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Experimental measurement and numerical modeling of the creaming of mPCM slurry

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Abstract

The slurry of mPCM has been widely used for enhancing heat transfer and reducing building energy consumption. Because of intrinsic density differences between mPCM and water, the slurry is subject to creaming phenomena. As a consequence the viscosity of slurry increases and the thermal properties decrease. Up to now no quantitative analysis about the creaming of mPCM has been done. In the paper experimental measurement and numerical modeling of the creaming of mPCM slurry is presented. Using the optical method, the temporal-spatial distribution of volume concentration is recorded. Based on the conservation model, the process of creaming has been simulated.

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Keywords: phase change slurry; renewable energy; creaming; PCM; thermal storage; numerical simulation

1. Introduction

The phase change materials (PCM) have been widely used for enhancing heat transfer and reducing building energy consumptions [1]. In buildings they act like an almost iso-thermal reservoir of energy due to the large amount of heat that they absorb or release during their phase transition. Different PCMs are available on the market and they can be chosen to select the most suitable phase change temperature range for a specific application. Recent technology advances developed an always liquid form of these materials, called phase change slurry (PCS) [2]. To obtain the slurry many solutions are available on the market and the dispersion of micro-encapsulated PCM (mPCM) in a carrier fluid (generally water) represents one the most promising ones [3]. Nowadays, many different applications were proposed in literature [4]. For instance, an interesting use of these materials is their integration as heat transfer fluid in solar thermal systems [5].

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Delgado et al [6] showed that one of the possible drawbacks related to the use of these materials is the occurrence of sedimentation/creaming phenomena. In a mixture, creaming is the movement of the solid particles towards the superior part of the suspension as a result of gravity. Sedimentation is the opposite movement towards the inferior part. PCS based on mixture of mPCM and water are subject to sedimentation or creaming because of the intrinsic density differences between the two elements composing the solution. While the heat transfer fluid is not in motion, the two phases of the slurry likely to show creaming. A layer of more concentrated mPCM appears in upper part of the mixture. Hence the viscosity of slurry increases and the thermal property decreases. Serale et al. [7] listed the creaming phenomenon as one of the main possible drawbacks in the storage tank based on PCS.

Nevertheless, as far as we know in literature there are only few experimental investigations of this phenomenon [8]. Moreover, up to now no quantitative analysis about it has been done. The purpose of this paper is to report the preliminary results of a study concerning this creaming behavior of PCS. Outcomes are carried out by the comparison between experimental measurement and numerical modeling. The paper is organized as follows: Experimental method and experimental results are given in Section 2. Numerical modeling and analysis are given in Section 3. Possible solutions to reduce creaming are presented in Section 4.

2. Experimental tests

2.1. Description of the investigated PCS

The materials selected for the experiments was the PCS suggested by Serale et al. [9] as the most suitable for the application as innovative heat transfer fluid in the primary loop of a solar thermal system. It is a PCS based on a mixture of water and micro-encapsulated n-eicosane as mPCM. This material was chosen primarily for its melting temperature range, particularly favourable for the application. At the temperature set for the tests the PCM inside the capsules remains always in the solid phase. In Table 1 the most important properties of the micro-encapsulated n-eicosane at 20° C are summarised.

Table 1. Concentration of the four samples of PCS used in the experiments [4].

Material	Average particle size	Melting temperature	Latent heat	Capsule composition	Thermal conductivity	Density
n-eicosane	17-20 μm	37 °C	190-20 kJ/kg	0.85 wt. PCM 0.15 wt. Shell	0.230 W/mK	856 kg/m^3

A property of any PCS is that the mixture characteristics are strongly related to the relative concentration of the two components of the mixture. For this reason in this experiment different possible concentrations are considered. In particular, the tests were carried out using the specifications listed in Table 2. These are the most plausible concentrations of the PCS used as heat transfer fluid in actual cases. First, the concentration was verified during samples preparation by weighting the amount of materials on an electronic scale. Afterwards, a gravimetric test was performed drying the samples in an oven until reaching constant weight, to obtain a more reliable result.

Table 2. Concentration of the four samples of PCS used in the experiments.

