RESEARCH ON SUITABILITY OF COOLING CAPACITY OF COLD STORAGE AREA UTILIZING BIOGAS AS SECONDARY REFRIGERANT SYSTEM

by

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The biogas produced by the waste fruit and vegetable pile retting during the cold storage process is utilized. Subsequent to the decompression and purification treatment, a temperature control strategy is implemented in the enhanced cold storage area through the side load cooling cycle. The subsequent results demonstrate that the implementation of a biological natural gas cooling cycle, in conjunction with the criss-cross placement of shelves and a cargo frame tilt angle of 15°, as compared to shelf flat loading, results in a gradient distribution of regional temperature differences. This approach has been demonstrated to enhance the temperature uniformity index by 26.19%, increase the cooling rate by 3.36%, and reduce energy consumption by approximately 10.05%. Furthermore, the variation amplitude of the temperature non-uniformity coefficient of the shelf section is relatively gentle, with an average deviation of approximately 5.53%. The efficacy of this system in regulating temperature in time-sharing zones has been demonstrated. This system has been developed to facilitate the optimization of cold capacity, thereby ensuring the appropriate matching of cold storage capacity to the diverse needs of fruit and vegetable storage in different temperature zones.

Keywords: *biogas, utilizing biogas as secondary refrigerant system, temperature uniformity, suitability of cooling capacity*

Introduction

Presently, China stands as a major agricultural nation, with fruits and vegetables playing a pivotal role in the country's economy. The agricultural sector in China is of paramount importance for domestic food security and also exerts a substantial influence on international trade. The production and consumption of fruits and vegetables are extensive, with a wide variety of produce being cultivated across different regions, from the fertile plains to the mountainous areas.

Cold storage, characterized by its constant temperature performance, has been demonstrated to effectively maintain the freshness of various products, including crops, fruits,

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and vegetables [1, 2]. A substantial body of research has underscored the significance of cold storage in the post-harvest management of agricultural products. For instance, in the research by Nazari *et al.* [3], it was found that cold storage at 7 ºC is commonly used for banana fruits. However, it has been demonstrated that storage at such low temperatures can result in chilling injury. The present study investigated the effect of exogenous dopamine treatment during cold storage of banana fruits. The results demonstrated that 150 µM dopamine treatment promoted the biosynthesis of phenols, flavonoids, endogenous proline, and γ-aminobutyric acid, which effectively alleviated chilling injury. This finding suggests that the combination of suitable refrigeration conditions with alternative treatment methods may enhance the preservation of fruit quality. Li *et al.* [4] focused on the storage of tomato fruits at low temperatures. A study was conducted to investigate the role of hydrogen sulfide in enhancing the chilling tolerance of tomato fruits stored at low temperatures. In the present study, the impact of sodium hydrosulfide (NaHS) solution concentrations on the fumigation of tomato fruits as a source of hydrogen sulfide was examined. The fruits were stored at 4 °C for 25 days, after which the results indicated that treatments with 1 mM and 1.5 mM NaHS promoted the accumulation of endogenous hydrogen sulfide. Consequently, the activities of pivotal enzymes in energy metabolism were augmented, and the levels of cellulose and hemicellulose were elevated. This approach led to a mitigation of the deleterious effects stemming from cold storage. The present study underscores the potential of cold storage, when employed in conjunction with advantageous substances such as hydrogen sulfide, to enhance the quality and shelf life of vegetables. Zengin *et al.* [5] conducted a study to examine the effect of calcium and ethanol generator pads (EGP) on mulberry fruit during cold storage. Mulberries are distinguished by their elevated water content and fragile texture, characteristics that render them highly perishable. The researchers treated mulberries with EGP, 1% calcium chloride ($CaCl_2$), or a combination of both and stored them at 0±0.5 °C with 85-90% relative humidity for 21 days. The investigation revealed that the application of EGP treatments alone resulted in an extension of the shelf life of Bursa Siyahi to 18 days and Kenmochi to 15 days. The present study demonstrates that the application of cold storage, in conjunction with appropriate post-harvest treatments, can effectively prolong the shelf life of highly perishable fruits, such as mulberries. Nikzadfar *et al.* [6] investigated the potential of cold plasma technology in the post-harvest preservation of fresh fruits and vegetables that are not packaged. Cold plasma has been demonstrated to generate reactive species that possess antimicrobial properties, thereby exerting an influence on the quality characteristics of fruits and vegetables. A rigorous investigation was conducted into the discrepancies between in-package cold plasma systems, encompassing both direct and indirect methodologies.

