

## Research Article

# Preparation and Thermal Properties of Eutectic Hydrate Salt Phase Change Thermal Energy Storage Material

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Received 28 July 2017; Accepted 10 January 2018; Published 26 February 2018

Academic Editor: Hamidreza Shabgard

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In this study, a new cold storage phase change material eutectic hydrate salt ( $K_2HPO_4 \cdot 3H_2O - NaH_2PO_4 \cdot 2H_2O - Na_2S_2O_3 \cdot 5H_2O$ ) was prepared, modified, and tested. The modification was performed by adding a nucleating agent and thickener. The physical properties such as viscosity, surface tension, cold storage characteristics, supercooling, and the stability during freeze-thaw cycles were studied. Results show that the use of nucleating agents, such as sodium tetraborate, sodium fluoride, and nanoparticles, are effective. The solidification temperature and latent heat of these materials which was added with 0, 3, and 5 wt% thickeners were  $-11.9$ ,  $-10.6$ , and  $-14.8^\circ C$  and 127.2, 118.6, 82.56 J/g, respectively. Adding a nucleating agent can effectively improve the nucleation rate and nucleation stability. Furthermore, increasing viscosity has a positive impact on the solidification rate, supercooling, and the stability during freeze-thaw cycles.

## 1. Introduction

The development of cities is accompanied by huge energy consumption; people have gradually realized that the energy storage technology has very good ability to improve this situation, which can effectively improve the energy utilization ratio and reduce losses. Phase change material (PCM) is an effective latent heat thermal storage material. It has been widely used as a thermal functional material in thermal and cold energy storage fields, like solar energy storage [1], industrial waste heat utilization [2], building heating and air conditioning [3], thermal management of mobile devices [4], and so on. All of these are aimed at realizing the conversion of energy beyond the restriction of time and space. Thus, the study of PCM is of great significance for energy storage [5]. PCM can be mainly divided into two categories of organic and inorganic. However, organic PCMs such as paraffin wax [6] and some organic compounds [7] are poor in low thermal conductivity and have flammability, which greatly limits the application of PCMs [8]. Therefore, the study of inorganic PCM has attracted much attention of researchers.

Salt hydrates [8] as an inorganic PCM have an advantage in higher heat storage capacity, suitable cold storage temperature [9], nonflammable, and so on. Thus, it would be more suitable and safer than organic PCM in energy storage application especially cryogenic storage. The traditional ice storage and water storage cannot reach the temperature of low-temperature cold storage. The temperature requirement of low cold storage is between  $-20$  and  $-30^\circ C$ , and the high-temperature cold storage is between  $0$  and  $4^\circ C$ . However, the ice storage and water storage systems can only reach  $0^\circ C$ , which cannot meet requirements of low-temperature application. Adding inorganic salts in the water can ensure that the amount of phase change latent heat almost unchanged and reduce the phase change temperature of cool storage material at the same time. Compound salts can not only further reduce the melting point of solidification but also optimize and modify the overall physical properties of certain materials. Many researchers have studied the compounded eutectic hydrate salt to achieve more suitable phase change temperature and better cold storage performance. Li et al. [10] have studied the preparation, characterization, and modification of a new phase change material  $CaCl_2 \cdot 6H_2O - MgCl_2 \cdot 6H_2O$  eutectic

hydrate salt. As a result, its phase change temperature and latent heat are 21.4°C and 102.3 J/g, respectively. Liu et al. [11] studied the energy storage characteristics of a novel binary hydrated salt by means of SEM, XRD, and DSC techniques. It was concluded that the phase transition temperature was 27.3°C, the degree of supercooling was 3.67°C, and the enthalpy of phase transition was 220.2 J/g. Efimova et al. [12] proposed a ternary hydrated salt mixture suitable for use in air conditioning systems and carried out the thermal analysis. It was concluded that the material has a melting temperature of 18–21°C and an enthalpy of fusion of 110 kJ/kg. However, different from organic PCM [13], inorganic PCM such as salt hydrates has a significant supercooling [14, 15] and relatively poor stability, which greatly limit the life of phase change material and energy storage performance. In general, methods that can be used to effectively enhance the stability of the material are additions of the thickener [16], nucleating agent [17, 18], microencapsulation [19] or nanocomposite modification [20], and so on. Tyagi [21] et al. studied the supercooling behavior of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  and the effect of pH value, which indicates that the supercooling of PCM can be removed or decreased by adjusting the pH value. Bilen et al. [22] studied the modification of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  PCM system and selected different nucleating agents. Pilar et al. [23] used  $\text{SrCO}_3$  and  $\text{Sr}(\text{OH})_2$  as nucleating agents for  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ ; the results show that the addition of 1 wt%  $\text{SrCO}_3$  and 0.5 wt%  $\text{Sr}(\text{OH})_2$  almost fully suppress the supercooling and improve the performance of this PCM system. For phase separation, Wang et al. [24] studied the thermal stability of a novel eutectic ternary system by placing the salt mixture in an argon atmosphere with a constant heating rate. In order to determine the accurate upper limit of the working temperature of the ternary salt, Sharma et al. [25] used a differential scanning calorimeter to carry out 1500 times melting and freezing cycles to study the changes in thermal properties of thermal energy storage materials. At present, the inorganic salt hydrate phase change cold storage materials have a good application prospect in refrigerator energy-saving field.

