Experimental study on cold storage phase-change materials and quick-freezing plate in household refrigerators

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Abstract In this study, a low-temperature phase-change material (PCM) and a quick-freezing plate filled with the material applied in household refrigerator were developed. A calculation model of the storage capacity of the PCM was established, and air blast freezing and quick-freezing plate methods were compared experimentally. An NH_4Cl solution with a mass fraction of 15% was successfully used as PCM for quick-freezing plates in household refrigerators. A household refrigerator freezing chamber with a single smooth quick-freezing plate significantly reduced the amount of time required for food to pass through the maximum ice crystal generation zone, and this amount of time was 1/6 or 3/5 of that for the refrigerator without a quick-freezing plate in natural convection or air blast freezing. The rate of water loss when air blast freezing was used was 4.26%, whereas that when the quick-freezing plate was used was only 1.60%.

Keywords cold storage phase-change material (PCM) quick freezing plate refrigerator

Nomenclature

M_p, amount of phase-change material (PCM, kg)
M_f, maximum amount of pork for quick freezing in a plate freezer with PCM (kg)
C_f, specific heat of pork at 15.6 °C (kJ kg^{-1}°C^{-1})
t_f, initial temperature of pork before quick freezing (°C)
t_{ice}, temperature of ice crystal formation (°C)
H, latent heat of phase change of PCM (kJ kg^{-1})

1 Introduction

Quick freezing has long been recognized as a preferred food preservation method for the maximum retention of the natural color, appearance, flavor, nutritional value, and other properties of food. This process facilitates the rapid freezing of food such that only small ice crystals are formed. Consequently, the time required to pass through the zone of maximum ice crystal formation is reduced, and recrystallization of water and damage (squeezing or rupturing) to cell membranes are avoided [1].

Commercially frozen foods are usually "quick frozen" by using various equipment, such as plate freezers, blast freezers, cryogenic freezers, and fluidized freezing beds [1].

With regard to plate freezers, Cao et al. [2] introduced a fluid supply system for ejector throttling in plate freezers. They investigated two types of fluid supply systems in terms of freezing time, overall energy consumption, and uniform temperature distribution and compared them with the fluid supply system of a thermodynamic expansion valve. The results showed that the freezing time of the fluid supply system of the ejector in this working condition is 14% shorter than that of the thermodynamic expansion valve. Power consumption was reduced by shortening the working time of the compressor, condenser, and other equipment. Dopazo [3] performed an experimental analysis of freezing processes by using a horizontal plate freezer with CO_2 as the refrigerant. CO_2 was supplied from an experimental CO_2/NH_3 cascade refrigeration system facility with 9 kW refrigeration capacity at −50 °C. The experimental facility, data acquisition system, and experimental methodology were described. The experimental results included the temperature evolution of the product to be frozen, CO_2 evaporating temperature, and freezing times. The results showed a link between freezing time and CO_2 average evaporating temperature. The observed trend showed that a temperature reduction of 1 °C causes a reduction of approximately 2 min in freezing time. The experimental results also included the refrigeration capacity of the facility, the electric power of compressors, and the cascade system COP. The refrigerant evaporated in the plate freezer to achieve quick freezing of food. The plate itself is equivalent to an evaporator. If a refrigerator is to be used in this manner, a flat evaporator must be set up for the refrigerator. Considering that the start of the refrigerator compressor is controlled by the set temperature of the freezing chamber, the problem is that when food needs to be frozen quickly when placed in the refrigerator, the temperature of the refrigerator freezing chamber may still be within the set temperature range, and the compressor may not work, which will prevent the plate evaporator from producing refrigerant evaporation achieving quick freezing.

With regard to blast freezers, the effects of cryogenic and air blast freezing techniques on the quality of catfish fillet during frozen storage were evaluated in a previous study by using blast freezers. Fresh channel catfish fillets were cryogenically frozen with liquid CO_2 using a pilot plant-size cabinet-type cryogenic freezer or by air blast freezing to −21 °C. The cryogenically frozen catfish fillets presented better quality characteristics than the blast-frozen catfish fillets after six months of storage [4]. Air blast freezing is a conventional quick-freezing technique, in which vigorous circulation of cold air enables moderate freezing. Household refrigerators have been the main devices for household food storage in recent years, and several manufacturers have enhanced the function of quick freezing by air blast freezing. However, this approach is limited by the high energy consumption of refrigeration systems at low cooling medium temperatures and high rates of water loss.