Sample No.	Mass Concentration	Volume Concentration
A	0.25	0.280
B	0.30	0.334
C	0.35	0.386
D	0.40	0.438

2.2. Experimental set-up

Four Falcon™ 50mL conical centrifuge tubes were used to hold as many samples of the different concentrations. A metallic support was selected to carry the tubes, keeping them vertically without interfere in the visual field. A webcam was placed 50 cm in front of the samples. It was programmed with Matlab to snap a picture every 5 minutes for monitoring how the creaming phenomenon evolved. Backwards a 40 x 12 cm OLED was put in order to maintain a constant apparent illuminance to use as reference in post-processing elaborations. Fig.1 shows a schematic diagram of this experimental setup. All these devices were placed inside an insulated thermostatic chamber (1° C internal temperature control accuracy) to maintain the samples at a constant temperature (20° C), thus ensuring not influence of temperature variations on the system. An electronic scale (sensibility of 0.01 g) and a ventilated oven were used as auxiliary device to determine the exact sample concentration.

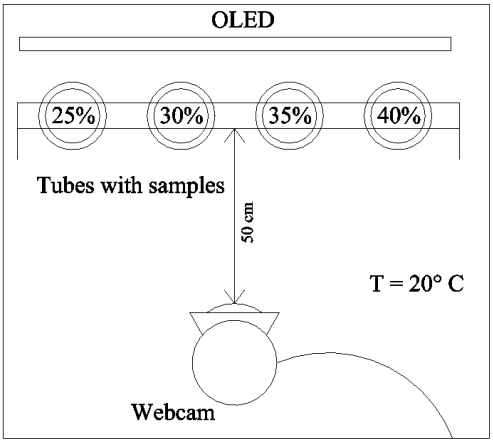
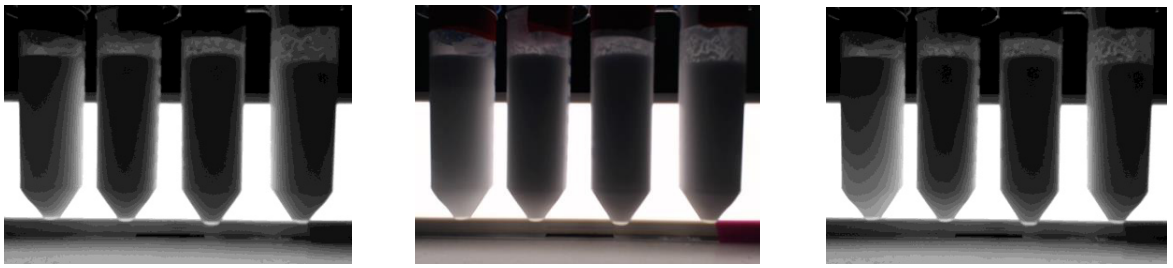


Fig. 1. Schematic of the experimental setup.

2.3. Results of the experiments

The tubes filled with the samples of PCS at different concentrations were monitored snapping pictures with the webcam every 5 minutes for a global period of 2800 minutes. The photos shown in Figure 2 highlight the evolution of the creaming of the PCS two components. In particular, it was found that the material concentration is directly related to the illuminance of the background. On one hand the water is almost transparent to the light radiation, while on the other hand the PCS becomes opaque. For this reason, the higher the illuminance passing through the sample the lower the mPCM concentration. The amount of light radiation flux through the samples varies at different height during time, according with the concentration changes due to the creaming phenomenon. It is clear to observe that after almost 1000 minutes the process reaches a quasi-steady state and seemingly the conditions remain practically constant until the end of the experiment.