It can be seen above that most of the research on hydrated salt cold storage has focused on the development of energy storage materials for air conditioning. There is a lack of research on the energy storage materials with phase change temperature below 0°C. Otherwise, it is a meaningful attempt to study the improvement of supercooling and cycle stability of ternary eutectic system from the point of fluid viscosity and different nucleating agents added. In this paper, firstly, a  $\text{K}_2\text{HPO}_4 \cdot 3\text{H}_2\text{O} - \text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O} - \text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$  ternary salt system was prepared, modified, and synthesized. Then the contrast experimental method, step cooling method, and DSC technology were proceeded to investigate the thermal storage property and solidification behavior of eutectic hydrate when adding different amounts of nucleating agent and thickener.

## 2. Materials and Experimental Methods

*2.1. Preparation of Hydrated Salt-Based PCMs.* Preparation of hydrated salt phase change material (HSPCM) is the major key step to ensure the performance of PCM in cold storage

application. The proper mixing and stabilization are required in order to achieve stable HSPCM. In the present study, deionized water (DI water) as the base PCM; sodium dihydrogen phosphate dihydrate, dipotassium hydrogen phosphate trihydrate, and sodium thiosulfate pentahydrate as hydrated salts; nanoactivated carbon, sodium tetraborate, and sodium fluoride as nucleating agents; polyethylene glycol 400 as a dispersant; and sodium alginate as a thickener were used to prepare the HSPCM. The used materials are listed in Table 1. After a large number of experimental analysis, the hydrated salts with the same mass ratio (6 wt%) were mixed with DI water by a magnetic stirrer (MVP22-1) for 10 min to make the mixed solution system uniform. Before using the nanoparticle as a nucleating agent, the solution needs to be adjusted to weak alkaline by 10 wt% NaOH, followed by being mixed with nanoparticles and dispersant through magnetic stirring for 10 min. Afterwards, this mixture was ultrasonicated for 60 min at a frequency of 40 kHz and another 20 min stirring to make the nanoparticles dispersed as evenly as possible. The preparation process of nanocomposite hydrated salts is shown in Figure 1. The nanocomposite fluid can be considered accessible when it is observed that the formulated nanofluid undergoes no visual sedimentation over time.

*2.2. Experimental Setup.* Table 2 shows the uncertainty to measure results caused by experimental equipment. Figure 2 shows the schematic of the experimental setup to conduct the studies during the solidification of the HSPCM. The cooling chamber of 0.108 m<sup>3</sup> has the cooling ability to freeze 5 kg reagent from 25°C to -18°C in 24 hours. In the first experiment, the temperatures were measured by the armored thermocouple (T-Type) floating at the same location in the containers filled with reagents. The signal of temperature was monitored continuously for every 10 s, and the experiment was continued until the PCM completely solidified. When measuring the percentage of solidification, three samples of different viscosity were put in a square container with a small thickness. On the upper surface, the square container was divided into a grid scale, and then the three samples were put into the cooling bath during the first trial. The solidified mass was calculated by observing the grid value change of the solid area from the initial state of the liquid PCMs. The thermal properties of eutectic mixtures were obtained by using a differential scanning calorimeter (DSC, NETZSCH 200F3). The surface tension was tested by a surface tension meter (BZY-1). The step cooling analysis method was employed to examine the values of supercooling. In addition, the thermal stability was measured by the freeze-thaw cycles test, which was performed in three containers with a volume of 150 ml. The hydrated salt PCM mixture was cycled repeatedly through 20, 30, and 50 times within a freezer. Temperature data acquisition system was used to study the supercooling change after several freeze-thaw processes. The weighing of drug used a high precision electronic balance with an accuracy of ±0.002 g. All the armored thermocouples are connected to a data logger of Agilent 34970A to store the continuous data generated during the experiments.

TABLE 1: Experimental materials.

Experimental materials	Purity	Application
Sodium dihydrogen phosphate dihydrate ( $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ )	AR	Hydrated salt
Sodium alginate	CP	Thickener
Sodium thiosulfate pentahydrate ( $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ )	AR	Hydrated salt
Dipotassium hydrogen phosphate trihydrate phosphate ( $\text{K}_2\text{HPO}_4 \cdot 3\text{H}_2\text{O}$ )	AR	Hydrated salt
Nanoactivated carbon (100 nm, heat treatment)	AR	Nucleating agent
Sodium tetraborate	AR	Nucleating agent
Polyethylene glycol 400	AR	Dispersant
Sodium fluoride	AR	Nucleating agent

