube with constant wall temperature. Heat Transfer Eng, 2008, 29(1): 97—106.

[67] Ravi G, Alvarado J l, Marsh C, et al. Laminar flow forced convection heat transfer behavior of a phase change material fluid in finned tubes. Numer Heat Transfer, 2009, 55(8): 721—738.

[68] Zeng R, Wang X, Chen B, et al. Heat transfer characteristics of microencapsulated phase change material slurry in laminar flow under constant heat flux. Appl Energ, 2009, 86(12): 2661—2670.

[69] Kousksou T, Rhafiki T E, Omari K E, et al. Forced convective heat transfer in supercooled phase-change material suspensions with stochastic crystallization. Int J Refrig, 2010, 33(8): 1569—1582.

[70] Sabbah R, Seyed-Yagoobi J, and Al-Hallaj S. Heat transfer characteristics of liquid flow with micro-encapsulated phase change material: numerical study. J Heat Transfer, 2011, 133(12): 121702-121702-10.

[71] Chen Z, Shan F, and Fang G Y. Dynamic heat transfer characteristics modeling of microencapsulated phase change material slurries.

Chem Eng Technol, 2012, 35(5): 834—840.

[72] Scott D A, Lamoureux A, and Baliga B R. Modeling and simulations of laminar mixed convection in a vertical pipe conveying slurries of a microencapsulated phase-change material in distilled water. J Heat Transfer, 2012, 135(1): 011013-011013-13.

[73] Kurnia J, Sasmito A, Jangam S, et al. Heat transfer in coiled square tubes for laminar flow of slurry of microencapsulated phase change material. Heat Transfer Eng, 2013, 34(11—12): 994—1007.

[74] Lenert A, Nam Y, Yilbas B S, et al. Focusing of phase change microparticles for local heat transfer enhancement in laminar flows. Int J Heat Mass Tran, 2013, 56(1): 380—389.

[75] Song S, Liao Q, Shen W, et al. Numerical study on laminar convective heat transfer enhancement of microencapsulated phase change material slurry using liquid metal with low melting point as carrying fluid. Int J Heat Mass Tran, 2013, 62(Supplement C): 286—294.

[76] Song S, Liao Q, and Shen W. Laminar heat transfer and friction characteristics of microencapsulated phase change material slurry in a circular tube with twisted tape inserts. Appl Therm Eng, 2013, 50(1): 791—798.

[77] Seyf H R, Wilson M R, Zhang Y, et al. Flow and heat transfer of nanoencapsulated phase change material slurry past a unconfined square cylinder. J Heat Transfer, 2014, 136(5): 051902-051902-10.

[78] Lu H W, Seyf H R, Zhang Y W, et al. Heat transfer enhancement of backward-facing step flow by using nano-encapsulated phase change material slurry. Numer Heat Transfer, 2015, 67(4): 381—400.

[79] Khakpour Y and Seyed-Yagoobi J. Evaporating liquid film flow in the presence of micro-encapsulated phase change materials: a numerical study. J Heat Transfer, 2015, 137(2): 021501-021501-9.

[80] Rhafiki T E, Kousksou T, and Zeraouli Y. Thermal performance of microencapsulated phase-change-material slurry: laminar flow in circular tube. J Thermophys Heat Transfer, 2015, 24(3): 480—489.

[81] Liu L, Alva G, Jia Y, et al. Dynamic thermal characteristics analysis of microencapsulated phase change suspensions flowing through rectangular mini-channels for thermal energy storage. Energ Buildings, 2017, 134(Supplement C): 37—51.

[82] Roy S K and Avanic B L. Turbulent heat transfer with phase change material suspensions. Int J Heat Mass Tran, 2001, 44(12): 2277—2285.

[83] Ma F, Zhang P, and Shi X J. Investigation of thermo-fluidic performance of phase change material slurry and energy transport characteristics. Appl Energ, 2017.

[84] Languri E M, Rokni H B, Alvarado J, et al. Heat transfer analysis of microencapsulated phase change material slurry flow in heated helical coils: A numerical and analytical study. Int J Heat Mass Tran, 2018, 118(Supplement C): 872—878.

[85] Hao Y L and Tao Y X. A numerical model for phase-change suspension flow in microchannels. Numer Heat Transfer, 2004, 46(1): 55—77.

[86] Xing K Q, Tao Y X, and Hao Y L. Performance evaluation of liquid flow with PCM particles in microchannels. J Heat Transfer, 2005, 127(8): 931—940.

[87] Tao Y X, Xing K Q, Maloji P, et al. Low-Reynolds number limit of heat transfer enhancement with phase-change material slurry flow in micro/minichannels. J Enhance Heat Transf, 2007, 14(2): 105—122.

[88] Kuravi S, Kota K M, Du J, et al. Numerical investigation of flow and heat transfer performance of nano-encapsulated phase change material slurry in microchannels. J Heat Transfer, 2009, 131(6): 062901-062901-9.