With regard to cryogenic freezing, Cui et al. [5] investigated the changes in the quality of *Trichiurus haumela* under −10 °C, −20 °C, and −30 °C and found that a low temperature is suitable for preserving the fresh-like characteristics of food because of the short period required for food to pass through the zone of maximum ice crystal formation. Tan et al. [6] adopted high-pressure CO_2 quick-freezing technology, which allows food to pass through the zone of maximum ice crystal formation within 2–3 min. However, the devices used in this technology cannot meet domestic needs because the freezing chamber temperature of a domestic refrigerator is between −24 °C and −18 °C. Although cryogenically frozen food exhibits excellent quality characteristics, cryogenic freezing is unsuitable for quick freezing using a household refrigerator because of the high operation cost.

With regard to fluidized freezing, Xu et al. studied the effect of liquid nitrogen fluidized-bed freezing and obtained the shortest freezing time at approximately −40 °C [7]. Zeng et al. [8] presented an improved quick-freezing device in which the food to be frozen is packed in a plastic bag and immersed in a tank filled with a sodium chloride solution. This approach can significantly reduce the heat transfer resistance between the food and cooling medium, but it is expensive and presents a potential safety hazard.

Freezing time is the most important parameter in evaluating the effect of quick freezing [9–13]. Salvadori et al.[9] proposed a simplified analytical method for predicting the freezing time for unpackaged frozen food. The prediction equation was simple, and the results showed better accuracy than the simulated results under usual freezing conditions for different products. Becker et al. [10] reviewed semi-analytical/empirical food freezing time prediction methods applicable to regularly shaped food items (flat, column, and ball). The performance of these methods was evaluated by comparing their results with experimental freezing time data. Guan et al. [11] and Yin et al. [12] derived finite-difference equations for flat food items through the element balance method. The simulated results were in excellent agreement with the experimental results. Tu et al. [13] reported that the factors that affect freezing time include food thickness and room temperature.

Several quick-freezing technologies, such as high-pressure freezing, dehydrofreezing, and ultrasound-assisted freezing (UAF), have been independently investigated [14–22]. High-pressure freezing promotes instantaneous and homogeneous ice nucleation in fruits and vegetables. Dehydrofreezing reduces damage to plant texture by removing a part of water before freezing. UAF is effective in initiating nucleation and the subsequent growth of crystals. The effects of ultrasound irradiation temperature and ultrasound intensity on freezing and nucleation in strawberry samples have also been examined. In a previous study, the application of ultrasound irradiation at different temperatures induced nucleation with a lower degree of supercooling than that of the control samples [15]. In another study, the application of power ultrasound during immersion freezing significantly affected the freezing rate of mushrooms. Ultrasound at 0.39 W cm^2 (20 kHz) resulted in the highest textural hardness values in the three mushroom varieties tested. Polyphenol oxidase and peroxidase enzymatic activities were also significantly reduced by the increase in ultrasound power during UAF. These results indicate that UAF is a suitable technology for the industrial freezing of mushrooms [16].

These novel freezing technologies form small and uniform ice crystals. However, these technologies are not widely applied because of issues in reliability and operation cost [14].

The short literature review above indicates that several practical quick-freezing methods are mainly based on low-temperature thermal conduction (fluidized freezing beds with −40 °C), blast freezers (with −21 °C), and low-temperature convection cooling (cryogenic freezing with CO_2 quickly freezing). These methods are all based on spending the smallest amount of time in the ice crystal generation zone. Maria et al. [23] reported that the evaluation index for the experimental effect is time (i.e., time of maximum ice crystal formation) from 0 °C to −5 °C.

When the ambient temperature is low, the amount of time required to pass through ice crystals is small, and this amount of time is determined by the difference in the heat transfer temperature of the frozen food and ambient temperature. Although the ambient temperature of a quick-freezing system is low and its quick-freezing effect is good, its energy efficiency is reduced and its energy consumption is increased. In this study, a cold storage plate for a refrigerator freezer was built. The quick-freezing effect can be equivalent to that of blast freezing if food thickness does not exceed the specified range. However, the energy consumption and the water loss of food is reduced.

In this study, a new quick-freezing plate with a phase-change material (PCM) was developed specifically for a domestic refrigerator. A patent was recently granted for a domestic refrigerator with a hollow plastic plate (similar to a drawer) filled with a cold storage material for quick freezing [24]. However, this refrigerator presents several drawbacks, such as difficult and costly manufacturing of the quick-freezing box, possible contamination of food due to the leakage of the cold storage material caused by incorrect sealing or defects, and large and heavy boxes [24].

