Energy consumption analysis and optimization of cold stores considering differential electricity price

Jie Wang[a,b], Qiusen Wang[a,b], Peng Yang*[a,b], Jie Yu[a,b], Li Xiao[b,c]

[a] *Division of Logistics and Transportation, Shenzhen International Graduates School, Tsinghua University, Shenzhen, 518055, China*

[b] *Institution of data and information, Shenzhen International Graduates School, Tsinghua University, Shenzhen, 518055, China*

[c] *Tsinghua-Berkeley Shenzhen Institute, Shenzhen International Graduates School, Tsinghua University, Shenzhen, 518055, China*

Abstract

Despite the rapid development of cold stores, most cold stores facilities exhibit high energy consumption. Reducing energy costs in cold stores is crucial for minimizing operating expenses and effectively managing the overall cold supply chain. Our objective is to optimize the operational strategy of cold stores based on differential pricing to minimize energy consumption. Firstly, we employ computational fluid dynamics simulation to model the operation of cold stores and determine optimal boundary conditions. Secondly, we propose a comprehensive method for accounting cold stores energy consumption by considering heat conduction from the enclosure structure as well as air seepage. Additionally, under the conditions of extra cool-storage at low electricity price, we divide the cold stores operation process into four stages and establish a mathematical model for optimizing energy consumption throughout the entire operational cycle based on differential electricity pricing policies. Finally, three cities are selected for case analysis purposes. The results demonstrate that all three cities achieve an average energy saving level exceeding 8%, with Harbin city achieving over 18% savings specifically, thereby validating that our optimization model can yield superior results in northern cities characterized by significant diurnal temperature variations.

Keywords: cold stores; Energy consumption; Energy saving; Operation; Differential electricity price

1. Introduction

According to the Global Cold Chain Alliance, the total cold stores capacity in China was 131 million cubic meters in 2020, an increase of about 25% over 2018 (1). At the same time, the energy consumption of cold stores is also increasing yearly (2). According to the survey (1), the maximum energy consumption of the unit storage is more than five times the minimum, which shows that under the same conditions, the energy consumption indicators of the unit product could be much different, and there is a great potential in the operation of the cold stores in terms of energy saving. Despite the rapid development of cold stores volume in China, numerous problems exist, such as unreasonable internal design structure and single operation mode mismatched with time-of-use price in most cold stores (3). In the food industry, for example, the energy consumption of refrigeration systems, including production, circulation and storage, accounts for 35.0% of the total energy consumption of the food industry (4), with a total energy consumption of 1,300 TWH/year worldwide. At the same time, most small cold stores lack a comprehensive consideration of energy consumption costs in the construction process, resulting in the cost of cold chain logistics being more than 40.0% higher than that of ordinary logistics (5). Reducing the energy consumption cost of cold stores is a significant problem to be solved in energy conservation and emission reduction.

Currently, the installed scale of new energy in China continues to expand, and the power consumption structure is changing rapidly. At the same time, the electricity load shows the characteristics of a "double peak" in winter and summer, and the power production and consumption sides fluctuate sharply in both directions (6). The time-of-use electricity price mechanism (7) is designed based on the time value of electric energy, which is a critical

Email address: yang.peng@sz.tsinghua.edu.cn (Peng Yang*)

arrangement to guide power users to cut peaks, fill valleys, and ensure the power system's safe, stable and economical operation (8). The time-of-use electricity price mechanism can be further divided into peak-to-valley and seasonal electricity prices. The peak-to-valley electricity price mechanism is to divide a day into peaks, flat sections, and troughs, and the seasonal electricity price mechanism is to divide the peak-to-valley periods into further summer non-summer to make different electricity prices for each period (9). Time-of-use pricing mechanism can give full play to the role of electricity price signals and guide power users to use less electricity in peak hours and more electricity in off-peak hours to improve the overall utilization efficiency of the system (10, 11). Many scholars have explored the application of time-of-use (TOU), which is a kind of differential electricity price policy, in various buildings, such as office buildings (12), supermarkets (13), solar trigeneration system (14), pricing electricity markets (15), energy system (16) and residential buildings (17), proving that differential electricity price strategy can reduce the total cost of electricity consumption. cold stores as large energy consumption, TOU price in the field of cold stores research value exploration. However, the existing studies generally have the following two deficiencies: On the one hand, the calculation of energy consumption of cold stores is not comprehensive enough, such as ignoring the large amount of cold air infiltration caused by opening and closing the door when picking up goods (18) and failing to consider the influence of the surrounding environment on heat dissipation to the cold stores through a large temperature difference (19). The above neglect will lead to excessive reduction of energy consumption and cost. On the other hand, some studies lack the analysis of energy consumption and the impact of energy-saving measures from the perspective of mathematical models, but through experimental simulation (20), resulting in the lack of applicability of the conclusions, which cannot be applied and extended to other cold stores.

In our study, we consider the operation of small cold stores and focus on the calculation and energy-saving optimization of cold stores energy consumption under the time-sharing pricing strategy. The study mainly explores the following questions:

1) Which kind of cold stores design scheme better combines cooling efficiency and energy saving?
2) How to achieve a more comprehensive and accurate cold stores energy consumption accounting?
3) How to optimize the scheduling strategy of cold stores based on TOU price to achieve energy savings and cost reduction? And are there differences among different regions and cities?

The main contributions of this paper are as follows: (1) We use the computational fluid dynamics simulation method to calculate and characterize the operation of cold stores under different parameter settings to explore the optimal boundary conditions of cold stores operation. (2) We use thermodynamics knowledge to calculate heat conduction from enclosure structure to cold stores and stimulation method and empirical formula to calculate the energy consumption accounting for air seepage caused by hot pressure, achieving a more comprehensive cold stores energy accounting. (3) With the operation energy consumption cost as the objective function, we are among the first to design the energy consumption optimization model for cold stores based on the differential electricity price by dividing the cold stores operation process into four states. (4) We explore the effect of outdoor temperature conditions on the model and the difference in the effect of this optimization model in different regions, providing management insights for practical cold stores operation solutions.

The relevant literature is reviewed in the second section. In section 3, we summarize this study's methodological framework and technical route. Section 4 simulates the operating conditions under different wind speeds, fan positions, and goods stacking modes based on the ANSYS FLUENT platform. Section 5 presents the method of energy consumption accounting. In section 6, we design the optimization model of periodic energy consumption of cold stores. Numerical experiments of different cities are given in Section 7. Finally, we highlights the conclusions and recommendations for future works.

