STORAGE COLD CHAIN STORAGE AREA OPTIMIZATION AND ENERGY CONSUMPTION ANALYSIS

by

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The optimal refrigeration temperature control and pre-cooling system optimization of fruits and vegetables in the process of cold chain transportation are of paramount importance in ensuring product preservation, quality, and safety. This paper focuses on the changes in cold temperature and humidity of fruit and vegetable cold chain during storage and the temperature and humidity during pre-cooling, based on the optimal temperature of different fresh agricultural products during transportation and the existing cold chain transportation mode. A three-level pre-cooling storage mode and a series of full-temperature and wide-width storage cold chain storage and preservation collaborative call module are proposed to effectively improve the quality of cold storage and preservation of products, extend their storage period, and improve the storage quality of products. The objective is to expand the efficiency and temperature adaptability of cold chain agricultural products storage quality preservation technology.

Key words: *storage preservation, cold chain, storage, energy consumption*

Introduction

As scientific and technological advances in the field of cold chain logistics continue to accelerate, the technical specifications for the storage and preservation of agricultural products and cold chain transportation have gradually become more demanding [1, 2]. In light of the regional characteristics of logistics hub distribution and the high frequency of transactions in modern agricultural industrial parks, it is crucial to ensure that the temperature and humidity adjustment temperature range of industrial park storage is wide, that the storage refrigeration and preservation of single storage products are independently regulated, and that the pre-cooling and storage of agricultural products are reduced as much as possible. The decay rate of the link and the improvement of the rate and uniformity of pre-cooling and cooling of agricultural products have become a significant concern in today's society. In light of the challenges currently facing the transportation of fruits and vegetables, Jiang *et al.* [3] proposed a method to optimize the cold chain transportation of agricultural products based on the practical problems and development status of cold chain transportation. Wang *et al.* [4] optimized the cold chain system to address the challenges inherent in the fruit cold chain transportation process. Trotter, *et al.* [5] investigated the correlation between the cold chain transportation

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process and sustainable development and proposed a development plan for food cold chain transportation that takes into account local conditions. The current research focus of experts, scholars, and technicians in the field, both domestically and internationally, is largely concentrated on the reduction of economic costs associated with cold chain transportation, the advancement of cold chain system networking to enhance the economic efficiency of the transportation process, and the integration and application of cold chain transportation processes and Internet technology [6]. However, there is a paucity of research reports on the optimization of cold chain refrigeration systems for the storage and preservation of agricultural products, the pre-cooling and ventilation packaging of these products in the context of the cold chain transportation process, the prediction and analysis of heat transfer and energy consumption, and the calculation of a pre-cooling storage multi-level simulation model. Using dynamic economics [7] to optimize the cold chain is also promising.

Furthermore, there is a dearth of research on the realization of industrialization and the large-scale promotion and application of storage and cold chain industry. This paper employs a combination of theoretical analysis, numerical simulation, and model testing (laboratory testing) to investigate the temperature and humidity changes during the cold storage of fruits and vegetables and the temperature and humidity during the pre-cooling process. A three-stage pre-cooling storage mode and a series of full-temperature zones were proposed. The objective of the collaborative call module of cold chain storage and preservation of wide storage is to elucidate the heat transfer mechanism of pre-cooling storage of agricultural products. This will facilitate the improvement of the quality of cold storage and preservation of vegetables, thereby extending their storage period. This, in turn, will alleviate the sales pressure of local fruits and vegetables and other agricultural products. The objective is to enhance the efficiency and temperature adaptability of cold chain agricultural products storage and quality preservation technology.