The plate in this study consisted of an aluminum lid, a plastic shell, a cold-storage agent, and a cold-storage bag. The rate at which the temperature of food is reduced is critical in quick freezing. From a thermodynamic perspective, food releases a large amount of heat during freezing because of latent heat transfer. Placing food on a cold-storage freezing plate facilitates heat exchange between the food and cold-storage material, enabling the food to quickly pass the zone of maximum ice crystal formation [23]. This procedure can also lead to increased conduction and heat transfer from the food on the aluminum lid to the environment.

2 System description

The proposed cold-storage plate is shown in Fig. 1. The lid is attached to the plastic shell, and the cold-storage material is stored in a bag glued to the back of the lid. The plate is advantageous because it is simple to manufacture, small, lightweight, and inexpensive. The cold-storage material is enclosed in the bag to avoid leakage. The cold-storage material completed the cold storage cycle when the storage plate was placed in the refrigerator freezer for a long period. Compared with that in the case without PCM, the energy consumption of the continuous operation of the refrigerator was reduced by 18.6%, and the compressor ON-time ratio was reduced by 13.6% after PCM was adopted [25].

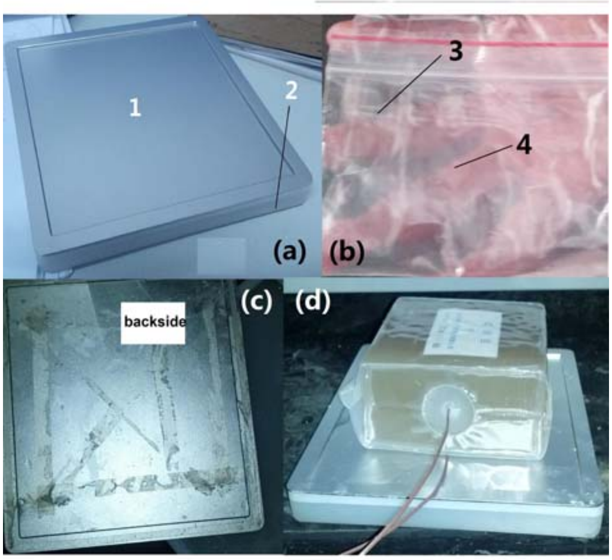


Fig. 1. Photographs of the cold storage plate for quick freezing

(a) aluminum lid, (b) cold storage material and bag, (c) backside of the plate, and (d) M-pack/food and quick-freezing plate

When food needs to be frozen quickly, the food is made into a sheet, the plate is removed from the refrigerator freezing chamber, the food is placed on the plate tray, the air between the food and plate is emptied, and the two are placed together in the refrigerator freezer chamber. At this time, heat is transferred quickly by conduction from the food to the phase-change cold-storage material filled in the plate, and food is quickly frozen. The quick plate freezer can also be removed from the refrigerator freezing chamber and used as a food plate at home or as a substitute for ice bags to maintain a low external temperature.

3 Calculation of the amount of added PCM

The calculation of the amount of added PCM to meet the required energy was based on the following hypotheses.

(1) The amount of cooling required for rapid freezing of food is derived from the heat transfer between the cold storage plate freezer and food regardless of the heat transfer between the low-temperature freezer compartment and the surface of frozen food.

(2) The sensible heat absorption of the cold-storage material from the refrigerator set to the phase-change temperature of PCM is ignored.

(3) The variation in the specific heat of pork is ignored (the specific heat is calculated at 15.6 °C).

The amount of added PCM to meet the required energy was calculated as follows:

$$M_p = \left[M_f C_f \left(t_f - t_{ice} \right) \right] / H \ . \tag{1}$$

Table 1 shows the parameters used in the calculation of the amount of PCM. The parameters in Table 1 were incorporated into Equation (1) to obtain a theoretical PCM of 100 g for the quick-freezing plate (size of 180 mm×180 mm×20 mm). The actual coefficient used was assumed to be 1.20, and the amount of added PCM was 120 g.

Table 1. Parameters for PCM calculation

Parameters	Units	Value
H	kJ kg^{-1}	304
t_f	°C	26
T_{ice}	°C	−5
M_f	kg	0.3
C_f	kJ kg^{-1}°C^{-1}	3.27

4 Methodology and test setup

4.1 PCM test rig

Different concentrations of NH_4Cl solution were used as PCM raw materials. NETZSCH DSC 200F3 240-20-460-L was used as the differential scanning calorimeter in the test temperature range of −50 °C to 60 °C at a test calibration rate of 5 °C min^{-1}. The sample was purged with high-purity nitrogen (99.999%) and flushed with a purge flow of 60 ml min^{-1}. The accuracy of the balance used in the experiment was 1/10000.