2. Literature Review

2.1. Computational fluid dynamics in cold stores

Computational fluid dynamics uses the computer's high-speed solution ability and imaging ability to calculate and present the control equation of each part of the fluid in real time

(21). CFD is applied to cold stores, which can accurately predict the air flow distribution inside the cold stores and the temperature field and velocity field of the cold stores (22). Yang *et al.* (20) simulate the internal and external environment by computational fluid dynamics of the small fruit and vegetable cold stores, considering the internal environment's flow field changes and setting the boundary condition as the unsteady state flow field condition. Xie *et al.* (23) used a combination of experiment and simulation to establish a turbulence model for the small cold stores and simulate the temperature and airflow field of the environment in the warehouse with the result of high confidence. Based on the above research, Xie *et al.* (24) added the Simple algorithm to optimize the simulation results and conducted a further study of the temperature distribution of the temperature field and the airflow distribution of the airfield in different directions of the refrigerator when the empty cold stores is cooled which demonstrated the relationship between the number of refrigerators and the number of air outlets. Tassou *et al.* (25) combined the fluid motion equation in the turbulence model with the energy equation to calculate the flow behavior of the ambient gas inside the cold stores, indicating that the gas in the internal environment of the cold stores does have the characteristics of a turbulent fluid. Hu *et al.* (26) simulated a small fruit and vegetable cold stores by the fluid turbulence model and concluded that the temperature uniformity in the small cold stores is related to the gas flow rate of the air outlet of the refrigerator. In order to compare the simulation effect of computational fluid dynamics in the actual cold stores operation, Tang *et al.* (27) used various meshing methods to model during the simulation. Sun (28) studied the changes in the ambient temperature and airflow fields inside the cold stores when the goods entered and exited the cold stores.

In reducing the energy consumption of cold stores, researchers are not limited to optimizing the internal structure of cold stores and cold stores insulation materials but also include physical devices developed to reduce the cooling loss of goods in and out. Chen *et al.* (29) verified that the use of air curtains in cold stores can effectively reduce the loss of cooling capacity when opening and closing the door by combining simulation and experiments. Wang (30) imagined the heat exchange of the internal and external environment when the cold stores was switched on and off as a natural convection state, then simulated and analyzed the operating condition parameters of the cold stores when the library door was opened. Li *et al.* (31) studied the time to reach the steady state from the unsteady state and finally obtained that the time required for the cold stores to re-reach the steady state was much longer than the time the door opened, which played an important role in promoting the development of air curtain. Robert *et al.* (32) used computational fluid dynamics simulation to study the crucial factors and influencing conditions of water loss on the surface of fruits and vegetables. Wang *et al.* (33) used PHOENICS software to simulate the flow and density characteristics of gases under unsteady state conditions in cold stores and to study the evaporation of the water of the goods. Nahor *et al.* (34) used the three-dimensional characteristics of computational fluid dynamics to simulate the operating conditions under empty and full-load cooling while ignoring the diversity of loaded goods. Smale *et al.* (35) elaborated and explained the various physical parameters during cold stores operation by establishing a mathematical model. Chourasia *et al.* (36) (37) researched how goods are placed in cold stores and simulated the internal temperature and airflow fields. Alemayehu *et al.* (38) took boxed fruits as an example to study the temperature field distribution and airflow field distribution inside the cold stores under different stacking forms of boxed fruits and used the flow field distribution data obtained from the cold stores of the enterprise to verify the authenticity of the simulation results.

2.2. Energy consumption accounting in cold stores

Eighty percent of the energy consumption of the cold stores refrigeration system is the cooling load in the cold stores (39). Brito *et al.* (40) simulated the cooling load of eight cold stores used for purchasing, preserving and selling agricultural fruits and vegetables, and concluded that 85% of the cooling load during cold stores work comes from the temperature difference between inside and outside and when goods enter and exist the cold stores. Gong *et al.* (41) studied the insulation materials of cold stores, showing that the heat energy conducted by the external environment through the four walls around the cold stores accounted for one-third of the total heat load of the cold stores and reduced the heat energy transmitted by the external environment to the inside of the cold stores through heat convection could effectively reduce the energy consumption level of the cold stores. Starting from the structure of the four walls of the enclosure cold stores, Liu *et al.* (42) studied the influence of the enclosure structure with different characteristics on the temperature change in cold stores. Zhou (43) studied and compared the envelope structure of automated cold stores and analyzed the influence of thermal insulation structure on the temperature increase in cold stores under different design concepts.

The research of heat transfer measurement through the opening and closing of the cold stores door when the goods enter and exit the cold stores is usually achieved by combining model simulation, empirical formulas, and experimental measurements (44). When the cold stores door is opened, the internal and external environment of the cold stores will be rapidly heat exchanged, and the temperature of the environment inside and outside the cold stores will change rapidly. In order to characterize the heat exchange of the internal and external environment of the cold stores when the door is opened, Brown *et al.* (45) assumed that when the cold stores door is opened, the internal and external environmental pressure of the cold stores is constant and that the defined center section is 50% of the height of the door. Tamm (46) modified the above empirical formula when calculating the height of the central section of the cold stores gate. Fritzsche *et al.* (47) combined the simulation results with the experimental results, considering the thermal convection effect and gas friction effect when the door is opened, and proposed a correlation coefficient to express the above properties. Since their formula does not consider the exchange of internal and external airflow when the cold stores door is opened, the formula is limited. Considering that when the cold stores door is opened, although the gas flow exchange level may be different, the gas quality exchange must be consistent, Gosney *et al.* (48) proposed a modified version of the calculation formula. Pham *et al.* (49) used the simulation and experimental results to estimate the exchange of internal and external gas when the cold stores door opened and proposed a modified version of Tamm's formula. Yang (50) combined numerical simulation experiments and empirical formulas to carefully analyze the flow field changes at the door when the door was opened under different wind speeds and outdoor temperatures. At low wind speeds, the calculated Computational Fluid Dynamics values align with Gosney's empirical formula, while at larger wind speeds of more than 2.2 m/s, the Fritzsche and the Pham formula agree better. He (51) summarized and compared the above five empirical formulas of cold air permeability, compared and corrected the above empirical formulas through the simulation conclusions of computational fluid dynamics, and obtained the Gosney formula and the calculation results of the Fritzsche formula and Tamm correction formula were consistent with the simulation results of computational fluid dynamics.