Model construction and analysis

In light of the current state of development in the fruit and vegetable storage and preservation industry, a model has been created for the cold storage of the extensive storage center in the full temperature area of the modern agricultural industrial park. Furthermore, the flow field of the cold storage has been numerically simulated. In order to enhance the quality of fruit and vegetable storage and extend the storage period, a model was developed and a numerical simulation was conducted for the cold storage of the agricultural products storage center. The causes of cold loss in the storage were analyzed, and recommendations were made to improve the flow field distribution. The schematic diagram of the cold storage model of the storage center is shown in fig. 1. In the figure, I represents the normal temperature area of gas transmission and ventilation, II represents the medium temperature area of pre-cooling and dehumidification pretreatment, III represents the cold storage and storage area, and IV represents the wide storage and preservation area in the full temperature area.

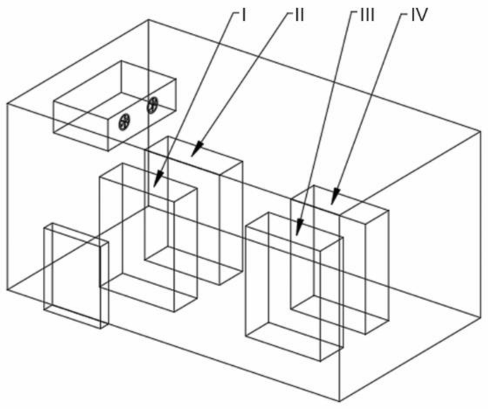

Figure 1. Schematic diagram of cold storage model of storage center

Simulation analysis

The pre-cooling and storage process of agricultural products can effectively enhance the value of fruits and vegetables by eliminating the primary process of hot and cold storage in the field at an optimal time after the picking of fruits and vegetables. The pre-cooling and storage model of agricultural products is depicted in fig. 2.

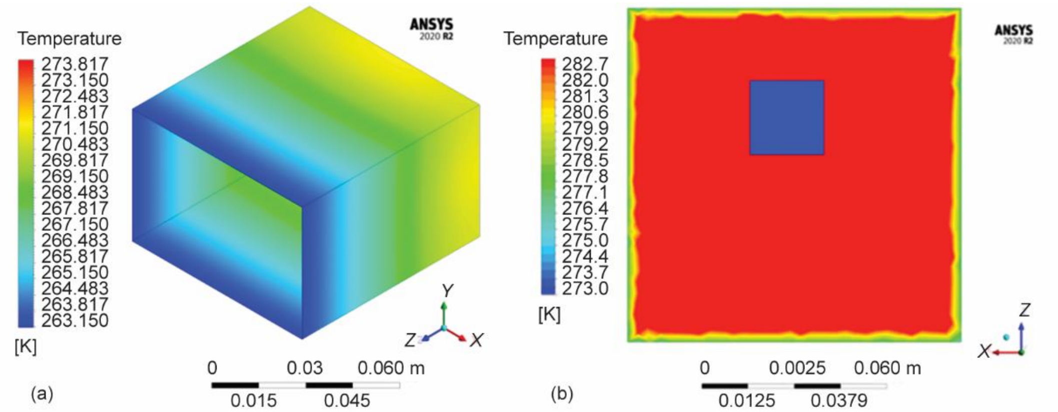

Figure 2. Pre-cooling and storage model of agricultural products storage; (a) wall temperature distribution and (b) initial state temperature

From the simulation of the flow field distribution in fig. 2, it can be observed that the positioning of the air cooler at the top of the warehouse results in a temperature gradient. Specifically, the temperature in the vicinity of the floor is higher than that at the top, and the temperature in the vicinity of the wall is higher than that in the shelf area. The process of pre-cooling and storage of agricultural products is a complex phenomenon involving heat and mass transfer, with numerous influencing factors. A simulation of the flow field temperature and air-flow field in the storage center was conducted for various types of fruit and vegetable storage, with the objective of exploring the heat transfer mechanism of fruit and vegetable pre-cooling storage processes and the factors affecting the storage quality of fruit and vegetables. Figure 3 illustrates the temperature field changes of various fruits and vegetables during storage. Figure 3(a) depicts the temperature distribution of sweet corn in cold storage, while fig. 3(b) shows the temperature distribution of apples in cold storage. Similarly, figs. 3(c) and 3(d) illustrate the temperature distributions of green pears and the reservoir, respectively. Finally, figs. 3(e) and 3(f) present the cross-sectional temperature distributions of cold storage I and cold storage II, respectively. Figure 3 depicts the temperature field changes of various fruits and vegetables during storage.