On the basis of the calculation result, a solvent with a specified mass was weighed, and a solution with a relative concentration was prepared. All solution concentrations were in mass fraction (%), and the sample mass was 5.00–15.00 mg with an accuracy of 0.01 mg. In the experiment, the reference sample and the sample were placed in the same type of sample vessel. Three identical parallel samples were created for each sample, and tests were repeated using three samples for consistency. After adding a sample to the sample vessel, the sample was rapidly heated to the upper limit of the required temperature range at a heating rate of 20 °C min^{-1} and then rapidly cooled to the lower limit of the required temperature range at the same absolute value of the cooling rate. To ensure the reproducibility of the experiment, the initial experimental temperature was changed, maintained constant for 2 min, and reduced at a cooling rate of 5 °C/min. For the NH_4Cl solution with mass fractions of 15%, 18%, and 20%, the temperature variations during the freezing and melting phases were tested, and the curves were drawn.

4.2 Quick-freezing test rig of the refrigerator quick-freezing plate with PCM

The test packages used were fresh pork with different dimensions, such as 40 mm×40 mm×3 mm, 40 mm×40 mm×6 mm, and 40 mm×40 mm×9 mm, 40 mm×40 mm×12 mm. The quick-freezing plate was filled with PCM composed of an NH_4Cl solution with 5% of mass fraction.. The quick-freezing plate types were single plate, single ribs, and double plate. A T-type thermocouple with a temperature range of −40 °C to 125 °C and accuracy of ±0.5 °C was used for temperature measurement. A 34970A Agilent data acquisition instrument was used to collect data, and BCD-212VBP was the experimental refrigerator with the set-point temperature of −20 °C in the freezing chamber.

4.3 Methodology

4.3.1 Methodology for testing the quick-freezing time of a refrigerator with/without a quick-freezing plate

The freezing times of two identical test packages [fresh pork (40 mm×40 mm×3 mm, 40 mm×40 mm×6 mm, 40 mm×40 mm×9 mm, 40 mm×40 mm×12 mm separately)] were examined. One of the test packages was placed on the quick-freezing plate with PCM located in the freezing chamber, and the other package was directly placed in the freezing chamber. The testing process was performed in the Refrigerator Standard Laboratory of the Refrigerator Research and Development Center of the Midea Group in Hefei, China. The experiments were performed under constant temperature and humidity according to the GB12021.2-2015 standard. Prior to the experiments, the quick-freezing plate was placed in the freezing chamber with the set-point temperature of −20 °C, and test pork 1# and 2# were placed in the laboratory (26 °C) for a sufficiently long time to balance the temperature. Then, test pork 1# was placed directly in the freezing chamber, and test pork 2# was placed at the center of the plate located in the freezing chamber. A T-type thermocouple was mounted at the center of the test packages, as shown in Fig. 2.

(a) single-rib plate (b) double-layer smooth surface plate

Fig. 2. Photographs of the T-type thermocouple arrangement in the test pork of the quick-freezing plate

4.3.2 Methodology for testing the quick-freezing time of a refrigerator with the quick-freezing plate or air blast freezing

A conventional household refrigerator equipped with a strong wind fan was installed in the freezing chamber for air blast quick freezing and to enhance the convection heat transfer. These characteristics improved the rate of food freezing. The effects of the quick-freezing plates with a single smooth surface and strong wind fan blast freezing were examined. The degree of food freshness was verified by determining the amount of frozen pork juice after the loss of water (rate of water loss) and calculating the rate of water loss using the weighing process.

4.3.3 Methodology for testing the quick-freezing time of a refrigerator with quick-freezing plates of different structures

The quick-freezing performance of the quick-freezing plate was improved by intensifying the heat transfer and increasing the heat transfer area by experimentation. Three quick-freezing plate structures, namely, single smooth surface, single rib surface, and double-layer smooth surface, were used.

(1) Double-layer smooth surface

The quick-freezing plate with a double-layer smooth structure is shown in Fig. 2(b). Two quick-freezing plates were used to hold the food face-to-face, which increased the contact area between the plate and food and enhanced the heat conduction and heat transfer to reduce the quick-freezing time.

(2) Low-rib and single smooth surfaces

The heat transfer area was increased by changing the quick-freezing plate with a single smooth structure into a low-rib structure (Fig. 3).

