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A Controlled Conditions of Dynamic Cold Storage Using Nano Fluid as PCM

Bin Liu[1], Zhaodan Yang[1], Yahui Wang[1] and Rachid Bennacer[1,2]

Abstract: The dynamic thermal history of storage product system is related to the insulation and also to the inertia. Use a new porous media doped with nanofluid PCM to improve the system efficiency. The analysis of the porous sponge thickness with 8 mm, 16 mm and 20 mm, the integrated nanofluids with 0.1%, 0.15% and 0.2%, the mass of the PCM and the initial temperature of the stored product with -1°C, 4°C, 12°C is achieved in order to underline the advantages of the new saturated porous media (sponges) with the phase change material (PCM) /Al_2O_3-H_2O nanofluid. The carrots are used as the experimental object in the experiments by orthogonal method. And the integral value of average temperature of the air in the box is an index to judge the effect of cool storage. The transportation temperature and duration are mainly affected by the pre-cooling temperature of products, the storage materials, the nanofluids mass fraction, the thickness of porous sponge. Compared with range values, the optimal combination of all the factors for the effect of cool storage is as following: the thickness of porous sponge of 20 mm, the mass fraction of 0.2%, the mass of cold storage materials of 0.4 kg, and vegetables pre-cooling temperature of 4°C. Under constraint of mass (or volume) transportation we demonstrate that the thickness of sponge of 16 mm instead of 20 mm, and nanofluids mass fraction of 0.15% instead of 0.2% could be enough. The equivalent variable is defined basing on theoretical basis to interpret the experiment and analysis.

Keywords: Al_2O_3-H_2O nanofluids, Phase change material (PCM), cold storage.

Nomenclature

m	The mass of phase change of PCM, kg
m_1	Air mass in the cold storage tank, kg
c_p	Specific heat of the air, J/(kg·°C)
A	Area of heat exchange, m^2
V	The volume of air in the container, m^3
T_A	Ambient temperature, °C
T	Air temperature in the chamber, °C
T_m	Temperature of the cool storage material, °C
h_a	The heat transfer coefficient of PCM with the air in the tank, J/(m^2·°C)

[1]Tianjin Key Lab of Refrigeration Technology, Tianjin University of Commerce, Tianjin, P.R.C., 300134.
[2]ENS-CachanDpt GC / LMT, 61 Av du Président Wilson 94235 CachanCedex, France.

f	Respiration heat, J/s
U	Inner energy, J/kg
Greek Symbols	
τ	Time, s
ρ	Mass density, kg/m^3

1 Introduction

The refrigerated transportation is vital for the food cold chain, which can prevent or slow down the microbial growth and the nutrient loss in vegetables and fruits [Eduard, Miró, Farid et al. (2012); Frias, Luo, Kou et al. (2015)]. Generally, the mechanical refrigeration method is used in the transportation. It is good suitable for a long-distance transportation compared with the cool storage tank with phase change material (PCM), but the latter does not need to install the refrigeration equipment in the transport vehicle, and the use of PCM could enhance the efficiency in different low temperature applications. Besides, it is more economical than the former in the cases of the short-distance transportation and the small load. It is well known that the transport tank should be designed to keep a low temperature for a long time, and reduce the temperature fluctuations during transit [Oró L et al. (2012); Benjamin and Mohammed (2010); Smale (2006)]. So, it is required that the PCM must have good thermal conductivity and large phase change latent heat.

The chilled water is the most used among PCMs with high latent heat [Oró et al. (2012)]. However, water has larger degree of subcooling. So many researchers focus their interests on improving the thermal conductivity and reducing the subcooling degree of PCMs. Masuda et al found that the heat transfer coefficient of mixed liquor increased by 30% after adding Al2O3 nanoparticles with volume fraction of 4.3% to the water [H Masuda et al. (1993)]. After that, a large number of scholars began to study the physical properties of nanoparticles. Because of the well thermal properties, the nanofluids have aroused people's attention [Salman, Mohammed, Munisamy et al. (2013); Yimin and Wilfried (2000); Dhinesh and Valan (2016); Azmi, Abdul Hamid, Usri et al. (2016); Shahrui et al. (2016)]. Nanoparticle-enhanced phase change materials (NEPCM) could improve the thermal conductivity of the base materials [Khodadadi and Hosseinizadeh (2007)]. Compared with water, the complete solidification time of CuO nanofluids with 0.5 wt%, 1.0 wt%, 1.5 wt% and 2 wt% could be enhanced by 10.71%, 16.07%, 19.64% and 27.67%, respectively. And the complete melting timecould be enhanced by 7.14%, 14.28%, 25% and 28.57% [Harikrishnan and Kalaiselvam (2012)]. Because the effect of particle size fraction on heat transfer was obvious, it was required that the nanoparticles were distributed evenly and stably in the suspension [Rakib et al. (2015)]. In other words, the preparation of nanofluids is the first key step in applying nanoparticles to change the heat transfer performance of conventional fluids, and there are some effective methods of preparing the homogeneous suspensions, such as changing the pH value of the suspensions, using the surface activators or the ultrasonic [Yimin and Qiang (2000)]. Nevertheless, the aggregation and precipitation of nanoparticles are still easy to occur with time. Recently some people used nanodiamond (ND) attaching the magnetite (Fe_3O_4) nanoparticles and made Fe_3O_4 nanoparticles dispersed uniformly on the outer surface of the ND particles.