The temperature of fruits and vegetables is set according to their pre-cooling and storage environment. Figure 3 illustrates the simulation prediction, which indicates that based on the model test setting, sweet corn is located at the bottom of the cold storage. Furthermore, the temperature of the lower layer inside the cold storage is higher than that of the upper layer. However, due to the influence of convective heat dissipation, the contact time between sweet corn and cold air is longer, resulting in a lower internal temperature of sweet corn. The apple is situated on the middle shelf of the cold storage. The temperature field in the middle is intricate, and convective heat dissipation is pronounced. The green pear is situated on the upper shelf, which is in close proximity to the upper temperature zone. The temperature distribution within the cold storage indicates that the temperature is relatively low in the upper area. As the refrigeration process continues, the cold air area of the internal temperature field gradually expands and becomes increasingly stable and uniform. As the fan is situated above the cold storage, the temperature above the storage is low. As the air outlet area of the air cooler shifts and the area of the recirculation area increases, it tends to shift to the area near the shelf and the floor. This results in a close proximity of the temperature distribution area of the cross-section (I, II) to the wall surface of the cold storage. The temperature gradient of the flow field gradually becomes uniform.

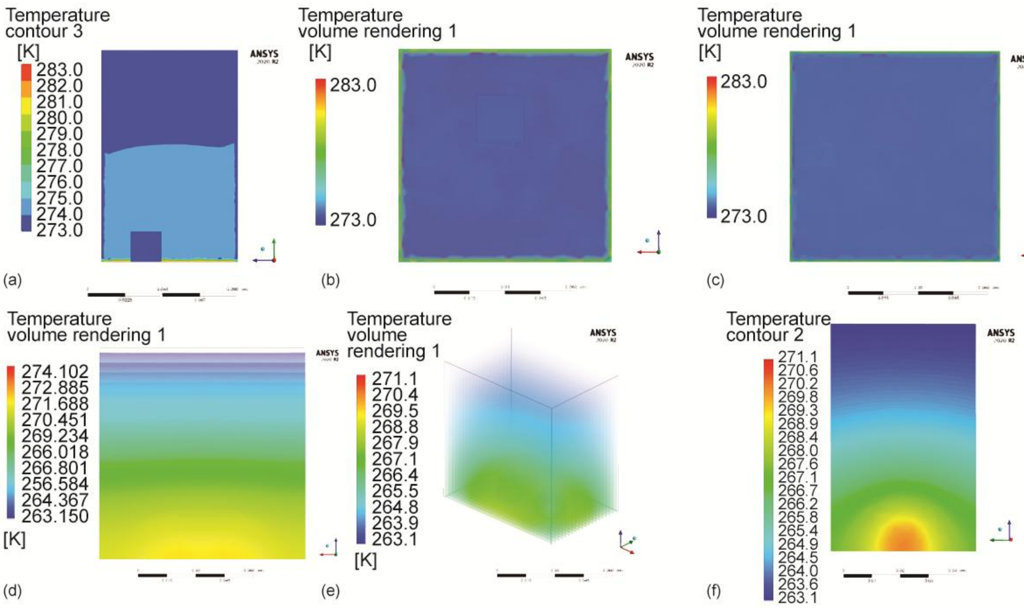

Figure 3. Temperature field changes of different kinds of fruits and vegetables during storage; (a) the sweet corn cold storage temperature distribution, (b) the apple cold storage temperature distribution, (c) the green pear cold storage temperature distribution, (d) the temperature distribution in the reservoir, (e) cross-section temperature of the cold storage I, and (f) cross-section temperature of the cold storage II

Storage treatment (pre-cooling, storage)

In light of the preceding simulation results, a model test was conducted to assess the impact of temperature and humidity fluctuations within fruits and vegetables before and after pre-cooling. This was done with the objective of optimizing the flow field distribution within the warehouse, enhancing the quality of cold storage for goods, and reducing energy consumption.