2.3. Operation optimization of cold stores based on TOU price

By analyzing the energy consumption sources of cold stores, it can be found that the refrigeration system composed of compressors as the main components of cold stores is a large energy consumption user of cold stores (39). The components in the refrigeration system can maintain the frequency conversion working mode under the principle of automatic control and adjust their energy consumption power according to the external cooling load level (52). However, due to the lack of an effective operation adjustment mode, the energy-saving efficiency of the frequency conversion cold stores is low (53–55). By studying the energy balance of cold stores, Liu (18) established the cold stores operation strategy based on the peak-to-valley electricity price mode. It is concluded that excessive cold stores can reduce energy consumption mainly due to the TOU price and the significant influence of external ambient temperature on the energy consumption of cold stores is noted. However, it ignores the large amount of cold air penetration caused by opening and closing the door when the cold stores picks up the goods and does not consider the influence of the surrounding environment to dissipate heat into the cold stores through higher temperature differences during excessive cold stores. Zhao (19) carried out numerical simulation and experimental verification of the energy consumption of cold stores in a city in the northern region, finding the significant influence of the external ambient temperature on the energy consumption level of the cold stores. He established the mathematical expression of the ambient temperature outside the warehouse and the internal temperature of the cold stores and analyzed the degree of influence of each parameter of the cold stores on the internal temperature drop of the cold stores at the quantitative level. However, the impact of energy consumption analysis and energy-saving measures is not given from the perspective of a mathematical model, so the conclusion cannot be applied and generalized to other cold stores in the region and other regions.

From the above literature review, computational fluid dynamics is an effective method for simulating and analyzing cold stores operating conditions, which will be applied in Chapter 4. Although many scholars have put forward empirical formulas in cold stores energy consumption accounting, there still needs to be a more comprehensive and accurate accounting method, which will be supplemented in Chapter 5. The energy consumption estimation considered by the existing research on energy consumption optimization of cold stores is not comprehensive enough. Therefore, Our research attempts to fill the research gap and put forward a more applicable energy consumption optimization model, mainly carried out in Chapter 6.

3. Methodology

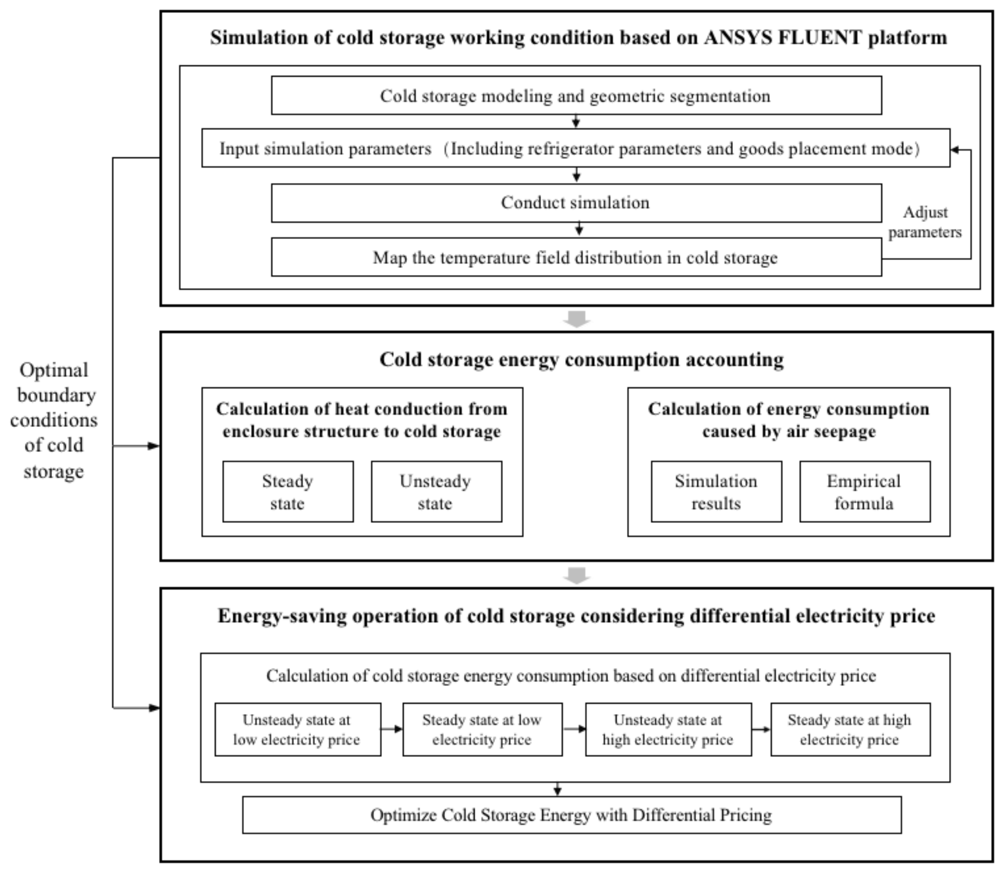


Figure 1: The technical route of the research

In this chapter, we focus on the specific methods to achieve the research problems of the article. The technical route of the research is shown in Fig. 1. First, as the basis of energy consumption accounting and optimization, we use the computational fluid dynamics method to simulate cold stores and determine the optimal boundary parameters. The cold stores is modeled and meshed by NX software and ANSYS FLUENT platform. Then, the refrigerator's position, the refrigerator's wind speed, and the mode of the goods in the cold stores are simulated, and the best boundary parameters are selected by calculating and drawing the temperature distribution diagram in the cold stores.

Secondly, we propose a more comprehensive energy consumption calculation for cold stores. The primary consideration is heat conduction from the enclosure structure to cold stores and energy consumption accounting for air seepage caused by hot pressure. For heat transfer from the outside world to the cold stores through the enclosure structure, the cold stores is considered a steady state and an unsteady state, and the heat conduction in the two states is calculated, respectively. For the thermal penetration caused by opening and closing doors, the permeability is calculated by simulation method and compared with the results calculated by empirical formula.

Finally, considering differential electricity price, the cold stores operation is optimized. Based on differential electricity price, we set the cold stores to over-store cold when the cold stores with high energy consumption runs at valley hour electricity price and reduce energy consumption when the cold stores runs at peak hour electricity price. This operation scheduling mode can reduce the overall energy consumption cost of the cold stores operation. On this premise, the cold stores is divided into four stages, in which energy consumption is calculated respectively. The relationship between the total operating energy consumption of the cold stores, the ambient temperature, and the set temperature is obtained. After that, in the case of a given ambient temperature, the optimal cold stores setting temperature is found so that the energy consumption cost of the cold stores is lowest.