[89] Kuravi S, Du J, and Chow L C. Encapsulated phase change material slurry flow in manifold microchannels. J Thermophys Heat Transfer, 2010, 24(2): 364—373.

[90] Alquaity A B S, Al-Dini S A, Wang E N, et al. Numerical investigation of liquid flow with phase change nanoparticles in microchannels. Int J Heat Fluid Flow, 2012, 38(Supplement C): 159—167.

[91] Alquaity A B S, Al - Dini S A, and Yilbas B S. Investigation into thermal performance of nanosized phase change material (PCM) in microchannel flow. Int J Numer Method H, 2013, 23(2): 233—247.

[92] Kondle S, Alvarado J L, and Marsh C. Laminar flow forced convection heat transfer behavior of a phase change material fluid in microchannels. J Heat Transfer, 2013, 135(5): 052801-052801-11.

[93] Kondle S, Alvarado J L, and Marsh C. Laminar heat transfer behavior of a phase change material fluid in microchannels with staggered pins. J Heat Transfer, 2017, 139(6): 062401-062401-8.

[94] Petrovic A, Lelea D, and Laza I. The comparative analysis on using the NEPCM materials and nanofluids for microchannel cooling solutions. Int Commun Heat Mass, 2016, 79(Supplement C): 39—45.

[95] Wang Y, Chen Z, and Ling X. An experimental study of the latent functionally thermal fluid with micro-encapsulated phase change material particles flowing in microchannels. Appl Therm Eng, 2016, 105(Supplement C): 209—216.

[96] Roberts N S, Al-Shannaq R, Kurdi J, et al. Efficacy of using slurry of metal-coated microencapsulated PCM for cooling in a micro-channel heat exchanger. Appl Therm Eng, 2017, 122(Supplement C): 11—18.

[97] Inaba H, Zhang Y, and Horibe A. Transient heat storage characteristics on horizontal rectangular enclosures filled with fluidity slurry of micro-encapsulated phase-change-material dispersed in water. J Therm Sci Tech—JPN, 2006, 1(1): 66—77.

[98] Inaba H, Zhang Y, Horibe A, et al. Numerical simulation of natural convection of latent heat phase-change-material microcapsulate slurry packed in a horizontal rectangular enclosure heated from below and cooled from above. Heat Mass Transfer, 2007, 43(5): 459—470.

[99] Diaconu B M, Varga S, and Oliveira A C. Experimental assessment of heat storage properties and heat transfer characteristics of a phase change material slurry for air conditioning applications. Appl Energ, 2010, 87(2): 620—628.

[100] Diaconu B M, Varga S, and Oliveira A C. Experimental study of natural convection heat transfer in a microencapsulated phase change material slurry. Energy, 2010, 35(6): 2688—2693.

[101] Zhang Y, Wang S, Rao Z, et al. Experiment on heat storage characteristic of microencapsulated phase change material slurry. Sol Energy Mater Sol Cells, 2011, 95(10): 2726—2733.

[102] Zhang Y, Rao Z, Wang S, et al. Experimental evaluation on natural convection heat transfer of microencapsulated phase change materials slurry in a rectangular heat storage tank. Energ Convers Manage, 2012, 59(Supplement C): 33—39.

[103] Sabbah R, Seyed-Yagoobi J, and Al-Hallaj S. Natural convection with micro-encapsulated phase change material. J Heat Transfer, 2012, 134(8): 082503-082503-8.

[104] Wang L, Zhang J, Wang Y, et al. Experimental study on natural convective heat transfer of tube immersed in microencapsulated phase change material suspensions. Appl Therm Eng, 2016, 99(Supplement C): 583—590.

[105] Hasan M I. Numerical investigation of counter flow microchannel heat exchanger with MEPCM suspension. Appl Therm Eng, 2011, 31(6): 1068—1075.

[106] Wu W, Bostanci H, Chow L C, et al. Heat transfer enhancement of PAO in microchannel heat exchanger using nano-encapsulated phase change indium particles. Int J Heat Mass Tran, 2013, 58(1): 348—355.

[107] Kong M-S, Yu K, Alvarado J L, et al. Thermal performance of microencapsulated phase change material slurry in a coil heat exchanger. J Heat Transfer, 2015, 137(7): 071801-071801-8.

[108] Sabbah R, Farid M M, and Al-Hallaj S. Micro-channel heat sink with slurry of water with micro-encapsulated phase change material: 3D-numerical study. Appl Therm Eng, 2009, 29(2): 445—454.

[109] Ho C J, Chen W C, and Yan W M. Experimental study on cooling performance of minichannel heat sink using water-based MEPCM particles. Int Commun Heat Mass, 2013, 48(Supplement C): 67—72.

[110] Ho C J, Chen W C, and Yan W M. Correlations of heat transfer effectiveness in a minichannel heat sink with water-based suspensions of Al2O3 nanoparticles and/or MEPCM particles. Int J Heat Mass Tran, 2014, 69(Supplement C): 293—299.

[111] Ho C J, Chen W C, and Yan W M. Experiment on thermal performance of water-based suspensions of Al2O3 nanoparticles and MEPCM particles in a minichannel heat sink. Int J Heat Mass Tran, 2014, 69(Supplement C): 276—284.