The study also analyzed the impact of various parameters on the performance of cold plasma treatment, including voltage, treatment duration, and the nature of the product. The findings of this study suggest that cold plasma technology possesses the potential to serve as an effective tool in the preservation of the quality and safety of fruits and vegetables during cold storage. In their study, Kim *et al.* [7] sought to predict the moisture evaporation in vegetable storage drawers of a household refrigerator. An experimental apparatus was configured to assess various parameters, including temperature and humidity regulation, the configuration of cold airflow pathways, and the structural design of the drawer. A novel predictive model was developed through a quantitative assessment of moisture evaporation in fresh vegetables. The model exhibited a high coefficient of determination (93.2%) when tested with spinach and bok choy, which was in good agreement with real-refrigerator test data. This research is significant as it helps in optimizing the design of cold storage systems for vegetables, ensuring better preservation by controlling moisture evaporation.

In the domain of architecture, the exploration of clover-inspired fractal architectures with flexible folding skins offers a plethora of innovative solutions for sustainable building design. Concurrently, within the domain of fruit and vegetable storage, there are still pressing issues that need to be addressed.

At present, a considerable number of researchers are engaged in the optimization of refrigeration systems, the evaluation of fruit and vegetable storage efficacy, and other pertinent research domains. However, there is a paucity of literature addressing the challenges associated with fruit and vegetable ripening, centralized picking, substantial storage and import volumes, and diminished refrigeration capacity. A survey of the available literature reveals a broad array of options for the storage of fruits and vegetables. It is evident that the parameters for each option vary, while certain fundamental similarities emerge. The refrigeration process is vulnerable to a negligible quantity of spoiled fruits and vegetables (with a damage rate of approximately 20%), and conventional cold storage is inadequate in meeting the diversification of product cold needs or implementing directional classification adjustment.

The present paper utilizes a theoretical analysis and numerical simulation to demonstrate the potential of waste fruit and vegetable pile fermentation in the production of biogas. Subsequent to the processes of decompression and purification, the system engages in a temperature control strategy that involves the implementation of an efficiency-increasing cold storage division through the utilization of a side-load cooling cycle. Furthermore, the system incorporates a time-sharing and zoning module, which is designed to regulate the cold storage process. This approach has been demonstrated to be effective in enhancing the efficiency and temperature adaptability of fruit and vegetable storage quality preservation technology. It is imperative to enhance the energy efficiency of enterprises and curtail production costs.

The cold storage refrigeration process was subjected to a numerical calculation based on the k-ω SST model. Given the complexity and numerous influencing factors of the cold storage refrigeration system for fruits and vegetables, constructing an accurate mathematical model remains a challenging endeavor. The experimental cold storage, which measures 10 m by 8 m by 4 m, was selected as the research object. The shelves were designed to be installed in two configurations: a tiled loading configuration and a crisscross configuration. The tilt angle of the cargo frame was set to range from 5° to 20°, and the size of the cargo frame was 0.46 m × 0.48 m × 0.66 m. The cold storage evaporation tube is positioned at a distance of 10 cm from the shelf surface, while the adjacent shelves are separated by 6 cm in the *X*-direction and 4 cm in the *Y*-direction. The temperature in the cold storage room is set to –3 °C, and the initial temperature is 15 °C. This research on fruit and vegetable cold storage is consistent with the overarching trend of sustainable development, akin to the clover-inspired architecture that aspires to attain sustainable and intelligent building design. The objective of both approaches is twofold: first, to enhance existing systems, and second, to optimize resource utilization efficiency. In addition, both approaches are designed to address the diverse needs of modern society while minimizing adverse environmental impacts.

Physical model and boundary conditions

The cold storage refrigeration process was subjected to numerical calculation using the k-ω SST model. Given the inherent complexity and numerous influential factors of the cold storage refrigeration system for fruits and vegetables, the construction of an accurate mathematical model remains a formidable challenge. To address this challenge, an experimental cold storage unit measuring 10 m × 8 m × 4 m was selected as the research object. The shelves within this unit were designed to be arranged in two distinct configurations: tiled loading and crisscrossing. The tilt angle of the cargo frame was set to range from 5° to 20°, and its dimensions were 0.46 m × 0.48 m × 0.66 m. The cold storage evaporation tube was positioned at a distance of 10 centimeters from the shelf surface, with adjacent shelves separated by 6 cm in the *X*-direction and 4 cm in the *Y*-direction. The temperature in the cold storage room is set to –3 °C, and the initial temperature is 15 °C.