In order to reduce the aggregation and precipitation of nanoparticles and make them curing, the low-density sponge (porous media) is used to adsorb the nanoparticles, and the nano-PCMs are made into the cold transportation tanks. The 2 part of this paper shows that the sponge thickness, the mass fraction of nanofluid, the mass of PCM and the precooling temperature of the fruits and vegetables all influence the cold storage effect. In order to analyze the affecting factors of nano cool storage tank, this paper adopts the orthogonal test taking the carrot as the test object. The experimental index is the integral value of the temperature with time in the cold storage tank. This experiment will provide the theoretical basis for the later experiments and analyses, and give a theoretical reference for the storage and transportation of fruits and vegetables.

2 Energy analysis of cold storage transportation process

Eq. (1) gives the energy balance between the container and the environment during the transport.

The temperature in the tank is the average value of 10 measuring points taking the cold storage tank as the research object, and it is assumed that the temperature inside the cold storage tank is uniform at the same instant, and that the air is incompressible ideal gas due to the air flow rate lower than the 1/4 speed of sound.

$$\rho c_p V \frac{\partial T}{\partial \tau} = hA(T_A - T) + h_a A(T_m - T) + f(t) \tag{1}$$

With the increase of the mass fraction of Al2O3-H2O nano materials, the latent heat decreases and the ha increases [Heris et al (2006)]. The cool storage capacity increases with the increase of the mass of the cold storage materials. The respiration of fruits and vegetables is related to the precooling temperature. The distribution of temperature is affected by the volume fraction of the nanoparticles and the voids [Rakib et al. (2015)]. The thermal resistance increases and the h decreases with the sponge thickness increasing. So, from Eq.1 we can find that the key factors affecting the cold transportation are the sponge thickness, the precooling temperature of the bio-products (foods in the present case), the mass fraction of nanofluid and the mass of PCM.

3 Materials and methods

3.1 Method for preparing nanofluid and cold storage material

The Al_2O_3 nanoparticles (Hangzhou Wanjing New Material Co. Ltd, Hangzhou, Chin) with an average diameter of 20 nm were suspended in de-ionized (DI) water as a working base fluid preparing the four different mass fractions of 0.1%, 0.15% and 0.2%. The homogeneous nanofluids were obtained by mixing with a certain amount of dispersants SDBS, being stirred by the magnetic heating agitator (Jintan Zhongda Instrument Co. Ltd, 78-1) for 20 min, and then vibrated by the ultrasonic (Kunshan Ultrasonic Instrument Co. Ltd, KQ-200VDE) for one hour. After that, the nanofluids were poured into the different thickness sponges, which were sealed in plastic bags to form the new cold storage materials.

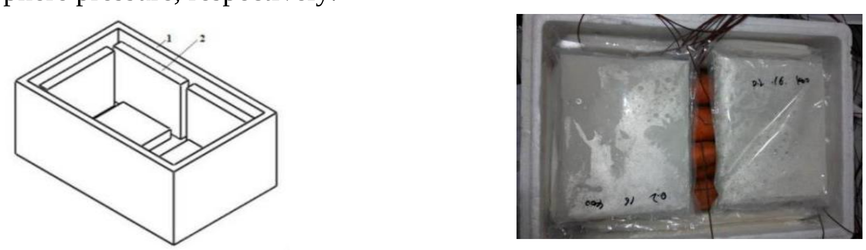
Physical parameters of the nanofluid were measured by Hot Disk thermal constant analyzer as shown in Table 1.