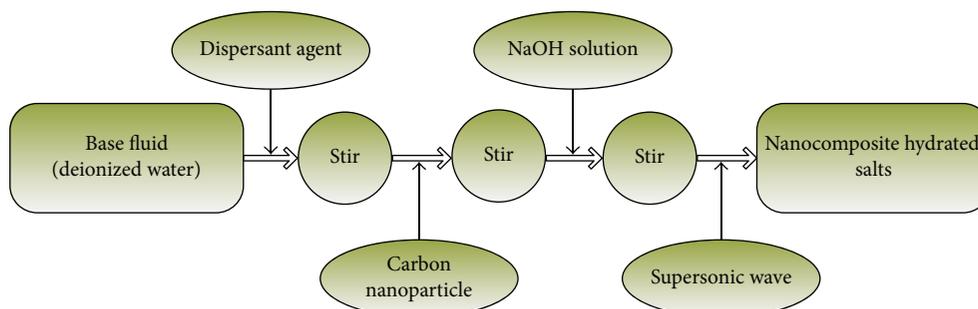


FIGURE 1: Nanocomposite PCM preparation flow chart.

TABLE 2: Result uncertainty analysis of experimental equipment.

Measured quantities	Deviation
Latent heat	$\pm 6$ kJ/kg
Mass	$\pm 0.002$ g
Temperature data logger	$\pm 0.06\%$
Volume (10 ml, 20 ml)	$\pm 0.06$ ml
Volume (100 ml)	$\pm 0.02$ ml
Thermocouple	$\pm 1.0\%$
Surface tension	$\pm 0.01$ mN/m
Viscosity	$\pm 2\%$ mps

### 3. Results and Discussion

**3.1. The Thermal Performance of Salt Hydrate PCM.** In order to assess the effect of thickener concentration on onset/end temperature and phase change heat absorption capacity during the phase change process, the thermal analysis was conducted in different cases of 0, 3, and 5 wt% sodium alginates, while the latent heat of melting process and onset/end temperature was measured with a differential scanning calorimeter (DSC), using measuring temperature range from  $-25$  to  $5^\circ\text{C}$  and constant heating rates of  $2\text{ K}\cdot\text{min}^{-1}$ . In the process of measurement, the temperature of the material rises constantly, and the heat flux of the sample was measured continuously. The heat flux is proportional to the instantaneous specific heat of the material. Melting phase change enthalpy was calculated through the area of the

endothermic peak in the DSC picture. In addition, the specific heat, heating rate ( $dH_m/dt$ ), phase change enthalpy, and specific heat satisfy certain relationships as follows:

$$\frac{dH_m}{dt} = m \cdot C_p \cdot \frac{dT}{dt}, \quad (1)$$

$$C_p = \frac{H_p}{\Delta t},$$

where  $H_m$ ,  $H_p$ ,  $C_p$ ,  $m$ ,  $T$ , and  $\Delta t$  represent the heat flux, melting phase change enthalpy, specific heat, sample mass, and the temperature difference, respectively, between the beginning and end of the melting process and time interval.

Figure 3 shows the DSC heat absorption curves of three eutectic hydrate salt nitrates with 0, 3, and 5 wt% thickeners separately. It is obviously seen that the onset and end temperature of the absorption peak become higher with the increase of the viscosity when the mass fraction is 3%. After that, with more thickener added, there is a substantial reduction with the durative increase of the viscosity. Through comparing the three samples, it was easily seen that several microparticles from the industrial sodium alginate scattered in the solution that may have the function of improving the solidification point in the case of low viscosity. However, when the fluid viscosity is increasing, the solidification point decreased adversely; the impact of microparticles gradually disappeared. Furthermore, the height of the absorption peak and the phase change enthalpy reached the maximum without the thickener and gradually decreased after adding the thickener. This is because the fluid viscosity affects the

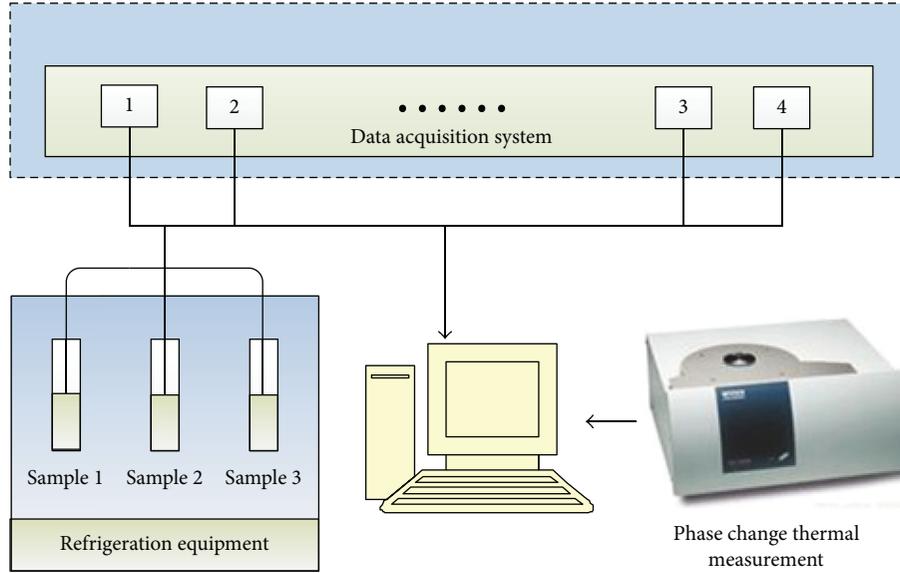


FIGURE 2: Schematic diagram of the experimental system.