4. Determining the optimal boundary parameters by simulation

4.1. cold stores setup

We consider a small suspended ceiling cold stores for frozen meat whose length, width, and height are 5.0m, 2.8m, and 2.5m. The air output of the refrigerator is 4000 cubic meters per hour, and its length, width, and height are 1.5m, 0.6m, and 0.5m, respectively. The PU insulation board is selected for the surrounding protection materials around the cold stores, its thickness is set to 100mm. In this part, we do not consider the influence of external heat penetration, which is the focus of energy consumption accounting in Chapter 5 and does not influence our determination of the optimal boundary parameters of cold stores. Therefore, we make some assumptions: (1) the cold stores is isolated from the external environment; (2) the internal structure does not affect the gas flow and compression; (3) the external temperature is constant during the cooling process.

The flow field distribution in the cold stores is due to the low temperature and a certain speed of the low temperature and a certain speed are blown into the cold stores by the air outlet of the refrigerator in the cold stores so that the air in the library is constantly convective under the action of pressure and temperature. Due to the high Reynolds number in this flow field, the flow field distribution in the cold stores can be considered as turbulent flow field (25, 26), the mathematical model shown in Appendix A. Then, based on the ANSYS FLUENT platform, the computational fluid dynamics method is used to simulate the flow field and temperature cloud in cold stores under different wind speeds, refrigerator positions, and goods stacking modes.

4.2. cold stores simulation without goods

First, we consider the case that there is no storage of goods in the cold stores, and determine the optimal location and wind speed of the refrigerator. Three kinds of refrigerator positions are stimulated: opposite the cold stores door, upper side, and the same side, as shown in Fig. 2. We used NX SOFTWARE (56) to model its geometric structure and then used ANSYS FLUENT PREPROCESS SOFTWARE (57) to divide the grid, and the division results are shown in Fig. 3.

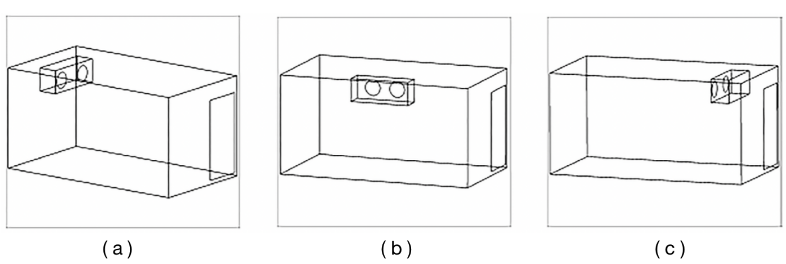


Figure 2: Different placement positions of the refrigerator. (a) Opposite the door; (b) On the side of the door; (c) On the same side of the door

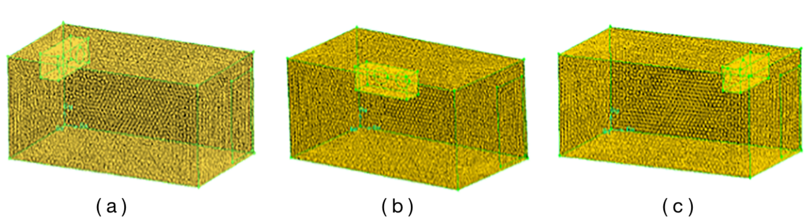


Figure 3: Grid division of different refrigerator placement positions in cold stores. (a) Opposite the door; (b) On the side of the door; (c) On the same side of the door

We set up the boundary conditions[1] empirically and choose the iteration step of 1 minute to analyze the influence of the refrigerator on the temperature field at different positions of the cold stores.

[1]**Inlet boundary**: the air velocity of the refrigerator outlet is set as 9.3 m/s, the size of the air temper-

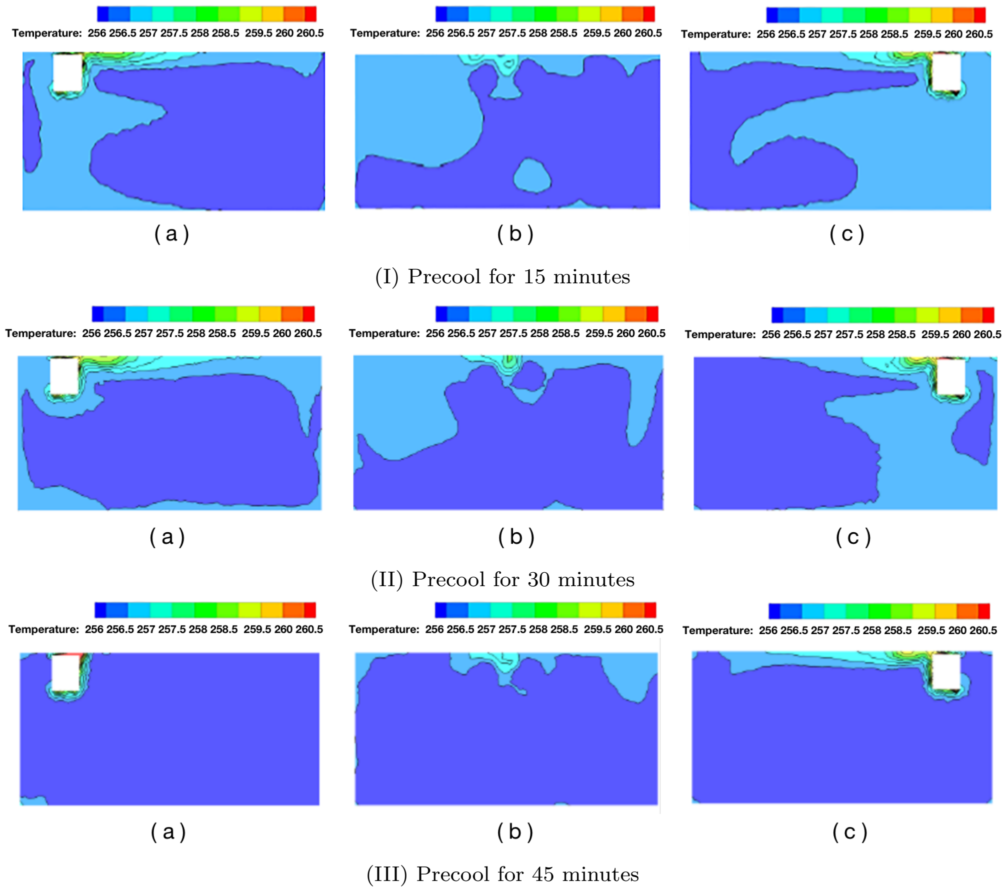


Figure 4: Z-plane temperature diagram inside cold stores. (a) Opposite the door; (b) On the side of the door; (c) On the same side of the door