Fig. 3. Quick-freezing plate with a low-rib structure

4.3.4 Methodology for testing the quick-freezing time of a refrigerator using pork slices with different thicknesses under varied freezing methods

The quick-freezing times for pork slices with 3, 6, 9, and 12 mm thickness under different freezing methods are shown in Fig. 4. These methods included quick freezing with a single, single rib, or double-layer smooth surface plate, air blast freezing without a quick-freezing plate, and natural convection freezing without a quick-freezing plate.

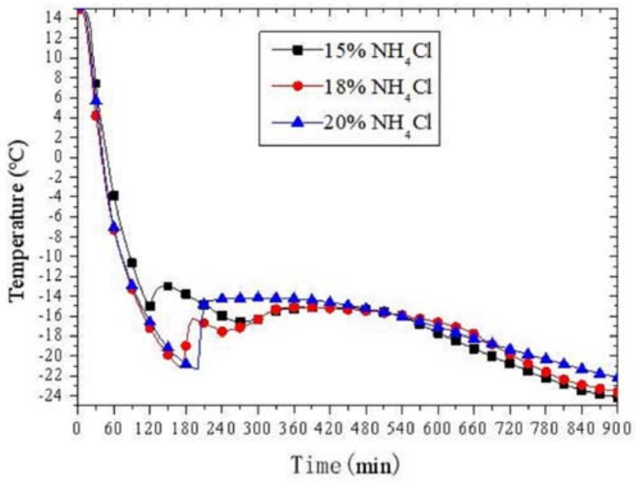
(a) Single smooth surface plate (b) Air blast freezing/ natural convection freezing

Fig. 4. Quick freezing with a single smooth surface plate and air blast freezing/natural convection freezing

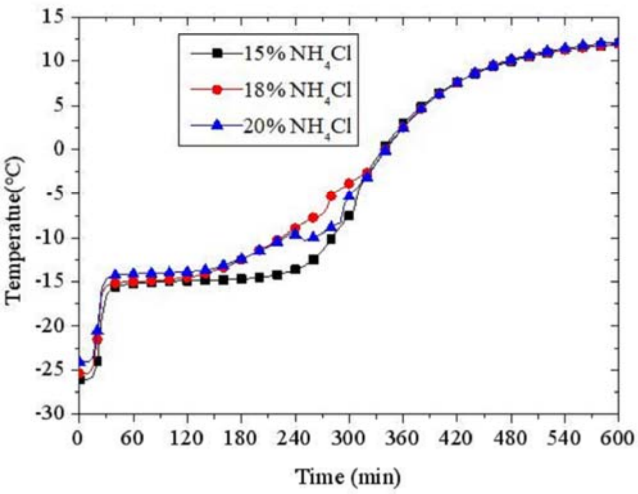
5 Results and Discussion

5.1 Experiment on PCM

The decreasing and increasing curves of the NH_4Cl solution with mass fractions of 15%, 18%, and 20% are shown in Fig. 5.



(a)Decreasing temperature curve of the NH_4Cl solution with mass fractions of 15%, 18%, and 20%



(b)Increasing temperature curve of the NH_4Cl solution with mass fractions of 15%, 18%, and 20%

Fig. 5. Decreasing and increasing temperature curves of the NH_4Cl solution with mass fractions of 15%, 18%, and 20%

For the NH_4Cl solution with a mass fraction of 15%, the minimum temperature during freezing was −16.6 °C, the initial temperature of the phase change process was −15.4 °C, the average temperature of the phase change process was −15.17 °C, and the sub-cooling degree was 1.5 °C. In the melting process, phase change started at −15.3 °C, and the average temperature of the phase change process was −15.34 °C.

For the NH_4Cl solution with a mass fraction of 18%, the minimum temperature during freezing was −21.2 °C, the initial temperature of the phase change process was −16.4 °C, the average temperature of the phase change process was −15.66 °C, and the sub-cooling degree was 4.8 °C. In the melting process, phase change started at −15.3 °C, and the average temperature of the phase change process was −15.21 °C.

For the NH_4Cl solution with a mass fraction of 20%, the minimum temperature during freezing was −21.4 °C, the initial temperature of the phase change process was −14.8 °C, the average temperature of the phase change process was −15.43 °C, and the sub-cooling degree was 6.6 °C. In the melting process, phase change started at −15.2 °C, and the average temperature of the phase change process was −14.8 °C.