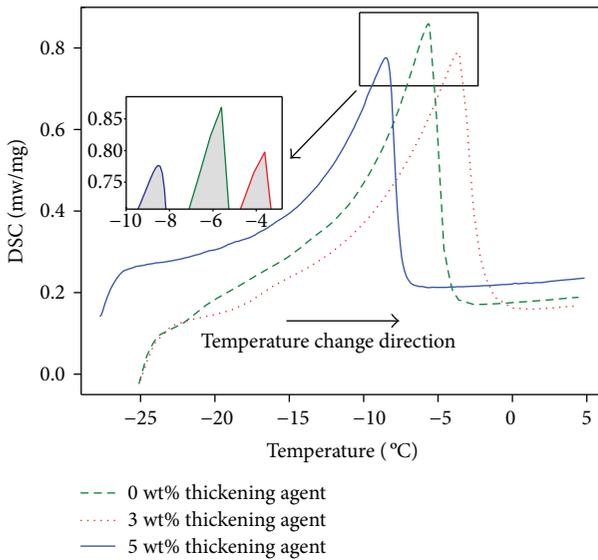


FIGURE 3: DSC curves of eutectic hydrate salt with three different amount of thickening agent.

convective heat transfer performance within the fluid. When the viscosity of the fluid increases, the effect of the microconvection of the fluid and the particles which can enhance heat conduction is gradually suppressed.

From Table 3, it is clearly observed that the onset temperature of the three samples is  $-11.9$ ,  $-10.6$ , and  $-14.8^{\circ}\text{C}$  while the end temperature is  $-4.6$ ,  $-2.3$ , and  $-7.5^{\circ}\text{C}$  separately. The peak temperature of the three sample is  $-5.0$ ,  $-2.4$ , and  $-8.3^{\circ}\text{C}$  in turn. By calculating the DSC phase change area which is divided by the phase change DSC curve and the onset/end baseline, it is concluded that the phase change enthalpies of the three samples are  $127.2$ ,  $118.6$ , and  $82.56\text{J/g}$ , respectively. Compared with similar studies [9], this material has an edge in storage ability.

TABLE 3: DSC measurements.

Data items	Thickener (wt%)		
	0	3	5
Area (J/g)	82.56	118.6	127.2
Peak sample temperature ( $^{\circ}\text{C}$ )	$-8.3$	$-2.4$	$-5.0$
Onset temperature ( $^{\circ}\text{C}$ )	$-14.8$	$-10.6$	$-11.9$
End temperature ( $^{\circ}\text{C}$ )	$-7.5$	$-2.3$	$-4.6$

TABLE 4: Melting latent heat of water and three samples.

Material	Melting latent heat (kJ/kg)
Ice	335
Hydrated salt with 0 wt% thickener added	127.2
Hydrated salt with 3 wt% thickener added	118.6
Hydrated salt with 5 wt% thickener added	82.56

Table 4 shows the melting latent heat change of the three samples with different additions of the thickener. It is not difficult to find that the melting latent heat of cold storage materials was reduced by 62%, 64.6%, and 75.3% as compared with ice. The increase of viscosity will reduce the heat absorption amount, thereby affecting the cold storage ability. Therefore, the thickener needs to be controlled in a suitable amount.

*3.2. The Nucleation and Supercooling Characteristics of Hydrated Salt PCM.* Supercooling is a process closely related to the crystallization process. Before the temperature returns to the original freezing point, the liquid solidifies below its normal freezing point and continues to decrease until complete solidification. When the degree of supercooling increased, the degree of the deviation from the equilibrium

state has risen, and the critical dimension of the ice core and the formation energy also decrease dramatically, which ultimately increases the probability of forming the nucleus. Calculating the absolute degree of supercooling following relation was used to measure the thermal storage performance of materials:

$$T_{sc} = T_m - T_s, \quad (2)$$

where  $T_{sc}$ ,  $T_m$ , and  $T_s$  represent the supercooling degree, melting point, and solidification temperatures, respectively.

The supercooling degree was measured by temperature change curves during the cooling process by putting a thermocouple at the three sample's center separately. During the solidification and crystallization process, the general liquid crystal is divided into the stable region (noncrystalline), substable region, and unstable region as shown below in Figure 4. Crystallization phenomenon only occurred in the unstable area. The viscosity and temperature change of the inorganic hydrated salt are both important factors which affect the nucleation.

Figure 5 shows four hydrated salts of different viscosities without adding the nucleating agent. The three-step cooling curve of ternary hydrate salt solution with different viscosities can be obtained to observe the supercooling. Comparing the four curves, the recovery process after the reduction of the temperature curve gradually decreases during the solidification process with the increase of the viscosity, which can consider that the supercooling is gradually reduced. This is because the increase in liquid viscosity will affect the diffusion of the fluid, reducing the driving force of crystallization, and thus, the supercooling is suppressed. Therefore, increasing the fluid viscosity will not only reduce the latent heat of phase transformation but also improve the stability of the phase transition and reduce the degree of supercooling. When the inorganic PCM is applied to the practical application, the viscosity should be appropriately increased to find a middle value of the best performance.