Fig. 4 depict the Z-plane temperature field after varying cooling times with the refrigerator placed in three positions relative to the cold stores door. The most pronounced temperature drop occurs within the first 15 minutes, with over 80% of the cold stores content below the maximum storage temperature[2] of the goods. Among the three placements, the refrigerator opposite the door achieves the most efficient cooling, since its airflow is not affected by the surrounding structure of cold stores, and the heat transfer effect of heat convection is the most full. However, when positioned on the same side as the door, the cooling is less effective, resulting in the high-temperature area in the warehouse concentrated on the side of the refrigerator. With the slow passing of refrigeration time, the refrigeration area of the three cases constantly expands. By 45 minutes, the refrigerator facing the cold stores door nearly cools the entire cold stores, while the other positions still have a refrigeration blind area.

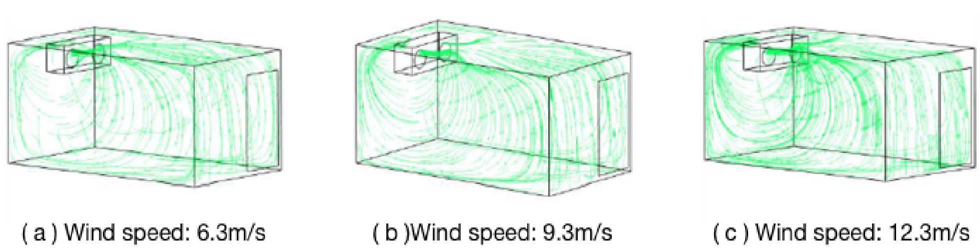
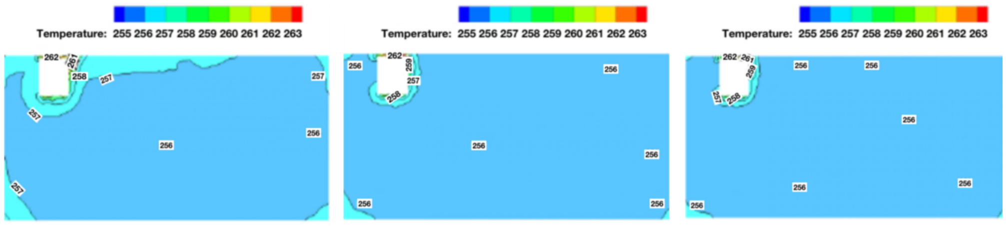


Figure 5: Flow diagram of cold stores at different refrigerator wind speeds

Moreover, we explore the refrigerator's wind speed, which significantly impacts the air distribution, refrigeration efficiency, and energy-saving performance of cold stores. The air speed of the refrigerator outlet is set to 6.3m/s, 9.3m/s, and 12.3m/s, and we obtain the distribution diagram of the cold stores gas flow field, as shown in Fig. 5. It can be seen

ature of the refrigerator outlet is set as -18°C; **Outlet boundary**: the boundary condition is set as the free outlet; **Surrounding surface**: the enclosure material of the refrigerator is set as stainless steel material, the enclosure material around the cold stores is set as polyurethane foam board, the boundary condition of the enclosing surface is set to the first type and the initial temperature of it is selected as room temperature.

[2]**Maximum storage temperature** refers to the highest temperature that certain goods or products can withstand during storage or transportation, exceeding which may cause the quality of the goods to decline or damage.



(a) Wind speed: 6.3m/s (b)Wind speed: 9.3m/s (c) Wind speed: 12.3m/s

Figure 6: Temperature cloud image of cold stores at different refrigerator wind speeds

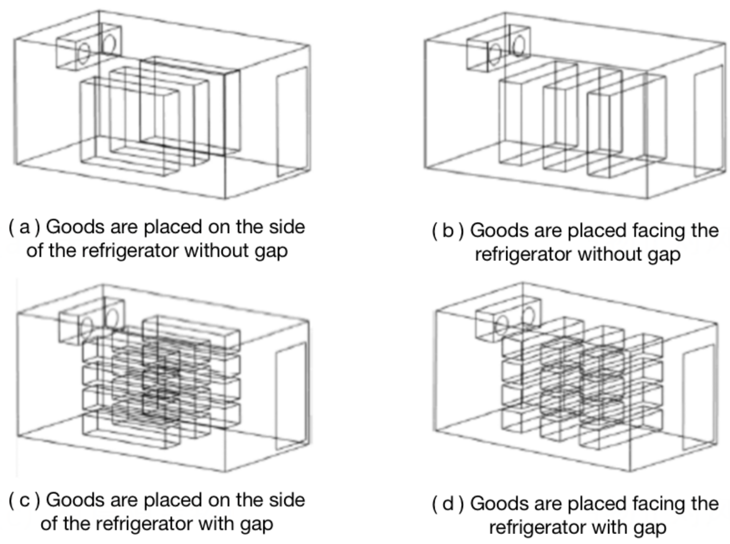


Figure 7: Different goods layout corresponding schematic

that, at a speed of 6.3m/s, part of the airflow slows down and stops at the cold stores door. With the increase in wind speed, the gas proportion in the return air area increases. However, at 12.3m/s, the high kinetic energy airflow back forms an obstacle, affecting the structure of the cold stores door and reducing the refrigeration efficiency. Besides, the cross-section diagram of the temperature field (Fig. 6) shows that there is still a high-temperature blind spot at 6.3m/s velocity. As the wind speed increases, these blind spots shrink, but the difference between 9.3m/s and 12.3m/s is slight, indicating that the marginal benefit of cooling decreases. Therefore, the wind speed of 9.3m/s is chosen for this cold stores, ensuring refrigeration efficiency, uniform cooling, and energy saving.

4.3. cold stores simulation with goods

Based on the stimulation result of Chapter 4.2, we place the refrigerator on the opposite side of the cold stores door, set the wind speed at 9.3m/s, and consider four goods placement methods, as shown in Fig. 7. The stacking method of the unlayered cache is 0.5m apart from the row, and that of the layered cache is divided into four layers in the space, with each layer spacing of 0.1m. The storage is located in the center of the cold stores, and its bottom layer is 0.1m above the ground. Then, we set up the boundary conditions[3] to simulate the cold stores with the goods to determine the optimal way to place the goods in the cold stores.