Model establishment

The cold storage refrigeration process is numerically calculated based on the k-ω SST model. The inherent complexity and numerous influential factors of the cold storage refrigeration system for fruits and vegetables render the establishment of an accurate mathematical model a challenging endeavor. To address this challenge, an experimental cold storage with dimensions of 10 m × 8 m × 4 m was selected as the research object. The model was configured to specify a cargo frame size of 0.46 m × 0.48 m × 0.66 m. The distance between the cold storage evaporation row pipe and the outer surface of the cargo frame is 10 cm. The distance between adjacent goods in the *X*-direction is 6 cm, and the distance between adjacent goods in the *Y*-direction is 4 cm. The construction of the cold storage wall consists primarily of aerated concrete block, with extruded polystyrene foam serving as the insulation material. The storage room is maintained at a temperature of –3 °C, with an initial working temperature of 15 °C. The configuration of the shelf enables two distinct loading methods: flat loading and criss-crossing. The tilt angle of the cargo frame is meticulously calibrated to range from 5° to 20°. The model diagram is shown in fig. 1.

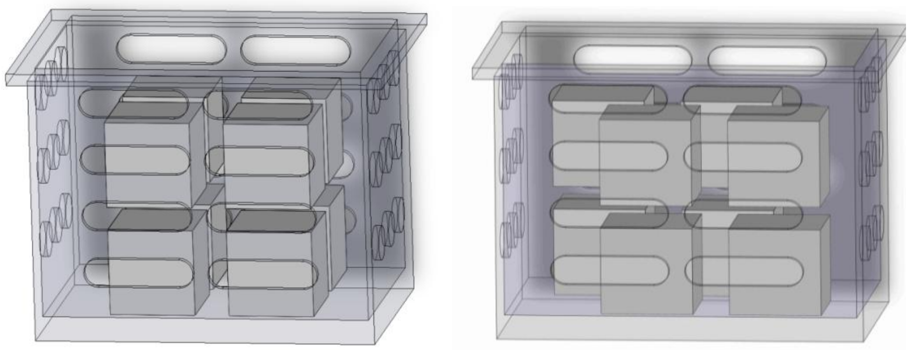

Figure 1. Physical model; (a) tiled loading and aligned placement and (b) criss-cross placement

Numerical methods and temperature distribution

The standard k-ω SST model was adopted for the numerical calculation of the cold storage refrigeration process. The objective of this calculation was to explore the temperature field changes of the goods. The energy conservation equation and continuity equation are [8]:

– Continuity equation:

$$\frac{\partial(pu)}{\partial x}+\frac{\partial(pv)}{\partial y}+\frac{\partial(pw)}{\partial z}+\frac{\partial p}{\partial t}=0 \tag{1}$$

where u, v, and w are velocity components in x-, y- and z-directions, respectively, and are zero if the air is an incompressible fluid.

– Energy conservation equation:

$$\frac{\partial V}{\partial t}+(V\nabla)V = f-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\nabla^2 V \tag{2}$$

where ρ is the fluid density, V – the velocity vector, p – the pressure, and f – the external force per unit volume of fluid. If only gravity is considered, then $f = \rho g$, ∇ is Hamiltonian operator, and μ – the dynamic viscosity.

– The standard k-ω equation:

$$\frac{\partial(\rho k)}{\partial t}+\nabla(\rho U k)=\nabla\left[\mu+\frac{u_t}{\sigma_k}\right]+P_\mathrm{k}-\rho\varepsilon$$
$$\frac{\partial(\rho\omega)}{\partial t}=\nabla(\rho U\omega)=\nabla\left[\left(\mu+\frac{u_t}{\sigma_k}\right)\nabla\omega\right]+\frac{\gamma}{\nu_t}P_\mathrm{k}-\rho\beta\omega^2+2(1-F_1)\frac{\rho\sigma\omega^2}{\omega}\nabla k \tag{3}$$

$$\varepsilon = C_\mu k\omega \tag{4}$$

$$\mu_i=\frac{\beta k}{\omega}\frac{1}{\max\left(\dfrac{1}{\alpha'}\dfrac{SF_i}{a_i\omega}\right)} \tag{5}$$

$$F_1=\tanh(\arg_1^4) \tag{6}$$

$$F_2=\tanh(\arg_2^2) \tag{7}$$

$$\arg_2^2 = \max\left[2\frac{\sqrt{k}}{0.09od},\quad \frac{500\mu}{\rho d^2\omega}\right] \tag{8}$$

where K is the turbulent kinetic energy and ω – the dissipative term. The functions F_1 and F_2 are mixed, and U signifies the velocity gradient. The hyperbolic tangent function, arg, is also employed, along with the flow viscosity, denoted by μ_t. The P_k is the generation term of turbulent kinetic energy. The variables k and ω are yet to be determined, ρ – the fluid density, p – the pressure, S – the magnitude of strain rate, Δ – the Hamiltonian operator, μ – the dynamic viscosity, d – the distance to the nearest wall, α^*, α_I, β, and γ – the empirical constants.