**3.3. The Physical Characteristics of Hydrated Salt PCM.** In this experiment, the characteristics of the fluid itself were significantly changed with a constant increase in viscosity. From Table 5, we can find that ternary hydrate salt itself is more viscous than water whose viscosity is 2.04, 6.3, and 8.77 mpa·s, respectively. The viscosity of three solutions with 1.5, 2.5, and 3 wt% nucleating agent added was changed by adding a thickener. Results show that the salt solution with higher viscosity has a relatively lower degree of supercooling.

Figure 6 shows that the degree of supercooling is almost eliminated with the thickener and nucleating agent added simultaneously. It was seen that both the nucleating agent and the thickener have a dampening effect on supercooling. However, the amount of thickener should not be too much; otherwise, the heat capacity will drop dramatically; this is not economical. Therefore, rationally, selecting the amount of nucleating agent and thickener is improving the cold storage performance of inorganic solution better.

Figure 7 shows the mass fraction solidified at various time intervals during the solidification process with 0, 3, and 5 wt% thickeners added, respectively. Solidification time is

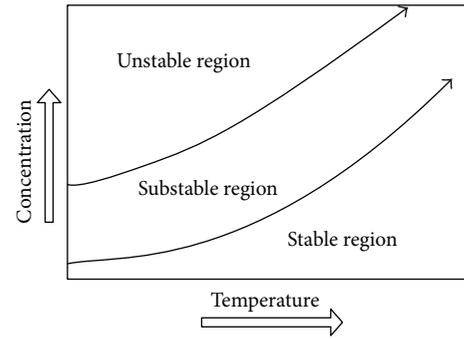


FIGURE 4: Supersaturation and super solubility curves of the solution.

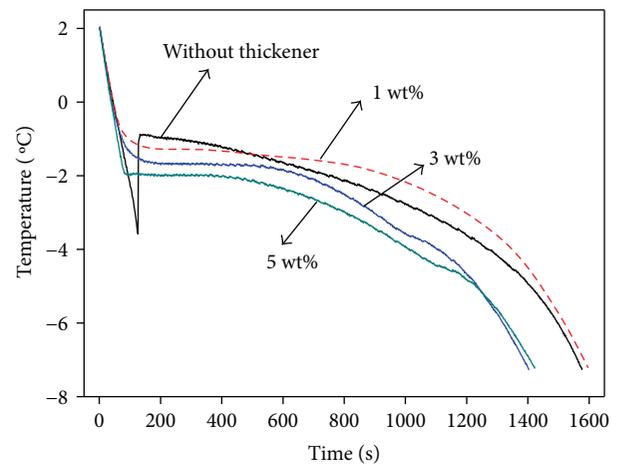


FIGURE 5: Step cooling curves of adding 1, 3, and 5 wt% thickeners in the solution without the nucleating agent.

TABLE 5: Viscosity of water and hydrated salts.

Material	Viscosity (mpa·s)
Ice	1
Hydrated salt with 0 wt% thickener added	2.04
Hydrated salt with 3 wt% thickener added	6.3
Hydrated salt with 5 wt% thickener added	8.77

also an important parameter which was used to measure the response time of a cold storage system. Under the same phase change enthalpy and time, storage medium which reached a higher percentage of solidification earlier has the quality to start next phase change circulation quickly, so as to improve the energy storage efficiency. It has been noted from Figure 7 that the solidification started about 40 minutes later from the start of the experiment and the hydrated salts with 5 wt% thickener appear crystal firstly, followed by the sample with 3 wt% thickener added. The above two samples began to appear crystal almost at the same time, only the sample without thickener crystallized slower which started at about 50–55 minutes. The crystallization rate of the three samples was also different in the solidification process. From

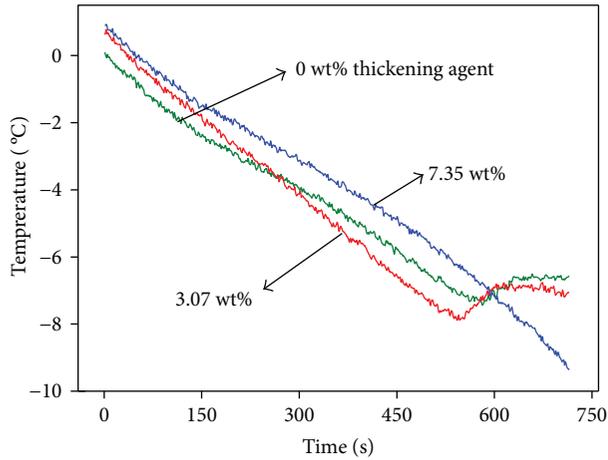


FIGURE 6: Step cooling curves of adding 0, 3.12, and 7.46 wt% thickeners and 2.5 wt% nucleating agent in the solution.