Fig. 8 shows the temperature field distribution of cold stores under different placing modes of goods. When the goods are placed on the side of the refrigerator, the temperature distribution in the cold stores is not uniform. In particular, when the goods are placed on the side of the refrigerator without a layer gap, a large number of low-temperature gases accumulated above the cold stores door can not quickly return to the refrigerator return air outlet, considerably slowing down the return airspeed, resulting in a high-temperature blind area under the chiller, and the refrigeration effect is not good. When the goods are placed facing the refrigerator, the temperature distribution in the cold stores is more uniform, and most areas can effectively cool down. Further, as we can see from the temperature distribution of the goods after 45 minutes of cooling, shown in Fig. 9, the goods arrangement

[3]The boundary condition settings are mainly based on those in Chapter 4.2. Moreover, the goods' storage mode is added and set as frozen meat products. The temperature of stored meat transported into the cold stores is set at room temperature, and the specific heat capacity of meat is selected to calculate the cold stores capacity of stored goods. The heat exchange mode between the internal environment of the cold stores and the stored meat is set as heat convection coupling.

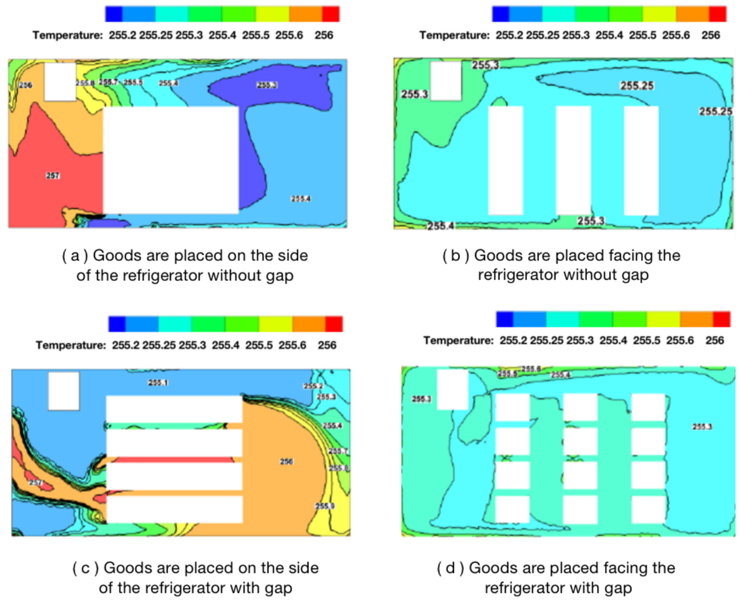


Figure 8: The temperature inside the cold stores

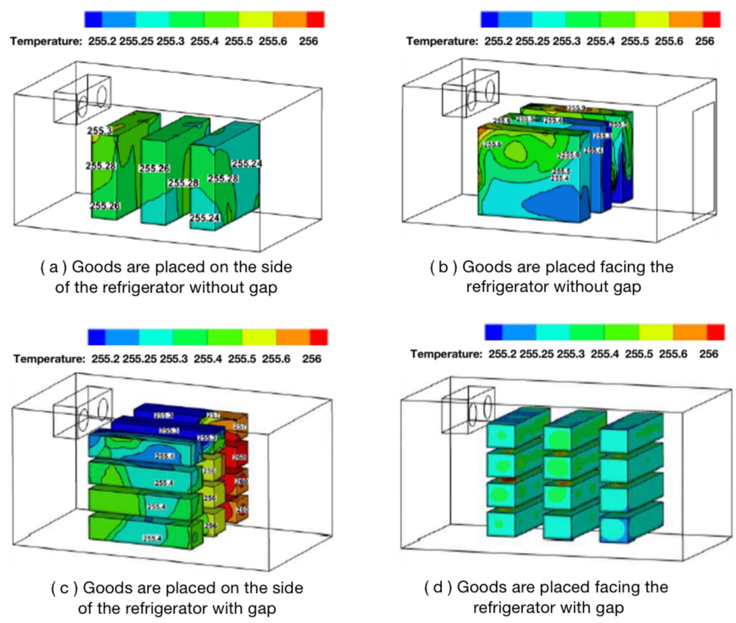


Figure 9: The temperature of goods in cold stores

without a layer gap will hinder the air return, resulting in a low temperature of the external goods and a slightly higher temperature of the internal goods. When there is a gap between the goods, especially when the goods are placed against the refrigerator, the temperature distribution of the goods is relatively uniform because the multi-layer obstruction gap slows down the gas flow rate. The gas slowly returns to the return air area, making the cooling area of the cold stores center relatively uniform and stable. Therefore, for this cold stores, the layered gap and the refrigerator-oriented discharging method are more conducive to the uniform cooling of goods and improve the refrigeration efficiency of the refrigerator.

5. Energy consumption analysis

Cooling load in the cold stores, which refers to the total heat that must be removed or replenished by the refrigeration system to maintain a specific temperature and humidity condition for a specific period (58), is the main energy consumption of the cold stores refrigeration system. Accurate cooling load estimation is the basis to ensure that the temperature inside the cold stores is maintained within the desired range while reducing unnecessary energy loss (59). Since the heat conduction from enclosure structure to cold stores and the energy consumption accounting for air seepage caused by hot pressure account for 85% of the cooling load sources (60), we focus on these two sources of these cooling loads and calculate the cold stores's energy consumption. Table 1 shows the definitions of symbols.

Symbol	Meaning and units
Q_{load}	Total power of cooling load during cold stores operation (W)
Q_{Wall}	Power that the outside world conduct heat into the cold stores through the enclosure in the cold stores (vault roof, fence and floor) (W)
EER	Energy efficiency ratio (cooling coefficient) at rated power of this refrigerator
T_{ini}	The initial temperature at which the cold stores starts a new operating cycle (°C)
T_c	The temperature set at which the refrigerator over-stores cold(°C)
T_0	The ambient temperature outside the cold stores when the cold stores is running(°C)
v	The speed of air seepage at the door of the cold stores (m/s)
A	The ratio of the heat exchange area of the insulation material around the cold stores to the thickness of the insulation material (m)
λ	The thermal conductivity of the material
c_p	The specific heat capacity of the air at the temperature (J/Kg°C)
c_v	The average specific heat capacity of the goods in the cold stores (J/Kg°C)
m_p	The quality of the air in the cold stores (Kg)
m_v	The quality of the goods in the cold stores (Kg)
t_{11}	Unsteady period of low electricity price
t_{12}	Steady period of low electricity price
t_{21}	Unsteady period of high electricity price
t_{22}	Steady period of high electricity price
W_0	The rated power of the refrigerator for operation (W)
W_{11}	Refrigerating power during the unsteady period of low electricity price
W_{12}	Refrigerating power during the steady period of low electricity price
W_{21}	Refrigerating power during the unsteady period of high electricity price
W_{22}	Refrigerating power during the steady period of high electricity price