The experiments indicated that the phase change temperatures of the freezing and melting phase change processes were about −15 °C for the NH_4Cl solution with mass fractions of 15%, 18%, and 20%, considering that the refrigerator freezer temperature is usually set at about −18 °C. The NH_4Cl solution with a mass fraction of 15% is suitable for use as a cold storage material for the plate freezer. The experimental results are shown in Table 2.

Table 2. Thermodynamic parameters of PCM

Phase change	Testing sample	Initial temperature of phase change (°C)	Lowest temperature of phase change (°C)	Degree of supercooling (°C)	Average temperature of phase change (°C)	Latent heat (kJ/kg)
Freezing	NH_4Cl solution with mass fraction of 15%	−15.42	−16.6	1.5	−15.17	304

5.2 Experiment on the quick-freezing plate with different structures

The performance of the quick-freezing plate was further optimized by analyzing the performance of quick-freezing plates with different structures and by comparing 40 mm×40 mm×6 mm pork pieces under natural convection conditions. PCM with 5% NH_4CL was used to compare the quick-freezing performance of the quick-freezing plates with single, single rib, and double-layer smooth surfaces. The experimental results are shown in Fig. 6. The quick-freezing performance of the quick-freezing plate with a single smooth surface was slightly higher than that with a single rib surface, and the quick-freezing performance of the quick-freezing plate with a double-layer smooth surface was significantly higher than that with a single smooth surface. The quick-freezing effect of the double-layer smooth surface was significantly higher than that of the single smooth surface. Fig. 6 shows that the time of maximum ice crystal formation was 15, 20, and 3 min for the single smooth, rib, and double-layer smooth surfaces, respectively.

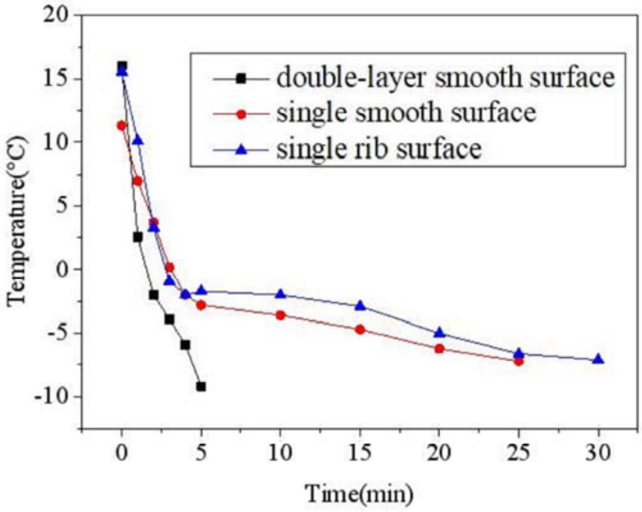


Fig. 6. Freezing curves of the quick-freezing plate with different plate structures

These results are attributed to the following phenomena. First, the fresh pork gradually contracted and hardened during the cooling process, although the rib structure increased the contact area between the fresh pork and quick-freezing plate to some extent, which resulted in a gap, small contact areas, and air thermal resistance.

Therefore, the quick-freezing performance decreased significantly. The use of the quick-freezing plate with a single smooth structure effectively avoided these problems. The quick-freezing plate with the double-layer smooth surface increased the contact area between the fresh pork and quick-freezing plate and effectively reduced air thermal resistance. Hence, this plate showed the best quick-freezing performance.

5.3 Experiment on quick-freezing performance with the quick-freezing plate and air blast freezing

The effect of the quick-freezing plate and strong-wind blasting on pork quick-freezing was investigated in the freezing chamber of a domestic refrigerator. The experimental results are shown in Fig. 7. The time (15 min) of the maximum ice crystal forming zone with the single smooth surface quick-freezing plate was 10 and 65 min faster than that of air blast freezing (25 min) and natural convection freezing (80 min). The rate of water loss in the pork using the three different methods was calculated and analyzed to thoroughly evaluate the capability to maintain the freshness of pork.