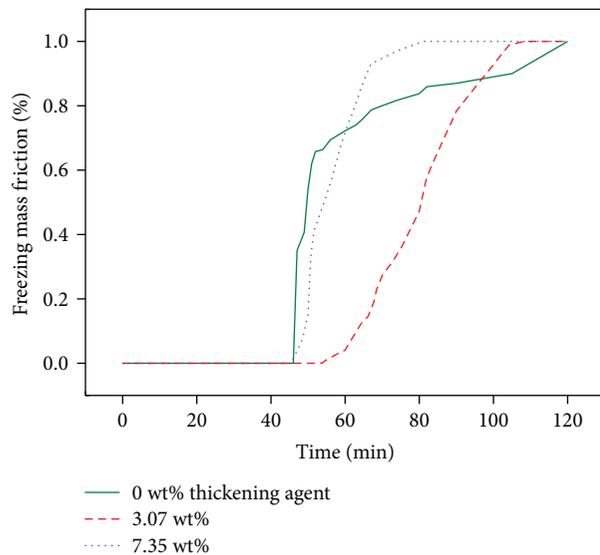


FIGURE 7: Solidification mass fraction curve of three samples with different nucleating agents added.

45 to 50 minutes, the sample with 3 wt% and 5 wt% thickeners added had the similar crystallization rate. However, the crystallization rate of the sample without adding a thickener was obviously slowed down while the rate of the other two samples kept stable all the time. Finally, the time of the complete solidification of these three samples was about 120, 100, and 75 minutes, respectively. It can be concluded that the increase of the viscosity of the cold storage fluid can effectively shorten the time of the complete solidification of the material. This is because the solidified PCM offers increasing thermal resistance between the solidified PCM and the surrounding heat transfer fluid as the freezing front moves away from the surface. From the previous conclusion, it is drawn that viscosity has the same effect on the storage capacity of phase change materials, so the viscosity selection should ensure both the storage capacity and the solidification rate at a right value.

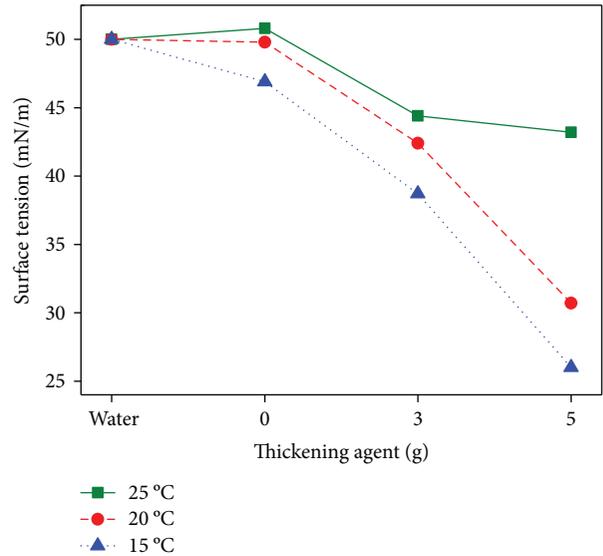


FIGURE 8: Surface tension of three samples within three different temperatures.

The viscosity of the hydrated salt affects not only the internal thermophysical properties of the fluid but also the properties of the fluid surface. Figure 8 shows the variation of surface tension change of hydrated salts and single water. It was found that the surface tension of hydrated salt is lower than that of the water, and the surface tension decreases as the viscosity increases gradually. This is due to the fluid with larger viscosity which has higher surface shrinkage resistance. In addition, the effect of temperature on the surface tension is very obvious; the surface tension decreases with the increase of temperature. This is because the increase of liquid temperature leads to the increase of molecular internal energy and the decrease of interaction force between molecules. Owing to the surface tension which originates from the attraction between molecules on the surface of the liquid, the decrease of attractive force leads to the decrease of surface tension.

**3.4. The Influence of Different Nucleating Agents to Hydrated Salt PCM.** In the above test, it was found that the supercooling phenomenon is a serious defect of the inorganic phase change material. Through many studies of the nucleation mechanism, it is proved that the supercooling also improved effectively by adding a nucleating agent. According to the crystal nucleation theory, for homogeneous nucleation process, the formation of the crystal needs to be larger than the critical size of the particles, but for heterogeneous nucleation, the surface affinity should also be considered [26]. Nevertheless, the effective crystallization depends on the value of the surface free energy. The aim of adding nucleation agent in the solution is to increase the surface affinity or to reduce the critical dimension so that the surface free energy is reduced. From Figure 9(c), it was discovered that the degree of supercooling ranges from about 3°C to 1.5°C as the mass fraction of  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$  increases from 1.5 wt% to 3 wt%. Therefore, sodium tetraborate is an ideal agent for