In order to explore the influence of different distribution angles of goods on the distribution of temperature uniformity, the temperature distribution in cold storage is analyzed numerically. As illustrated in fig. 2, the temperature distribution cloud diagram reveals the distribution of cargo tiled loading and the angle of cargo frame inclination, ranging from 5° to 20°. As illustrated in fig. 3, the temperature distribution cloud diagram reveals the distribution of goods positioned incorrectly and the angle of goods frame inclination (5° to 20°).

As demonstrated in figs. 2 and 3, the tilt angle of the cargo frame (5° to 20°) and the deviation of the return area from the refrigerated area exhibit a direct correlation with the temperature field distribution, which demonstrates an uneven trend. The temperature in the central and peripheral regions of the shelf continues to rise until a turning point is reached at an angle of 15°. At this juncture, the cooling amplitude is negligible and undergoes a gradual transition to a gentle state.

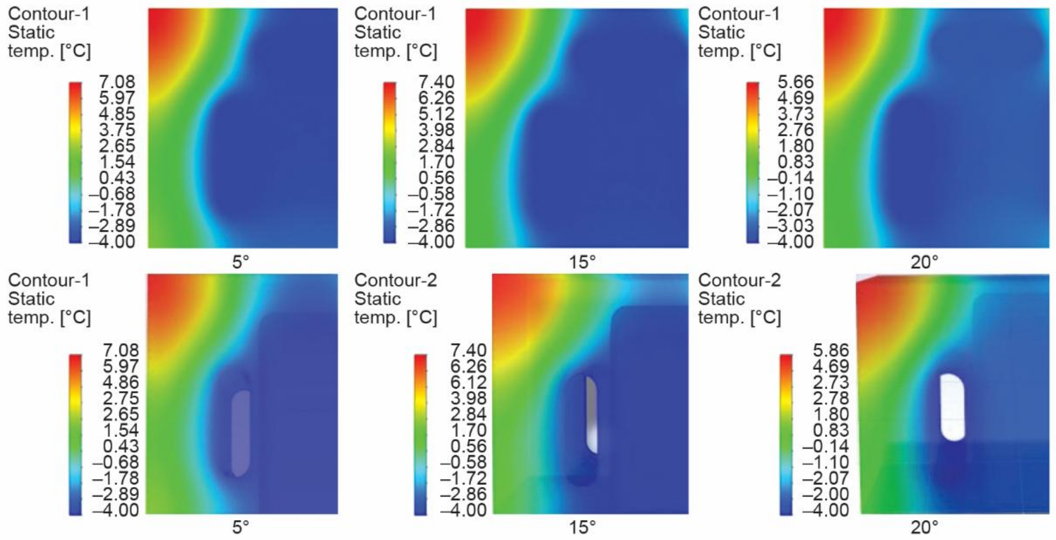

Figure 2. Temperature distribution of goods in tiled loading with different frame inclination angles