Table 1: Symbols definition of cold stores energy consumption model

5.1. Calculation of heat conduction from enclosure structure to cold stores

When the cold stores starts to operate, the temperature in the warehouse is different from the ambient temperature, and the refrigerator will use the rated power for cooling to ensure that the temperature quickly drops to the maximum storage temperature of goods. When the temperature in the warehouse reaches the set temperature level, the refrigerator will no longer operate at the rated power but operate at a lower energy consumption level and keep the temperature in the warehouse below the maximum storage temperature. Therefore, the refrigerator's operation alternates in these two ways and the cooling load dissipated by the envelope structure will experience two states of steady state and unsteady state during the operation of the cold stores.

5.1.1. Unsteady state

When the refrigerator precools or the set temperature of the refrigerator changes, it is an unsteady state that the temperature in the cold stores is constantly changing continuously, resulting in continuous changes in the temperature difference between inside and outside the warehouse at this time, the method of establishing a differential equation for the temperature change in a very short time can be used to seek the change function of the cooling load with time to solve.

Assuming that the cold stores begins to over-store cold at an initial temperature T_{ini} and sets the temperature $T_c < T_{ini}$, the cooling power of the cold air mechanism is W. In order to find the function relationship of the temperature T in the cold stores with time, take a minimal time period $[T, T + dT]$ in a small period, the temperature change in the cold stores is almost 0, and the energy consumption relationship is:

$$Wdt = -(c_p m_p + c_v m_v)dT + \lambda A(T_0 - T)dT + Q_0 dT. \tag{1}$$

where Q_0 represents the average power of other cooling loads during that period (here, we mainly consider the air seepage caused by hot pressure, which will be discussed in Chapter 5.2).

5.1.2. Steady state

During a steady state, the refrigerator always runs at the same set temperature, and the temperature difference between indoors and outdoors is basically unchanged, which can be simplified into a steady-state heat conduction model to solve. Generally, the enclosure material around the cold stores comprises inner and outer layers of fixed materials and internal insulation materials, as shown in Fig. 10. The steady-state model is regarded as a heat conduction model, and its heat transfer coefficient is the heat transfer coefficient after the three layers of materials are connected in series. However, since the fixed materials generally choose the materials with hard texture but poor insulation effect and thin thickness, the thermal insulation coefficient of the composite material can be approximately equal to the heat transfer coefficient of the thermal insulation materials in the middle of the fixed materials. The heat transfer equation is as follows:

$$Q_{Wall} = \lambda A(T_0 - T_C) \tag{2}$$

It can be seen from the above that the heat dissipation power of the envelope structure to the cold stores during the steady state and unsteady state is always closely related to the set temperature of the cold stores, the selection of insulation materials and the difference between inside and outside temperatures of the warehouse.

5.2. *Calculation of energy consumption accounting for air seepage caused by hot pressure*

Research related to heat conduction when the goods enter and exit the cold stores is usually implemented by the combination of model simulation, empirical formula, and experimental measurement. In order to obtain the simulation model results and the input parameters of the empirical formula, we simulate the state of the door when opening and closing, and the boundary conditions are designed the same as the working conditions introduced in Chapter 4.2. Then, parameters such as air temperature and velocity obtained by simulation are input into the empirical formulas reviewed in Chapter 2.2 (the specific formulas are presented in Appendix B and compared with the permeability obtained by simulation, as shown in Table 2.

It can be seen that the simulated permeability is most similar to the empirical formula proposed by Pham, who improved that proposed by Tamm by considering the internal and external gas exchange when the cold stores door is opened. Therefore, we use simulation data to calculate the heat loss caused by heat penetration when the cold stores is opened and closed.

Empirical calculation / Results	Simulate prediction	Empirical formula			
		Tamm(46)	Fritzsche(47)	Gosney(48)	Pham(49)(Tamm revised)
Permeability (m^3/s)	0.3216	0.4321	0.3374	0.3105	0.3292
Error rate	-	34.36%	4.91%	-3.45%	2.36%

Table 2: Comparison of air seepage energy consumption in cold stores

6. Energy-saving operation of cold stores considering differential electricity price

According to the simulation results, the pre-cooling time of cold stores is usually between 40-45min. When the set temperature drops, the time will become shorter, and the peak-valley period of industrial electricity consumption is usually longer than 120 minutes. Therefore, if the cold stores over accumulates at a low electricity price and reduces energy consumption at a high electricity price, it needs to experience stable and unstable stages at the low and high electricity price, as shown in Fig. 11. In this section, We first calculate the energy consumption of cold stores under these four states and then design the energy-saving operation strategy for cold stores under differential electricity price.

6.1. *Mathematical model of cold stores energy consumption based on differential electricity price*

6.1.1. *Calculation of energy consumption at low electricity prices*

Assuming that the cold stores begins to over-store cold at an initial temperature T_{ini} and sets the temperature $T_c < T_{ini}$, the cooling power of the cold air mechanism under low electricity price is W_{11}, in order to find the functional relationship of the temperature T in the cold stores with time, take a very small period $[T, T + dT]$ which the temperature change is almost 0, and the energy consumption relationship is found as:

$$W_{11}dt = -(c_p m_p + c_v m_v)dT + \lambda A(T_0 - T)dT + Q_0 dT, \tag{3}$$

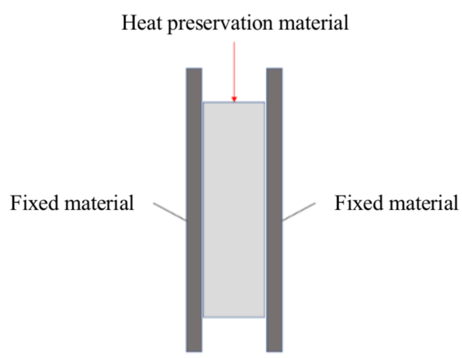


Figure 10: cold stores's insulation structure

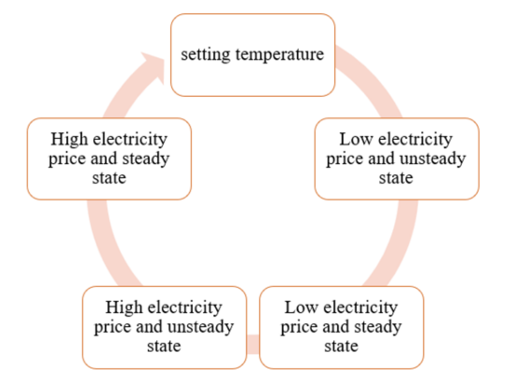


Figure 11: Four states in cold stores's operating cycle

where the value of Q_0 can be obtained in chapter 5.2 using simulation and empirical formulas. Through the transfer integral, we can get:

$$t_{11} = \int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0 - W_{11}} dT. \tag{4}$$