Fresh bananas, tomatoes, celery, apples, and other fruits were selected and classified on the fruit shelves after sampling and screening. Four copper-constantan thermocouples were assigned in advance, and the data were tested in a timely manner. The average value was calculated and analyzed. Comparative tests were conducted, including pre-cooling and refrigeration. The data acquisition process of the cold storage model test is depicted in fig. 4.

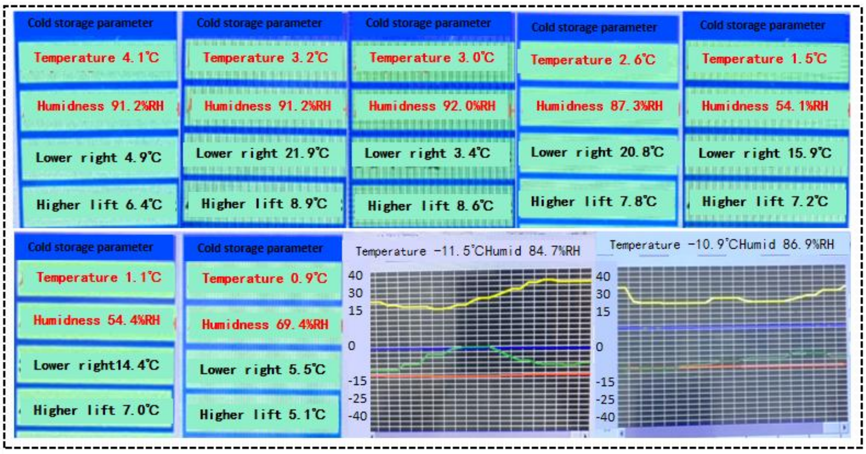

Figure 4. Process of model test data acquisition

The results of the simulation and model test comparative analysis of the cooling process of fruits and vegetables demonstrate that the effect of pre-cooling and storage is more pronounced. This approach aims to mitigate respiration, inhibit the corruption of fruits and vegetables, and enhance the efficiency and temperature adaptability of the storage quality and freshness technology of fruits and vegetables.

In accordance with the specifications for cold storage, four distinct storage areas were established in the model test: a normal temperature zone (temperature range of 8 °C to 12 °C, humidity range of 95% to 97%), a medium temperature zone (temperature range of 5 °C to 8 °C, humidity range of 94% to 95%), a storage zone (temperature range of –3 °C to 5 °C, humidity range of 90% to 95%), and a full temperature zone (temperature range of –3 °C to 16 °C, humidity range of 85% to 97%). The temperature fluctuations during the cold chain storage of fruits and vegetables are illustrated in figs. 5-7.

Figure 5 illustrates the temperature decline of sweet corn during cold storage. The temperature decreased rapidly from 15.2 °C to 9.2 °C within the first 10 minutes, and then more gradually from 9.2 °C to 0.8 °C over the subsequent 10-30 minutes. After this, the temperature remained relatively stable at 0.8 ±0.2 °C, which differed by 5.7% from the temperature change observed in the simulation process. The temperature of the apple decreased rapidly from 15.3 °C to 3.7 °C in 0-20 minutes, and then decreased more slowly to 1.4 °C in 20-25 minutes. After that, the temperature showed a dynamic change of 1.4 ±0.2 °C, which was 4.3% different from the temperature change in the simulation process. The temperature of the green pear exhibited a rapid decline from 15.6 °C to 10.3 °C within the first five minutes, followed by a gradual decrease from 10.3 °C to 1.3 °C over the subsequent five minutes. Thereafter, the temperature exhibited a dynamic change of 1.3 ±0.3 °C, which differed by 9.3% from the temperature and change observed in the simulation process. In conclusion, the simulation outcomes align well with the experimental findings.