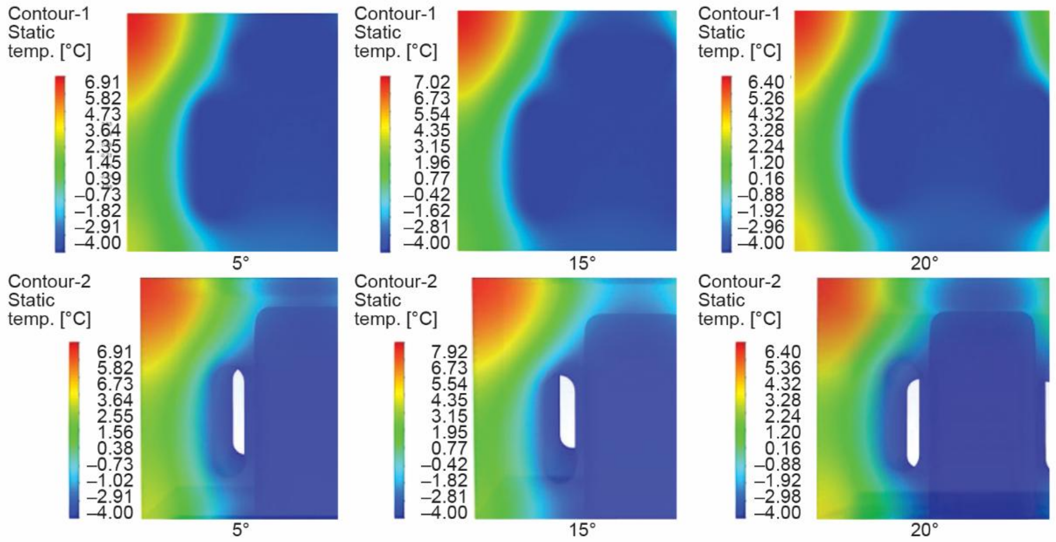

Figure 3. Temperature distribution of goods placed out of position and goods frame tilt angle

Firstly, the goods are tiled, and the goods frame tilt angle (5°~20°) temperature distribution is as follows: the temperature change in the center area of the shelf is –3.44 °C~–

3.02 °C, the temperature in the boundary area rises from 6.27 °C to 7.08 °C, and then gradually drops to 5.66 °C, which tends to be gentle.

Secondly, the goods are misplaced, and the cargo frame inclination angle (5°–20°) is not well-calibrated. The temperature distribution is characterized by a temperature change in the center area of the shelf of –3.49 °C to –3.43 °C, and a temperature increase from 5.97 °C to 6.66 °C in the boundary area, followed by a gradual decrease to 6.40 °C, which tends to be gentle.

The reflux area of the entire cold room flow field is substantial, and the reflux area is expanding and gradually approaching the cold room wall. Furthermore, the temperature field in the cold room demonstrates non-uniformity. Concurrently, a wide array of refrigerated fruit and vegetable products is currently available, necessitating precise temperature and humidity calibrations. The presence of distinct refrigerated zones necessitates localized surveillance. Additionally, the substantial throughput of fruits and vegetables necessitates the frequent entry and departure of merchants, thereby imposing heightened demands for effective refrigeration and fresh-keeping measures. Consequently, traditional cold storage has proven to be an inadequate solution for meeting the diverse storage requirements of fruit and vegetables. This phenomenon can be attributed to the implementation of directional classification adjustment difficulties and other issues.

Adaptability of cooling capacity of biogas cold storage area with enhanced cooling cycle

Biological natural gas cooling cycle coupled synergistic refrigeration system

In view of the aforementioned simulation, it is apparent that conventional fruit and vegetable cold storage systems are inadequate in addressing the prevailing challenges, including the cold diversification of products within the cold chain full temperature range and the adaptability of cold storage volumes to fluctuating temperatures. A study was conducted to examine the effectiveness of a temperature control strategy that increases efficiency in cold storage zoning. This strategy was implemented following the fermentation and decompression purification treatment of waste fruit and vegetable piles into biological natural gas. The study focused on the side-loading cold circulation system. The objective of the time-sharing and zoning module is to regulate the refrigeration process, thereby enhancing the efficiency and temperature adaptability of the storage quality and freshness technology of fruits and vegetables. This module is of great significance for improving the energy use efficiency of enterprises and reducing the production cost. Figure 4 illustrates the biogas cooling cycle in conjunction with a synergistic refrigeration system.

As illustrated in fig. 4, during the refrigeration process, a small amount of rotting waste fruits and vegetables are systematically monitored by the monitoring instrument for moisture (*i.e.*, wilting and shriveling) and subsequently transferred to the pile fermentation tank. At this juncture, the pneumatic valve K1 is opened while K2 is closed. The coupled auxiliary cooling system is powered by photovoltaic panels and inverters, thereby enhancing sustainability. Conversely, the pneumatic valve is switched, K2 is opened, and K1 is closed. Subsequent to the processes of decompression and purification, the substance is introduced into the bypass loaded cold circulation system, where it executes the functions of time-division and regional auxiliary cooling. Thereafter, it is integrated into the natural gas pipeline section (or cooking).