[112] Seyf H R, Zhou Z, Ma H B, et al. Three dimensional numerical study of heat-transfer enhancement by nano-encapsulated phase change material slurry in microtube heat sinks with tangential impingement. Int J Heat Mass Tran, 2013, 56(1): 561—573.

[113] Rajabifar B. Enhancement of the performance of a double layered microchannel heatsink using PCM slurry and nanofluid coolants. Int J Heat Mass Tran, 2015, 88(Supplement C): 627—635.

[114] Rajabifar B, Mohammadian S K, Khanna S K, et al. Effects of pin tip-clearance on the performance of an enhanced microchannel heat sink with oblique fins and phase change material slurry. Int J Heat Mass Tran, 2015, 83(Supplement C): 136—145.

[115] Rajabifar B, Seyf H R, Zhang Y, et al. Flow and heat transfer in micro pin fin heat sinks with nano-encapsulated phase change materials. J Heat Transfer, 2016, 138(6): 062401-062401-8.

[116] Deng X, Wang S, Wang J, et al. Analytical modeling of microchannel heat sinks using microencapsulated phase change material slurry for chip cooling. Procedia Eng, 2017, 205(Supplement C): 2704—2711.

[117] Alkan C and Sari A. Fatty acid/poly(methyl methacrylate) (PMMA) blends as form-stable phase change materials for latent heat thermal energy storage. Sol Energy, 2008, 82(2): 118—124.

[118] Şentürk S B, Kahraman D, Alkan C, et al. Biodegradable PEG/cellulose, PEG/agarose and PEG/chitosan blends as shape stabilized phase change materials for latent heat energy storage. Carbohydr Polym, 2011, 84(1): 141—144.

[119] Chen F and Wolcott M. Polyethylene/paraffin binary composites for phase change material energy storage in building: A morphology, thermal properties, and paraffin leakage study. Sol Energy Mater Sol Cells, 2015, 137: 79—85.

[120] Sarı A, Alkan C, Karaipekli A, et al. Preparation, characterization and thermal properties of styrene maleic anhydride copolymer

(SMA)/fatty acid composites as form stable phase change materials. Energ Convers Manage, 2008, 49(2): 373—380.

[121] Zeng J L, Zheng S H, Yu S B, et al. Preparation and thermal properties of palmitic acid/polyaniline/exfoliated graphite nanoplatelets form-stable phase change materials. Appl Energ, 2014, 115: 603—609.

[122] Khadiran T, Hussein M Z, Zainal Z, et al. Shape-stabilised n-octadecane/activated carbon nanocomposite phase change material for thermal energy storage. J Taiwan Inst Chem E, 2015, 55: 189—197.

[123] Qian T, Li J, Min X, et al. Polyethylene glycol/mesoporous calcium silicate shape-stabilized composite phase change material: Preparation, characterization, and adjustable thermal property. Energy, 2015, 82: 333—340.

[124] Kim D, Jung J, Kim Y, et al. Structure and thermal properties of octadecane/expanded graphite composites as shape-stabilized phase change materials. Int J Heat Mass Tran, 2016, 95: 735—741.

[125] Zhang D, Tian S, and Xiao D. Experimental study on the phase change behavior of phase change material confined in pores. Sol Energy, 2007, 81(5): 653—660.

[126] Tang F, Cao L, and Fang G. Preparation and thermal properties of stearic acid/titanium dioxide composites as shape-stabilized phase change materials for building thermal energy storage. Energ Buildings, 2014, 80: 352—357.

[127] Royon L, Guiffant G, and Perrot P. Forced convection heat transfer in a slurry of phase change material in an agitated tank. Int Commun Heat Mass, 2000, 27(8): 1057—1065.

[128] Royon L, Perrot P, and Guiffant G. Transport of cold thermal energy with a slurry as secondary biphasic refrigerant. Int J Energ Res, 2001, 25(1): 9—15.

[129] Ionescu C, Haberschill P, Kiss I, et al. Local and global heat transfer coefficients of a stabilised ice slurry in laminar and transitional flows. Int J Refrig, 2007, 30(6): 970—977.

[130] Royon L and Guiffant G. Forced convection heat transfer with slurry of phase change material in circular ducts: A phenomenological approach. Energ Convers Manage, 2008, 49(5): 928—932.

[131] Royon L and Guiffant G. Investigation on heat transfer properties of slurry of stabilized paraffin during a melting process. Energ Convers Manage, 2011, 52(2): 1073—1076.

[132] Royon L, Jacquier D, and Mercier P. Flow investigation of phase change material (PCM) slurry as a heat transfer fluid in a closed loop system. Int J Energ Res, 2009, 33(4): 333—341.

[133] Boujaddaini M N E, Mimet A, and Haberschill P. Forced convective heat transfer study of paraffin slurry flowing in a vertical rectangular channel. Int J Fluid Mech Res, 2013, 40(5): 405—419.

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