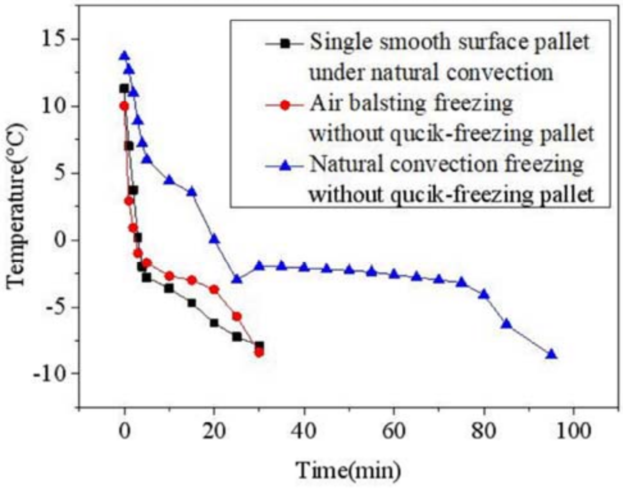


Fig. 7. Freezing curves of the quick-freezing plate with the quick-freezing plate or air blast/natural convection freezing

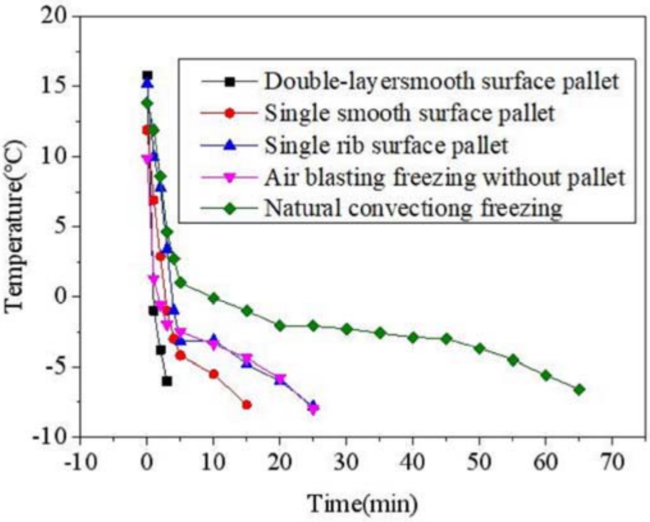
Table 3 shows that the air blast quick-freezing method resulted in a high loss of fresh pork juice due to the acceleration of food surface air velocity. This phenomenon affected food freshness. The rate of water loss using air blast freezing was 4.26%, and the rate of water loss using the quick-freezing plate was 1.60%.

Table 3. Weight loss of pork under different quick-freezing methods

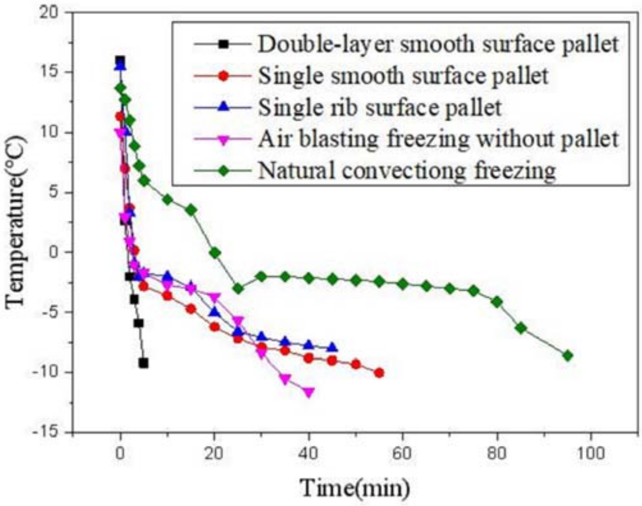
Quick freezing methods	Weight before quick freezing (g)	Weight after quick freezing (g)	Loss of weight (g)	Loss rate of water (%)
Air blast freezing	7.00	6.70	0.30	4.26
Quick-freezing plate with single smooth surface	7.00	6.89	0.11	1.60

5.4 Experiment on the quick-freezing time of a refrigerator with the quick-freezing plate for pork slices with different thicknesses

The quick-freezing time for pork slices with 3, 6, 9, and 12 mm thickness was tested under different freezing methods to elucidate the effect of food thickness on quick freezing. The methods included quick freezing with single, single rib, and double-layer smooth surfaces, air blast freezing without a quick-freezing plate, and natural convection freezing without a quick-freezing plate. The experimental results are shown in Figs. 8 and 9.