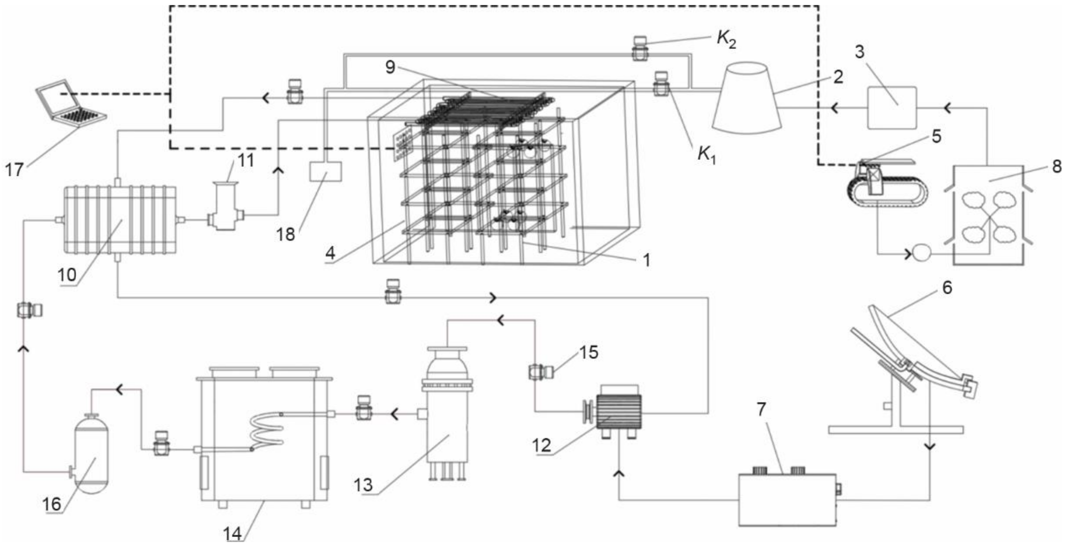

Figure 4. Biogas cooling cycle coupled synergistic refrigeration system; *1 – shelf, 2 – auxiliary cold cloth bag, 3 – phase conversion heat device, 4 – refrigerated room, 5 – fruit and vegetable sorting device, 6 – photovoltaic panel, 7 – inverter, 8 – pile fermentation tank, 9 – evaporation row tube, 10 – heat exchanger, 11 – expansion valve, 12 – compressor, 13 – oil separator, 14 – condenser, 15 – electronic valve, 16 – liquid reservoir, 17 – monitor, 18 – natural gas grid-connected, K1, K2 – pneumatic valves*

Reservoir area division

The experimental cold storage, measuring 10 m × 8 m × 4 m, was selected as the primary subject of study. The warehouse was meticulously divided into three distinct temperature control areas, taking into account the varied types of frozen fruits and vegetables, as well as the regional differences in cooling amplitude. This approach was adopted to address the diversified needs for product cooling and to implement directional classification regulation. The configuration of the cold storage partition is illustrated in fig. 5. As illustrated in the figure, the normal temperature range (5-8 °C, humidity 95-97%) is denoted by areas VII and VIII, while the cold storage range (temperature –3-–1 °C, humidity 95-97%) is denoted by areas IV, V, and VI. The temperature range of 5-3 °C (9 °F to 33 °F) and the medium temperature area 1 and 2 (temperature 3-5 °C, humidity 94-95%) are shown.

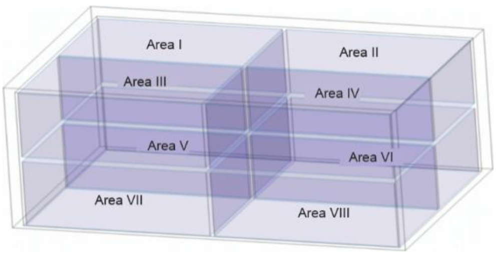

Figure 5. Cold storage cold storage area

Temperature distribution in the cold room of coupling enhancement

The biological natural gas cooling cycle was implemented, and the shelves were arranged in a horizontal and criss-cross configuration to investigate the impact of varying tilt angles of cargo frames on the temperature distribution within the cold storage facility.

Effects of flat loading of shelves and different tilt angles of cargo frames on temperature distribution

The strategic placement of shelves and cargo frames is paramount to maintaining temperature uniformity in the cold room and ensuring the quality of the goods. The temperature distribution, temperature difference change, and uniformity index change curves of the cold room of the shelf-tiled loading are shown in figs. 6-8, respectively.