As illustrated in figs. 6 and 7, the temperature of the cucumber reached 8.5 °C at approximately 20 minutes when it was not pre-cooled. Following pre-cooling, the temperature of the cucumber exhibited an initial increase, followed by a subsequent decline, reaching 8.3 °C after 20 minutes. The temperature range of the cold storage was 8.3 ±0.3 °C, with the temperature of the cucumber exhibiting an initial increase and subsequent decrease. The reason for this is that the cucumber is located above the cold storage and is in close proximity to the evaporator, which results in an increase in temperature. In the absence of pre-cooling, the temperature of the cabbage and tomatoes reached 0.6 °C and 0.8 °C within approximately 30 minutes, with a temperature dynamic range of 0.6 ±0.3 °C and 0.8 ±0.2 °C, respectively. The temperature of the cabbage exhibited minimal change following pre-cooling, with the cold storage temperature remaining stable at 1.3 ±0.2 °C and 1.5 ±0.1 °C after 20 minutes. In the absence of pre-cooling, the eggplant reached the refrigeration temperature of 11.3 °C in approximately 20 minutes. Following pre-cooling, the eggplant reached the refrigeration temperature of 11.3 °C after 10 minutes. The refrigeration temperature exhibited a dynamic range of 11.3 ±0.2 °C. In the absence of pre-cooling, the temperature of the celery reached 1.6 °C after 25 minutes. Following pre-cooling, the temperature of the celery in cold storage reached 1.4 °C after 20 minutes, with a dynamic change range of 1.4 ±0.2 °C. The cold storage temperature of bananas before and after pre-cooling reached 12.3 °C after 10 minutes, with a dynamic change range of 11.3 ±0.2 °C. In conclusion, the pre-cooling of fruits and vegetables can reduce the time required to reach the refrigeration temperature.

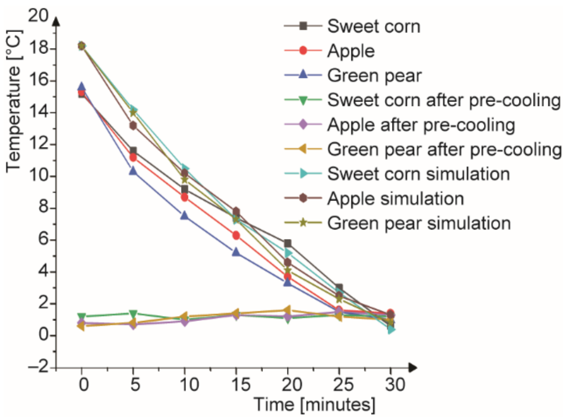

Figure 5. Comparison of pre-cooling before and after pre-cooling with simulated temperature

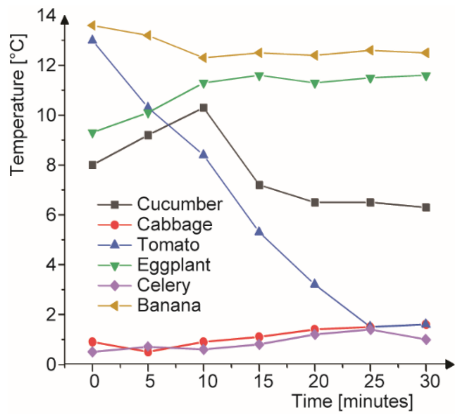

Figure 6. Changes of cold storage temperature of fruits and vegetables

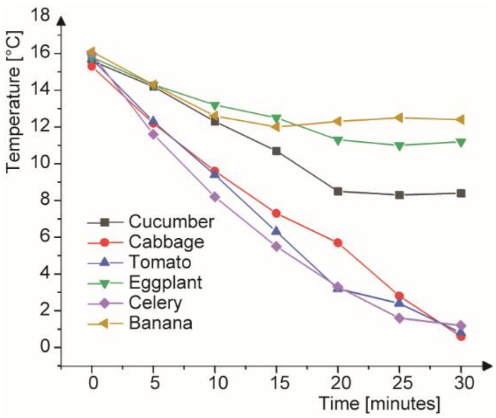

Figure 7. Temperature change during pre-cooling treatment and cold storage

Storage area optimization and energy consumption analysis

Optimal design of storage area

This paper proposes three types of pre-cooling storage modes and four types of cold chain storage and fresh-keeping areas.