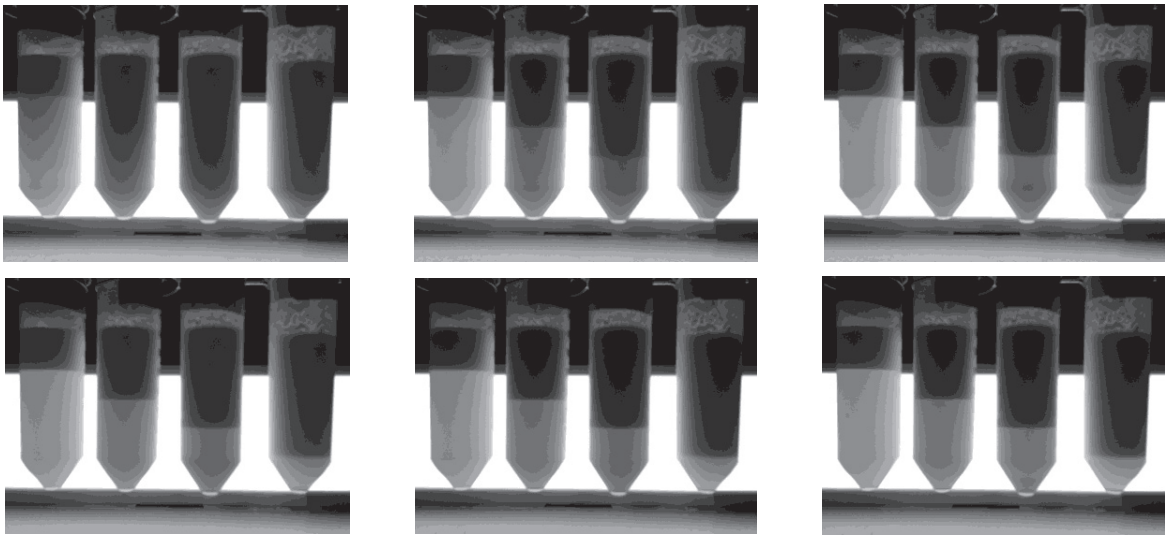


Fig. 2. Photos of the evolution of the creaming phenomenon in samples of PCS with different concentrations, from 0 minute to 2800 minute. (a) 0 min; (b) 50min; (c) 100 min; (d) 200 min; (e) 500min; (f) 1000 min; (h) 1500 min; (i)2000min; (j) 2800 min.

3. Creaming model and numerical simulation

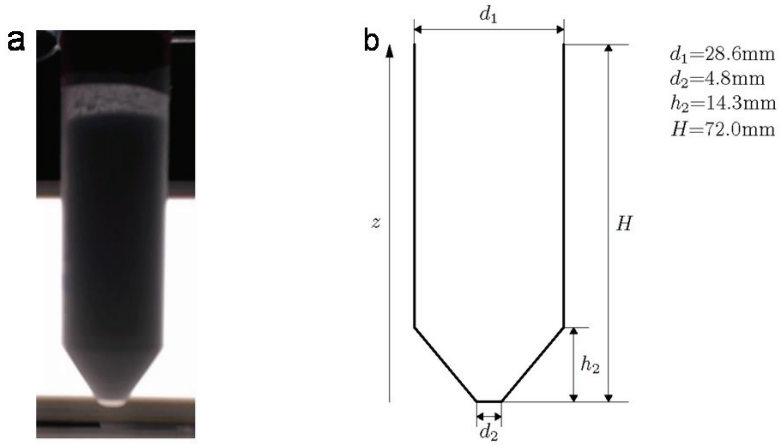


Fig. 3 (a) photo of a tube containing mPCM slurry; (b) diagram for the numerical mode

As shown in Fig.3, the creaming process was reduced to a one dimensional advection-diffusion problem in a cylinder with a variable cross-sectional area $S(z)$, and the volume concentration ϕ was considered as constant across each horizontal cross-section, i.e. $\phi=\phi(z,t)$. Using the model similar to refs.[10-11], the equation which describes the creaming is given by

$$\frac{\partial\phi}{\partial t}+\frac{1}{S(z)}\frac{\partial}{\partial z}\left(S(z)u_0\phi(1-\phi)^C\right)=\frac{1}{S(z)}\left(\frac{\partial}{\partial z}\left(S(z)D_0(1-\phi)^C\frac{\partial\phi}{\partial z}\right)\right), \tag{1}$$

where u_0 is the terminal velocity of a single particle of mPCM, C is the Richardson and Zaki index[12] and D_0 is

the diffusion coefficient [13]. In this model the initial conditions were set equal to $\phi(z,0)=\phi_0$, $0 \le z \le H$ and zero-flux boundary conditions at two ends. The generalized upwind finite volume method is used to solve the Eq.(1), and the simulation results are shown in Fig. 4. The parameters used in the model relative to the PCS are listed in Table 1 and Table 3. Results are strongly in accordance with the experimental data, that is, the creaming reaches a quasi-steady state after 1000 minutes regardless of different initial concentrations.

Table 3. Parameters used in the model and numerical simulation

Water density ρ_w	Acceleration of gravity g	Diffusion coefficient D_0	Richardson and Zaki index C	Terminal velocity of single mPCM particle u_0
1000 kg/m^3	9.81 m/s	10^{-8} m^2/s	4.65	$g(\rho_p-\rho_w)D_p^2/18\mu$