Table 1: Physical parameters of cool storage material

Physical parameters of cold storage materials	The mass fraction of particle in nanofluids/%		
	0.1	0.15	0.2
Conduction coefficient of liquid/W/(m·K)	0.58	0.63	0.75
Conduction coefficient of solid/W/(m·K)	0.35	0.36	0.37
Latent heat /kJ/kg	309	306	305

3.2 Container systerm

The polystyrene foam box with a storage volume of about 23.78 L (440 mm L×320 mm W×230 H×15 mm Thickness) was used in this study. One cool storage material bag was placed in the left and right sides of the box, and two cool storage materials bags were arranged in other sides of the box, respectively. The test device was shown in Figure 1. The bags should cover the cold biological products to maintain them at a low temperature and reduce the impact of ambient temperature. Before the test, the cool storage materials were placed into the cold storage of -10 °C to be frozen for 10 h. The vegetables used in the experiment were carrots, which were precooled for 12 min at -1°C, 4°C and 12°C at the atmosphere pressure, respectively.



(1) The EPS heat preservation box (2) Cool storage materials

Figure 1: The schematic diagrams of experimental setups

3.3 Test scheme

In the orthogonal experiments, we selected the following experimental conditions (Table 2) and the orthogonal experimental cases were summarized in Table 3.

Table 2: Factors and labels

factor \ label	1	2	3
A-thickness of sponge/mm	8	16	20
B-mass fraction of nanoparticles/%	0.1	0.2	0.15
C-mass of PCM/kg	0.35	0.4	0.3
D-precooling temperature/°C	12	4	-1

Table 3: Orthogonal experimental table

No.	factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The thermocouples were arranged for five in the corner and the center of the lower layer and upper layer of the box, respectively. The weight of the carrots was same in each box, and about 7 kg.

4 Results and discussion

4.1 Analysis of the integral value of test index

During the transportation, because the temperature of the carrots was affected by many factors, so the equivalent energy was defined to judge the performance of the cold transportation as Eq. (2) shown. The paper assumed that the cool storage materials and fruits and vegetables were the cold sources of air in the cold storage tank, and *x* stood for time.

$$Q_1 = \int_0^x c_p m_1 (T_A - T)\, d\tau = \int_0^x (U_0 - U) d\tau = \int_0^x U_0 d\tau - \int_0^x U d\tau \qquad (2)$$

The temperature range of the cold storage tank was mainly from -1.7°C to 12°C, and the specific heat capacity of air was assumed to be constant. Meanwhile, U_0 was a fixed value, so the equation was simplified as follow.

$$Q = \int_0^x T\, d\tau \qquad (3)$$

The integral value of formula (3) indicated the ratio of the sum of the internal energy from the initial time to the time *x* in the tank to the constant number $c_p \cdot m_1$. Therefore, the smaller the integral value, the better the cooling effect of the cold storage tank.

4.2 The temperature changes with time

Figure 2 showed the evolution of the air temperature in experiments. From Figure 2, it could be seen that the curves were divided into three stages, including the temperature decrease stage, the constant temperature stage and the temperature increase stage. At the beginning of the transportation, the temperature of the carrots would be reduced by the sensible heat of nanoparticle PCM with the temperature of -10°C. When PCM reached the phase change temperature, the temperature of air would be kept at a constant temperature. After that, the temperature of carrots increased continuously until the experiment was finished due to the heat transfer with the environment.

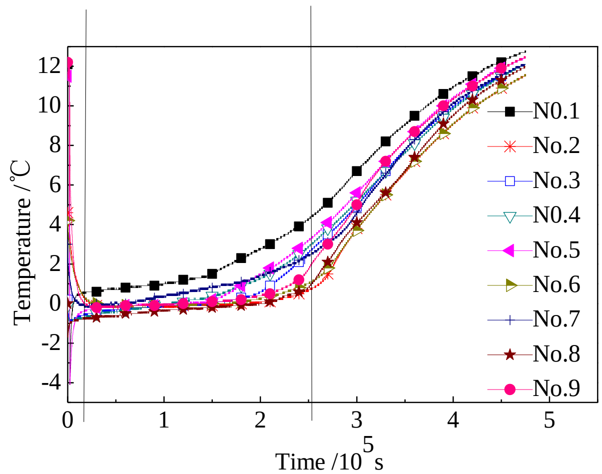


Figure 2: The change of the temperature inside the tank with time

Figure 3 showed the development of the equivalent energy during the transportation process. From Figure 3, it could be seen that the equivalent energy had a small increase in the first and second stages. Because the heat from the environment was absorbed by the PCM. While in the third stage, the equivalent energy increased quickly for the temperature increasing. The cases were ranked as 1>5>7>9>4>3>6>2>8 by comparing the value of the equivalent energy, which meant the condition in No.8 would be the best one among the 9 experimental conditions.