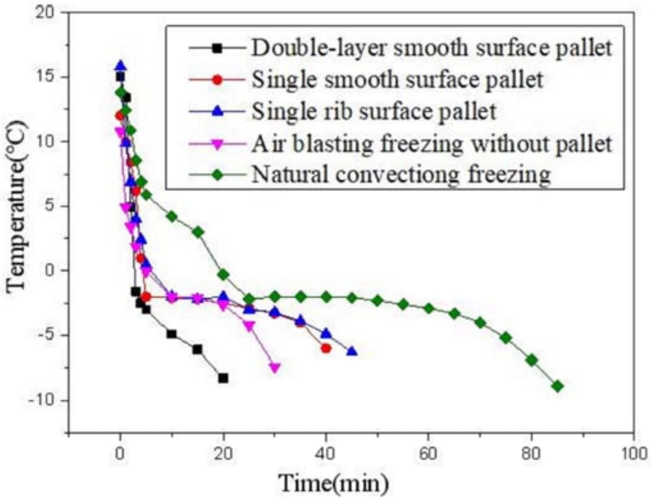


(a) 3 mm thick pork slice

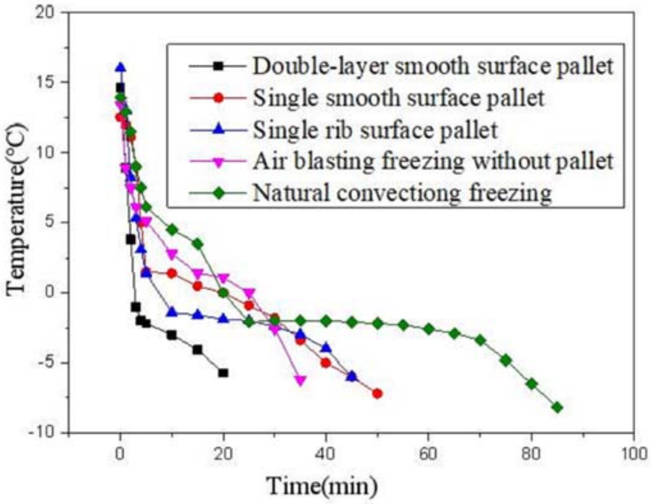


(b) 6 mm thick pork slice

Fig. 8. Freezing curves of different methods for 3 and 6 mm thick pork slices



(a) 9 mm thick pork slice



(b) 12 mm thick pork slice

Fig. 9. Freezing curves of different quick-freezing methods for 9 and 12 mm thick pork slices

Fig. 8 shows that the time of maximum ice crystal formation for the 3 mm thick pork slice using the quick-freezing plate with a single or double-layer smooth surface was obviously shorter than those of the other methods.

Fig. 9 indicates that the time of maximum ice crystal formation for the 12 mm thick pork slice using the quick-freezing plate with a double-layer smooth surface was shorter than those of the other methods. However, the corresponding time for the quick-freezing plate with a single smooth surface was longer than that of air blast freezing without a quick-freezing plate.

Therefore, the quick-freezing effect of the double-layer surface plate was better than that of the other conditions for various thicknesses of the experimental pork. For pork thickness of less than 6 mm, the quick-freezing effect of the single surface plate was better than that of air blast freezing. By contrast, the quick-freezing effect of the single smooth surface plate was worse than that of air blast freezing when pork thickness exceeded 6 mm.

6 Conclusions

The following conclusions were obtained.

(1) PCM (mass fraction of 5% NH_4CL solution) is suitable for use in the refrigerator quick-freezing plate. The quick-freezing plate with a double-layer smooth surface structure exhibited better quick-freezing performance than the plates with single smooth and rib surface structures. However, the double-layer smooth surface structure is complex and expensive to manufacture.

(2) A household refrigerator freezing chamber with a single smooth quick-freezing plate significantly reduced the time required for food to pass through the maximum ice crystal generation zone. The resulting time was 1/6 or 3/5 of that of the refrigerator without the quick-freezing plate in natural convection freezing or air blast freezing (the test food used was fresh pork with a dimension of 40 mm×40 mm×6 mm.).

(3) For various thicknesses of the experimental pork, the quick-freezing effect of the double-layer surface plate was better than those of the other conditions. For pork thickness of less than 6 mm, the quick-freezing effect of the single surface plate was better than that of air blast freezing. By contrast, the quick-freezing effect of the single smooth surface plate was worse than that of air blast freezing when pork thickness was more than 6 mm.

(4) Air blast quick-freezing method resulted in high loss of fresh pork juice and thus affected food freshness. The rate of water loss using air blasting and vertical blasting was 4.26% compared with that of the quick-freezing plate at only 1.60%.

7 Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No. 51776006) and Beijing Natural Science Foundation (Grant No. 3162008). The authors would also like to express their gratitude for the support of Qinghai Province Scientific and Technological Application Research Project (2016-NN-142), Beijing Social Science Fund (Grant No. S0011311201601), and New Talent Project of Beijing University of Technology (Grant No. 011000514117013).

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