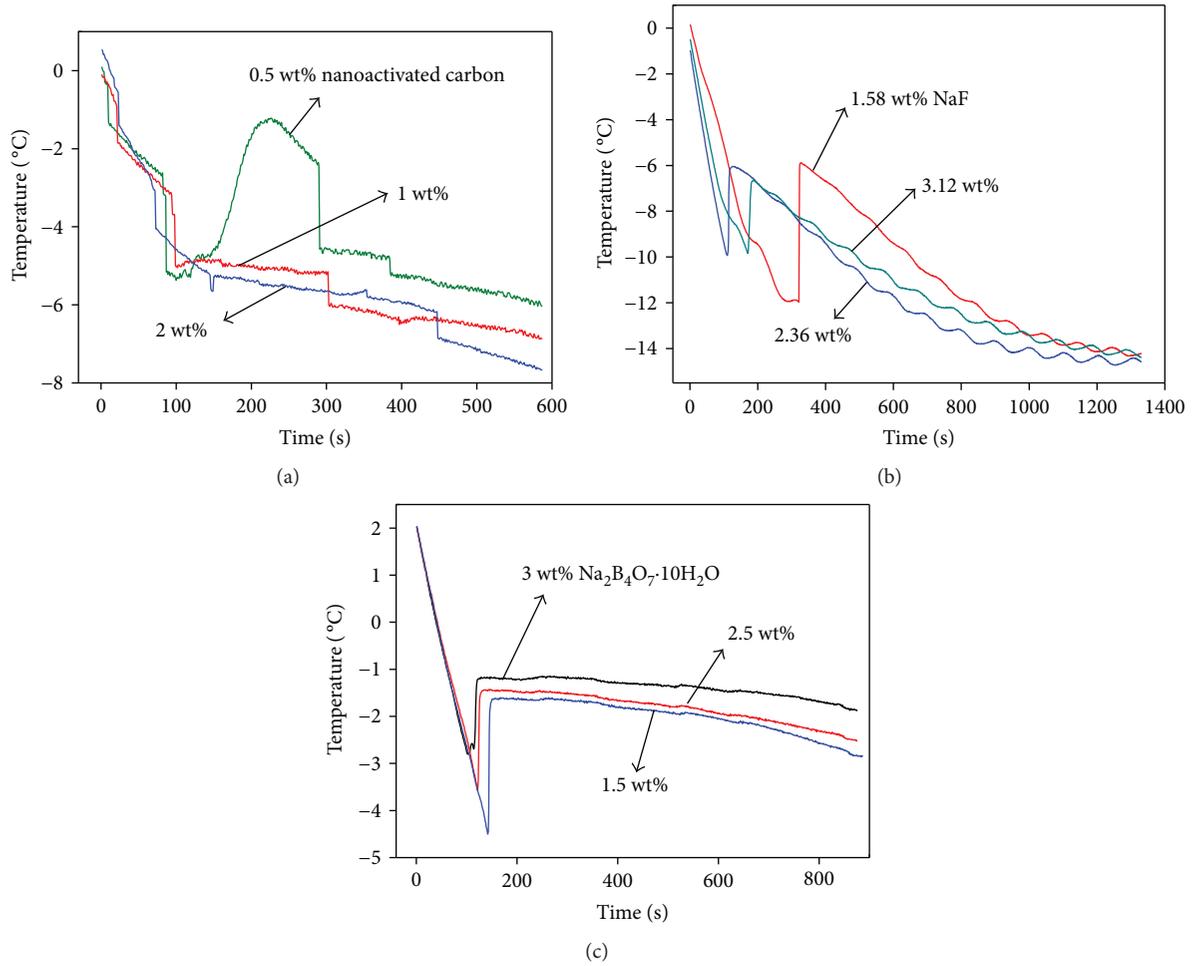


FIGURE 9: (a), (b), and (c) represent step cooling curves of adding three different kinds of nucleating agent (nanoactivated carbon, NaF, and  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) in ternary eutectic hydrate salts without a thickener.