- Set the pre-cooling mode. The first pre-cooling mode is a gear-pre-cooling mode, which is a cycle of 1-2 days, with a temperature of 9-10 ℃ and a humidity of 92%. The second pre-cooling mode is a gear-pre-cooling mode, which is a cycle of 3-8 days, with a temperature of 8-9 ℃ and a humidity of 93%. The third pre-cooling mode is a gear-pre-cooling mode, which is a cycle of 9-14 days, with a temperature of 8 ℃ and a humidity of 94%.
- Storage and preservation area:
  - Gas transmission, ventilation room temperature area (temperature 8-12 ℃, humidity 95%-97%).
  - Pre-cooling, dehumidification pretreatment medium temperature region (5-8℃ humidity 94%-95%).
  - Cold storage, storage area (temperature –3-5 ℃, humidity 90-95%).
  - Full temperature wide storage, preservation management (bagged transport, stacking, refrigeration, *etc.*) The area is characterized by a temperature range of 3~16 ℃ and a humidity range of 85%~97%.

Energy consumption analysis

The study examined the impact of temperature and heat flow changes on fruits and vegetables during storage. It also analyzed cooling loss and energy consumption in fruits and vegetables without pre-cooling and a pre-cooling model test. Figure 8 presents the energy consumption analysis of the storage process.

Figure 8 illustrates that the energy consumption of fruits and vegetables without pre-cooling storage and cold storage in different regions (medium temperature and room temperature) is approximately 694.2-711.9 W, while the energy consumption of fruits and vegetables with pre-cooling storage and cold storage in different regions (medium temperature and room temperature) is approximately 615.7-642.1 W. This represents a reduction of approximately 9.5%-10.6% in energy consumption compared to the former. The application of this technology can effectively enhance the storage quality of fruits and vegetables, prolong their storage period, and improve the preservation efficacy of fruits and vegetables within the storage turnover center.

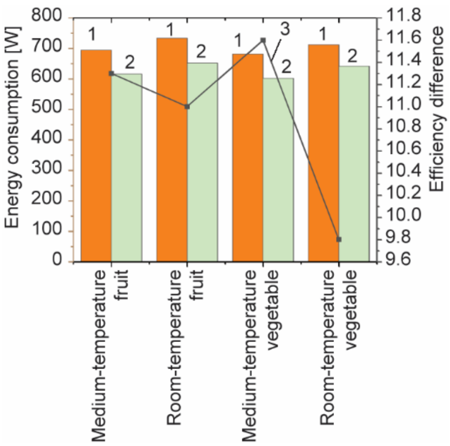

Figure 8. Energy consumption analysis during storage; *1 – not pre-cooled, 2 – precooling, and 3 – efficiency difference*

Conclusion

This paper examines the impact of temperature and humidity fluctuations on the cold chain transportation of fresh agricultural products. It considers the optimal temperature range for different types of produce during transportation and the existing cold chain transportation mode. The focus is on the changes in cold temperature and humidity of fruit and vegetable cold chains during storage and the temperature and humidity during pre-cooling. It was determined that the time required for pre-cooled fruits and vegetables to reach the cold storage temperature is 10-20 minutes shorter than that without pre-cooling, and the energy consumption is reduced. A reduction in energy consumption was observed. Based on these findings, a collaborative call module was proposed that included three pre-cooling storage modes and a series of full temperature zones and wide storage cold chain storage and preservation. The energy consumption of fruits and vegetables during pre-cooling storage was reduced by approximately 9.5-10.6% compared to that without pre-cooling storage.

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