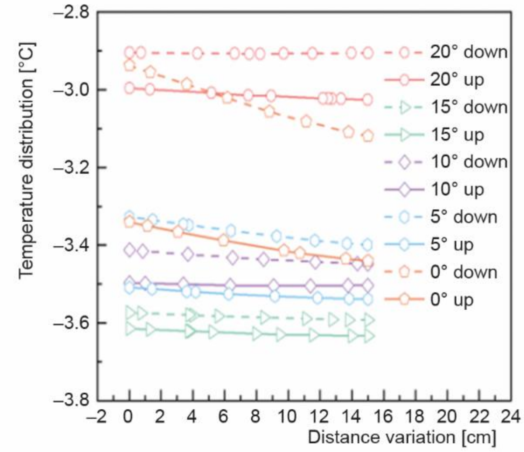

Figure 6. Shelf tiling loading temperature distribution

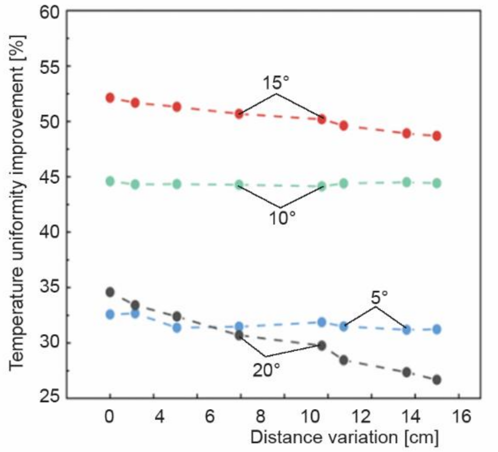

Figure 7. Temperature difference curve

As demonstrated in figs. 6-8, the temperature control of the cold storage area demonstrated an increase following the implementation of side load cooling. As the tilt angle of the cargo frame increased gradually (0°-20°), a significant decrease in temperature was observed in various temperature control areas, indicating a downward trend in temperature. The tilt angle of the cargo frame exerts a substantial influence on the efficacy of cooling. When the tilt angle ranges from 0°-5°, the cooling effect is pronounced, and the cooling amplitude is minimal. Conversely, when the tilt angle varies from 10°-15°, the temperature difference is approximately –3.4 °C, and the uniformity index is about 21.76%. This finding suggests that the temperature field undergoes a gradual softening, manifesting an overall homogenization tendency. Consequently, the cooling range and the temperature uniformity of the flow field (temperature difference: –3.4 °C; uniformity index: 28.44%) exhibited an enhancement. However, the reflux area deviated from the refrigerated area, the temperature field distribution exhibited an uneven trend, and the area of the reflux area gradually diminished. These phenomena did not contribute to the diversification of the cold storage use of classified fruits and vegetables or the appropriate matching of cold volume.

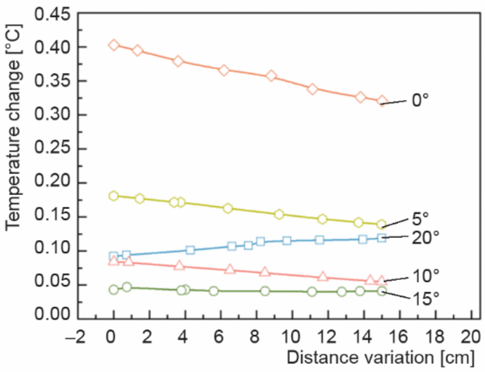

Figure 8. Temperature uniformity index change curve

Influence of criss-cross placement of shelves and different tilt angles of cargo frames on temperature distribution

As the cooling process continues, the area of the return area under the shelf decreases, gradually moves closer to the shelf, and approaches the cold room wall. Concurrently, the disparate tilt angles of the cargo frame exert a discernible influence on the temperature distribution within the cold storage facility. The figures presented herein illustrate the temperature distribution, temperature difference change, and uniformity index change curves of the cold room where shelves are crisscrossed. These figures are numbered as follows: figs. 9-11, respectively.