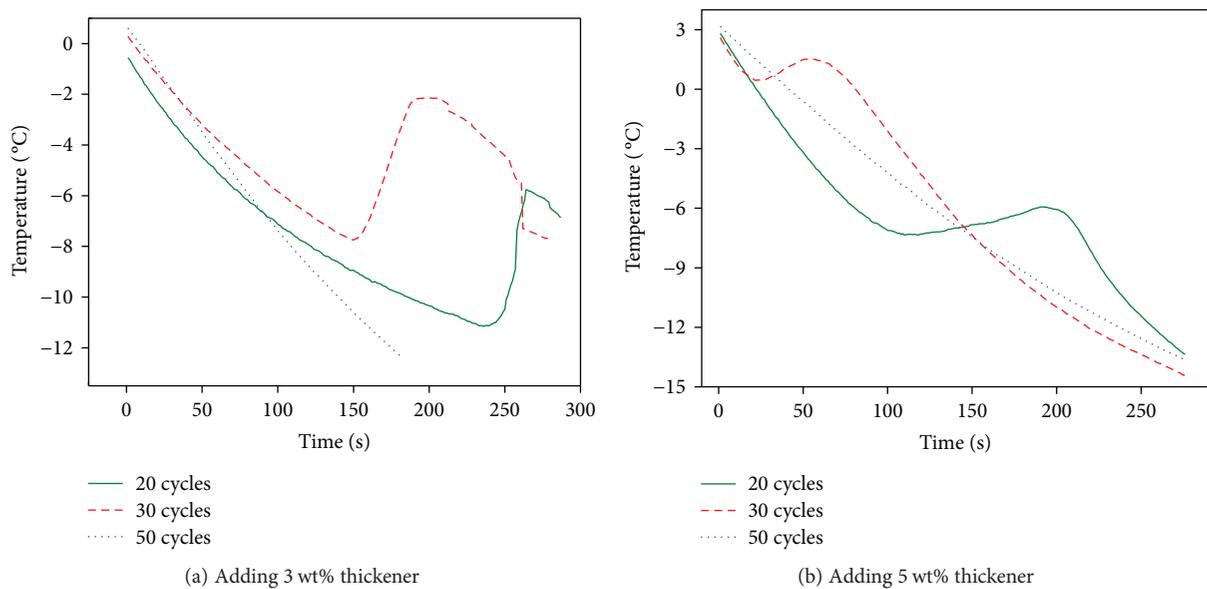


FIGURE 10: (a) and (b) represent the change of step cooling temperature curve after 20, 30, and 50 freeze-thaw cycles.

the inhibition of the supercooling. In order to further study the influence of nucleating agent on inorganic phase change materials, two other nucleating agents were chosen and three different proportioning were selected to add to the HSPCMs. In Figure 9(a), 0.5, 1, and 2 wt% nanoactivated carbon particles with a particle size of 100 nm were separately added into the ternary eutectic hydrate salts. It was seen that the addition of 0.5 wt% particles cannot inhibit the supercooling obviously. With the increase of the content of nanoparticles, the degree of supercooling is almost zero. Through the analysis of Figure 9(b), the amount of nucleating agent NaF added is 1.5, 2.5, and 3 wt%; when the 3 wt% NaF is added, the degree of supercooling is almost half of that of 1.5 wt% and the total supercooling degree is reduced to about 3°C, so the effect is remarkable. Then, increasing the content of the same kind of nucleating agent, the effect almost remains unchanged, compared to the result curve of the three nucleating agents. It is found that an excessive dose of the nucleating agent does little influence to the inhibition of supercooling and these three different nucleating agents all reduced the supercooling significantly. Adding inorganic salt, hydrated salt and nanoparticles all contribute to the nonhomogeneous nucleation.

**3.5. Thermal Cycling Test of Hydrated Salt PCM.** When using a cold storage material, life span is an important factor to measure the stability. In this experiment, adding a thickener in inorganic hydrated salt is an effective method to enhance the working life of materials and prevent phase separation phenomenon. The salt solution which was added 3 wt% and 5 wt% thickeners still maintained good stability, and there was no obvious phase separation phenomenon. However, a thin layer of crystal at the bottom after about 10 times of freeze-thaw cycles in the salt solution without a thickener appeared. As the freeze-thaw cycles continue, crystal thickness was increased, which severely affected the cold storage characteristics of the salt solution. After stirring or heating, the sample changed back to its initial state and no rapid degradation or irreversibility was observed. Therefore, to avoid the shortcoming of the phase separation mentioned above, the mixture can be stabilized by adding a thickener.

Figure 10 shows that the HSPCMs showed better stability as the number of freeze-thaw cycles increased. The cooling curve changed from an undulating curve into a smooth decline gradually after 50 or more cycles. The performance of the phase change material was more stable, and the supercooling phenomenon will also be reduced gradually. PCM is easier to crystallize than never to solidify due to the residual crystal which is not completely melted during the last process which will reduce the required energy of the next crystallization process during freeze-thaw cycles.

## 4. Conclusions

This experimental study was conducted on the preparation, modification, and characterization of a new ternary eutectic of inorganic salt hydrate phase change materials with 0, 3, and 5 wt% thickeners added into salt hydrate solution, and the effect of viscosity and nucleating agents on the

thermophysical properties and cold storage ability of PCM was measured by DSC and temperature acquisition system. The results of this study can be summarized as follows:

- (1) The increase of the viscosity will reduce the phase change enthalpy, which reduces the storage capacity. Meanwhile, the phase stability, supercooling, and phase separation will be significantly improved.
- (2) NaF,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ , and nanoactivated carbon were all proved to be effective nucleating agents. With the increasing content of a nucleating agent, the degree of cooling can be obviously reduced or even eliminated.
- (3) During the stability test of the inorganic material, the supercooling of inorganic materials will become smaller after 20, 30, and 50 freeze-thaw cycles.

## Nomenclature

$T_{sc}$ :	The degree of supercooling
$H_m$ :	Heat flux
$H_p$ :	Melting phase change enthalpy
$T_m$ :	The melting point temperature
$T_s$ :	The freezing point temperature
AR:	Analytically pure reagent
CP:	Chemically pure reagent
DI:	Deionized water
PCM:	Phase change materials
HSPCM:	Hydrated salt-based PCMs
STA:	Simultaneous thermal analyzer
XRD:	X-ray diffraction
DSC:	Differential scanning calorimeter.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

This work is financially supported by the Fundamental Research Funds for the Central Universities (Grant no. 2014QNB05).

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