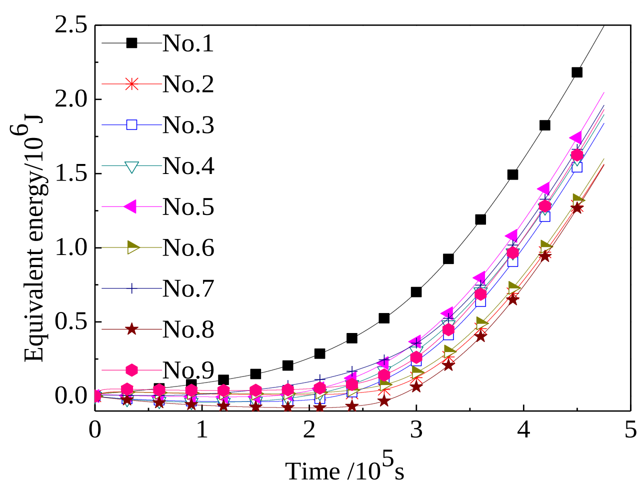


Figure 3: The equivalent energy during transportation

4.3 Analysis of orthogonal test results

At the end of the experiment, the integral value of each group and the range values (R) of the factors were shown in Table 3. From R, it could be concluded that the effect of the precooling was the largest, then, it was the mass fraction of nanoparticle, next it was the mass of PCM and the weakest effect was the thickness of sponge. When the mass fraction of nanoparticles and precooling temperature were changed, the index fluctuated greatly. But the index fluctuated weakly, when the thickness of sponge and the mass of PCM were changed. From Table 3, it also could be concluded that the optimal combination of all the factors for the effect of cool storage was as following: the thickness of porous sponge of 20 mm, the mass fraction of 0.2%, the quality of cold storage materials of 0.4 kg, and vegetables pre-cooling temperature of 4°C.

Table 3: the orthogonal experimental results

No.	factors				Equivalent energy
	A	B	C	D	
1	1	1	1	1	2496760.5
2	1	2	2	2	1564467.5
3	1	3	3	3	1839958.5
4	2	1	2	3	1897860.0
5	2	2	3	1	2047931.5
6	2	3	1	2	1601613.0
7	3	1	3	2	1961757.5
8	3	2	1	3	1559234.0
9	3	3	2	1	1931904.5
K_1	5901186.5	6356378.0	5657607.5	6476596.5	
K_2	5547404.5	5171633.0	5394232.0	5127838.0	
K_3	5452896.0	5373476.0	5849647.5	5297052.5	
R	448290.5	1184875.0	455415.5	1348758.5	

Note: K_i (i=1,2,3), It is the sum of index of the same label of each factor. And the subscripts i is the ith label of each factor. R is the difference between maximum and minimum values.

4.4 The influence of various factors on the integral value

From the values of K, four conclusions were given as follows:

Firstly, the integral value decreased with the sponge thickness. It indicated that the increasing sponge thickness enhanced the cold storage effect. At the same time, it could be seen that the integral value of the sponge thickness of 20 mm was close to that of 16 mm. So, the sponge thickness of 20 mm could be replaced by 16 mm economically.

Secondly, the effect of cold storage was improved with the increase of mass fraction of nanofluids. The integral value of mass fraction of 0.2% was approximately equal to that of 0.15%. The reason probably was that some nanoparticles completely were confined to the sponge, or aggregated into groups with the mass fraction of 0.2%.

Thirdly, the effect of cold storage was improved with the increase of the mass of PCM. Because the cooling time would be longer. If the mass of PCM was too big, the weight of the cold storage tank would increase leading to the high handling and transportation cost. When the load was constant, it had effect on the load of fruits and vegetables.

Finally, the optimal pre-cooling temperature was 4°C. The reason why the effect of 4°C was better than that of -1°C was as follows: Firstly, although the metabolic heat of fruits and vegetables, breathing heat and a variety of heat were related to the temperature, when the temperature was low enough, the effect of temperature on heat was little. The breathing intensity of fruits and vegetables was not proportional to their temperature. Secondly, the temperature of the fruits and vegetables reduced, when the precooling temperature decreased. Meanwhile, the temperature difference between the outside and inside would increase, so the heat flux would be enhanced accordingly, and the effect was not necessarily good.