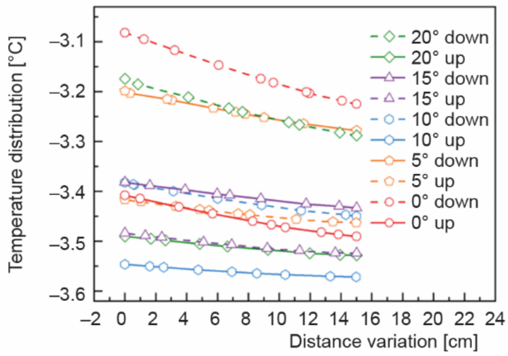

Figure 9. Temperature distribution

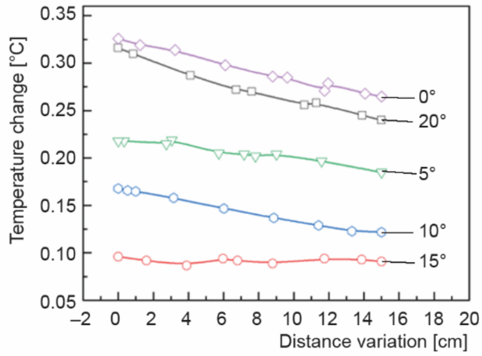

Figure 10. Temperature difference curve index change curve

As demonstrated in figs. 9-11, the efficacy of temperature control in the cold storage area, augmented by side-pass load cooling, exhibited a marked enhancement with an increase in the tilt angle of the cargo frame (0°-20°). Concurrently, a substantial decline in temperature was observed within diverse temperature control zones. The tilt angle of the cargo frame exerts a substantial influence on the efficacy of cooling. When the tilt angle ranges from 0°-5°, the cooling effect is pronounced, and the cooling amplitude is minimal. Conversely, when the tilt angle varies from 10°-15°, the temperature difference is approximately –3.45 °C, and the uniformity index is about 31.75%. This phenomenon suggests a gradual reduction in the intensity of the temperature field, indicating a homogenization trend. Consequently, the cooling range and the temperature uniformity of the flow field exhibited an enhancement, with a temperature difference of approximately –3.5 °C and a uniformity index of approximately 35.23%. However, the reflux area gradually deviated from the refrigerated area, the temperature field distribution exhibited an uneven trend, and the area of the reflux area diminished.

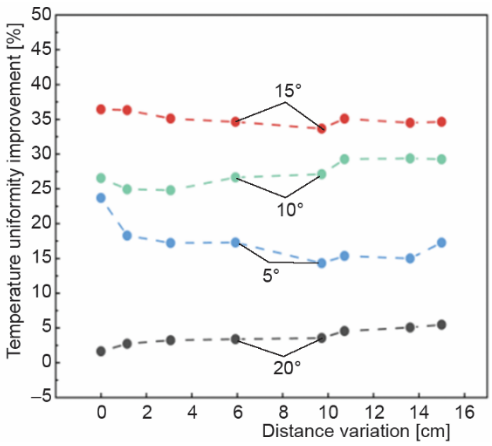

Figure 11. Temperature uniformity of shelves criss-crossing

These phenomena did not contribute to the diversification of the cold storage use of classified fruits and vegetables or the suitable matching of cold volume.

The findings indicated that by incorporating crisscrossing shelves and adjusting the tilt angle of the cargo frame to 15°, there was a 3.36% increase in cooling rate and a 10.05% reduction in energy consumption. This approach satisfied the diverse requirements for cooling fruit and vegetables and facilitated directional classification adjustment. Additionally, the cooling process was discernible, and the temperature field demonstrated a propensity for homogenization. In order to address the diverse requirements for the storage of various fruits and vegetables in refrigerated environments, the cold room has been designed to accommodate different storage capacities.

Conclusions

In the context of the global initiative to transform energy structures and achieve near-carbon neutrality, various industries are continually exploring innovative pathways to sustainable development. Achieving carbon neutrality is contingent upon the transformation of the electricity energy mix. In the domain of agricultural product cold chain logistics, there is an urgent need for technological innovations that are energy-efficient and high-performance.

A growing body of research has demonstrated the efficacy of a biological natural gas cooling cycle, in conjunction with the utilization of crisscross-arranged shelves and a cargo frame tilted at 15°, as a highly effective method for cold classification of fruits and vegetables. This approach offers substantial advantages for cold diversification, as it can be adaptively employed within diverse temperature zones within cold storage facilities, thereby enabling precise control of the storage temperatures required for various fruit and vegetable varieties. In the context of energy structure adjustments aimed at reducing carbon emissions and improving energy efficiency, the energy-saving characteristics of this cold classification technology for fruits and vegetables are highly consistent with this trend.

A comparison of the traditional flat-loading shelf method with the innovative approach reveals that, following the adoption of the latter, regional temperature differences within the cold storage exhibit a gradient distribution. This modification has led to a substantial enhancement in the temperature uniformity index, with an observed increase of 26.19%. The enhancement in temperature uniformity engenders a more stable storage environment for fruits and vegetables, while concomitantly effecting a substantial augmentation in the cooling rate by 3.36%. This facilitates the expeditious attainment of the optimal storage temperature by fruits and vegetables, thereby mitigating the potential for losses attributable to suboptimal storage conditions. In terms of energy utilization efficiency, this method demonstrates remarkable efficacy, achieving a reduction in energy consumption of approximately 10.05%, thereby addressing the pressing need for energy conservation and emission reduction. Concurrently, the deviation in the temperature uniformity of the cold flow field is reduced by approximately 5.53%, thereby further ensuring the stability of the temperature environment within the cold storage and providing robust support for the long-term preservation of fruits and vegetables.

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