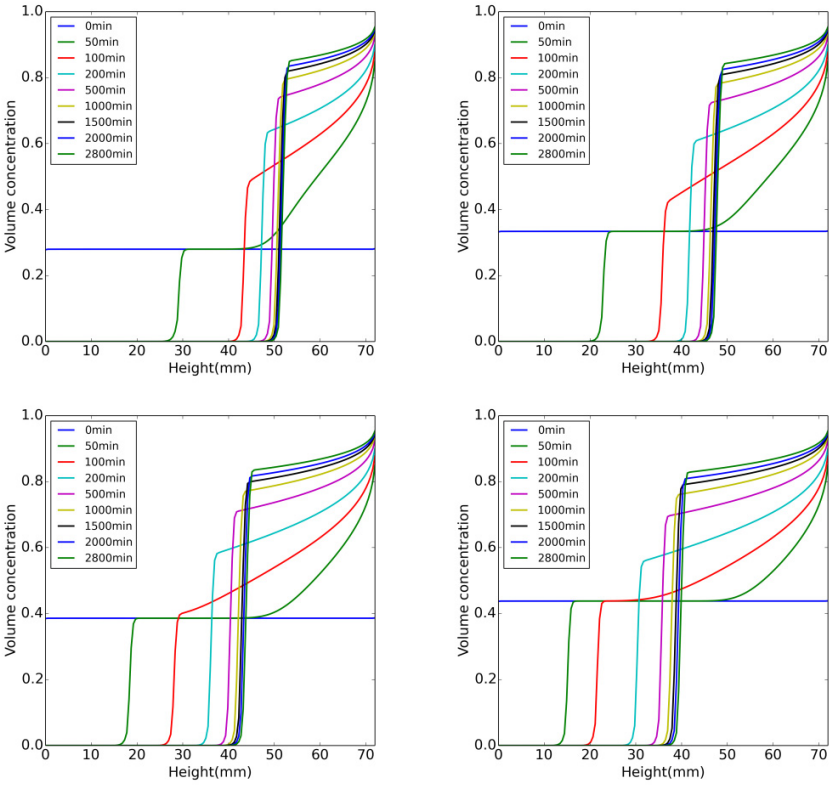


Fig. 4 Simulated volume concentration of PCS. (a) 20% wt. sample; (b) 25% wt. sample; (c) 30% wt. sample; (d) 40% wt. sample.

4. Possible methods to reduce creaming

Since the creaming of PCS is undesirable, it is important to reduce or slow down the creaming. Using the model above, three numerical experiments are conducted. The first is to decrease the size of mPCM particle to 10% of its current size, the second is to increase the viscosity of carrier fluid to 1000% of water viscosity, and the third is to decrease the density difference of PCM and carrier fluid to 10% of current value. The simulated results are shown in Fig.5. It is easy observed that decreasing the mean size, increasing the viscosity of solution and decreasing the density difference can reduce the creaming. Especially decreasing the mean size is more effective in all the three methods. This gives a theoretical guide for manufacturing the mPCM in the future.

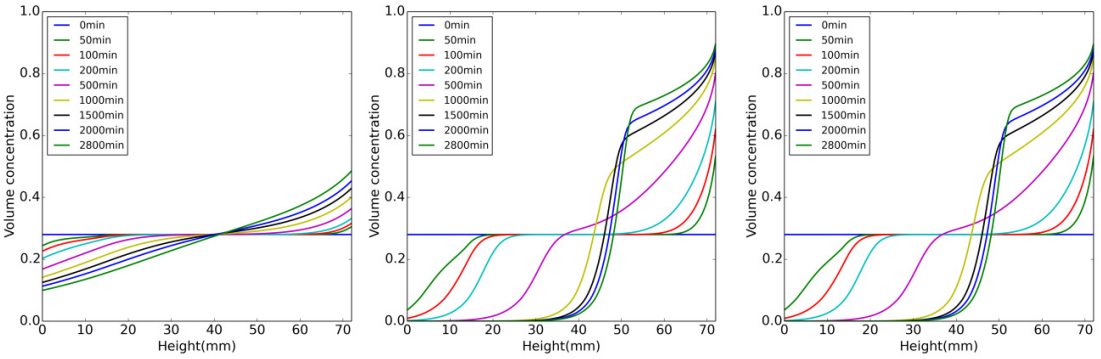


Fig. 5 Simulated volume concentration of PCS. (a) 10% of current mean size; (b)1000% of current viscosity; (c) 10% of current density difference;

5. Conclusion

Experimental measurement and numerical simulation were used to investigate the creaming of PCS. Both the experimental investigation and numerical simulation show an interesting result: the creaming process is not be influenced by the initial concentration. After almost 1000 minutes, the creaming reach a quasi-steady state and the conditions remain practically constant until the end of the experiment. The creaming process is influenced by the size of mPCM particle, the density difference between the mPCM and carrier fluid, and the viscosity of carrier fluid such as water. In order to reduce the creaming, deceasing the mean size of mPCM particle is more effective.

Future works will provide more detailed results of the experimental tests and will describe in a more accurate way the mathematical steps at the basis of the physical model. Furthermore some experimental test will be repeated above the melting temperature of the material, in order to further investigate the influence of this phenomenon.

Acknowledgements

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