5 Validation of the results of the optimal level test

Adding the optimal level as the 10th group and taking the level with sponge thickness 16 mm, nanofluid mass fraction of 0.15%, the mass of PCM of 0.4 kg, and precooling temperature of 4°C as the 11th group, the other conditions were same as the other 9 groups. The temperature was measured during the storage, and the integral values were calculated. The experimental results were shown in Figure 4 and Figure 5.

From Figure 4 and Figure 5, it could be concluded that the tenth and eleventh groups of the constant temperature stage significantly were better than the other groups, and the time of the constant temperature stage was about 3.35×10^5 s (93 h). At the end of storage, the integral value was smaller than the other 9 groups. Therefore, the experimental results showed that the optimal level was the thickness of porous sponge of 20 mm, nanofluid mass fraction of 0.2%, the mass of cold storage materials of 0.4 kg, and precooling temperature of 4 °C.

From Figure 4, the temperature and the time during the constant temperature stage (0~2°C) of the group 10 and the group 11 had a little difference, and the temperature difference between the two groups was 0~0.6°C in the temperature rising stage.

From Figure 5, it could be seen that the difference of integral value between the two groups at the end of the experiment was about 1×10^5 J. So, the experimental thermal insulation effect of the two groups was nearly same. Therefore, the porous sponge of 16 mm could be used instead of 20 mm, and the mass fraction of nanofluids of 0.15% instead of 0.2% economically.

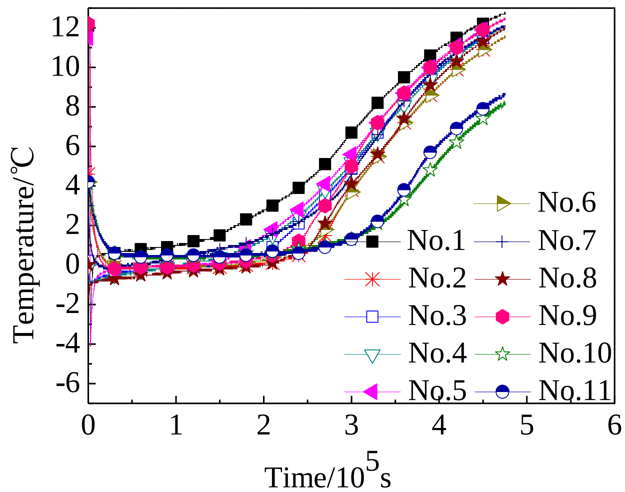


Figure 4: The change of inside temperature with time

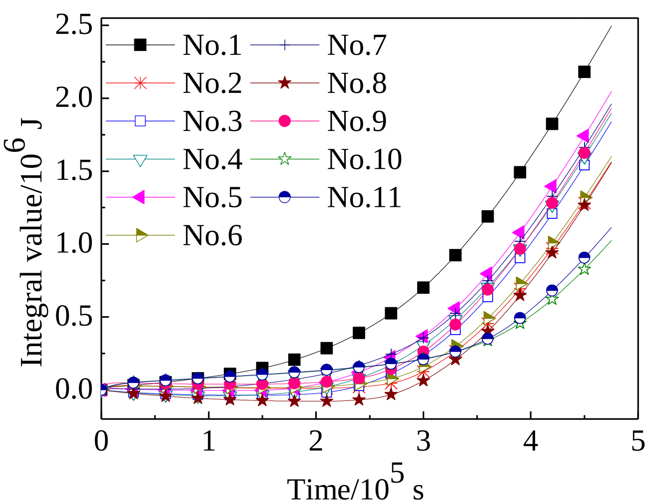


Figure 5: The change of integral value with time

6 Conclusion

The transportation temperature and duration are mainly affected by the pre-cooling temperature of products, the mass of cold storage materials, nanofluids mass fraction, the thickness of porous sponge. It is found that the optimal precooling temperature is 4°C. The integral value decreases with the sponge thickness, the nanofluids mass fraction and the mass of PCM increasing. The optimal combination of all the factors for the effect of cool storage is as follows: the thickness of porous sponge of 20 mm, the mass fraction of 0.2%, the mass of cold storage materials of 0.4 kg, and pre-cooling temperature of 4°C. Under constraint of mass (or volume) transportation we demonstrate that 16 mm porous sponge instead of 20 mm, and nanofluids mass fraction of 0.15% instead of 0.2% could be enough.

An equivalent variable is defined based on theoretical basis for a better analysis in this paper.

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