According to Formula 16, the system running time t_{11} in the unsteady process is obtained, then we get t_{12} by:

$$t_{12} = t_1 - t_{11}. \tag{5}$$

At the same time, after lowering the set temperature, the overall power of the refrigerator is rated power, so the refrigerating power during the unsteady period of low electricity price is:

$$W_{11} = EERW_0. \tag{6}$$

In the steady state, the refrigerator in the cold stores always operates at the same set temperature, the temperature in the cold stores remains unchanged, and the temperature difference between indoors and outdoors also remains unchanged. Therefore, This steady-state model can be simplified into a steady-state heat conduction model for solving and the refrigerating power during the steady period of low electricity price is:

$$W_{12} = \lambda A(T_0 - T_C) + Q_0. \tag{7}$$

6.1.2. Calculation of energy consumption at high electricity prices

Assuming that the cold stores enters the high electricity price stage after reaching the set temperature of $T_c < T_{ini}$, the refrigerator does not work, so its cooling power is 0. In order to find the functional relationship of the temperature T with time, take a very small period $[T, T + dT]$ in which the temperature change is almost 0, and the energy consumption relationship is:

$$0 = -(c_p m_p + c_v m_v)dT + \lambda A(T_0 - T)dT + Q_0 dT. \tag{8}$$

And we get:

$$T_{21} = \int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0} dT, \tag{9}$$

and

$$t_{22} = t_2 - t_{21}. \tag{10}$$

Similarly, the refrigerating power during the steady period of high electricity price is:

$$W_{22} = \lambda A(T_0 - T_{ini}) + Q_0. \tag{11}$$

6.1.3. Calculation of energy consumption of operating cycle based on differential electricity price

Since the high energy consumption cold stores accumulates cold when the valley time electricity price is running and reduces energy consumption when the peak time electricity price is running, it must go through the above four stages to complete the operation of one cycle. Therefore, the objective function of energy consumption in one cycle is:

$$min(power) = (t_{11}W_{11} + t_{12}W_{12}) + t_{22}W_{22}. \tag{12}$$

By adding the differential electricity price model, the objective function of energy consumption cost in a single cycle is:

$$min(price) = price_1(t_{11}W_{11} + t_{12}W_{12}) + price_2 t_{22}W_{22}. \tag{13}$$

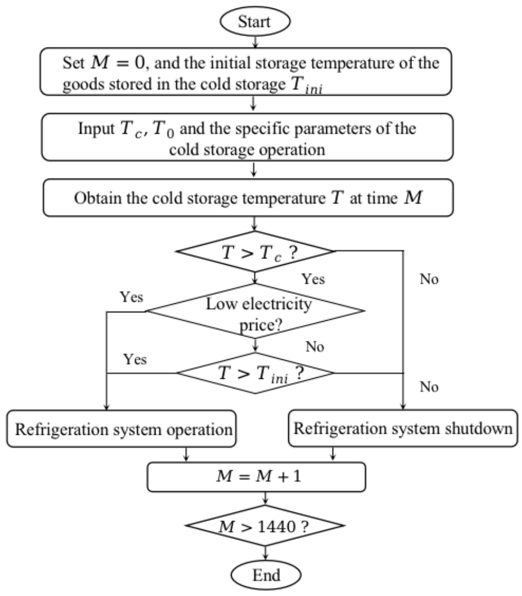


Figure 12: Operation scheduling flow chart based on differential electricity price

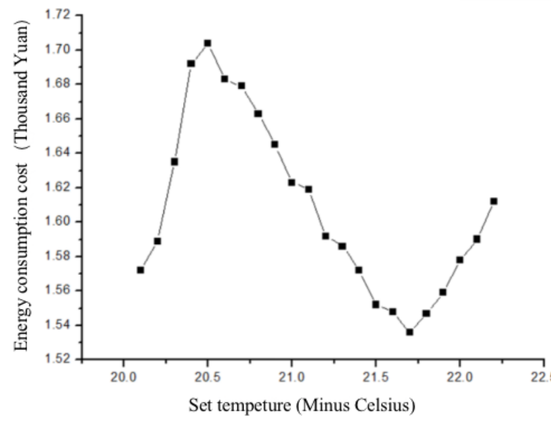


Figure 13: The optimal set temperature under ambient temperature in June in Harbin

By combining the equations (3)-(13), the following function expression can be obtained:

$$\begin{aligned} min(power) = (&\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0 - EERW_0)} dT EERW_0 + \\ [t_1 - &\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0 - EERW_0} dT][\lambda A(T_0 - T_c) + Q_0]) \\ +([t_2 - &\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T_{ini}) + Q_0} dT][\lambda A(T_0 - T) + Q_0]), \end{aligned} \tag{14}$$

$$\begin{aligned} min(price) = price_1(&\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0 - EERW_0)} dT EERW_0 + \\ [t_1 - &\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T) + Q_0 - EERW_0} dT][\lambda A(T_0 - T_c) + Q_0]) \\ +price_2([t_2 - &\int_{T_{ini}}^{T_c} \frac{c_p m_p + c_v m_v}{\lambda A(T_0 - T_{ini}) + Q_0} dT][\lambda A(T_0 - T) + Q_0]). \end{aligned} \tag{15}$$

6.2. Energy-saving operation strategy for cold stores based on differential electricity price

According to equation (15), after the specific parameters of the cold stores (cold stores structure, goods storage mode, specific parameters of the refrigerator, etc.) and the ambient temperature outside the cold stores T_0 are determined, the variable of the objective function is the set temperature of the cold stores T_c. Therefore, the characteristics of set temperature can be adjusted periodically according to the changes in the cold stores along with the differential electricity price. We design the energy-saving operation strategy of cold store considering differential electricity price, as shown in Fig. 12.

First, at the beginning of the cold stores operation scheduling process, set the initial temperature T_{ini} of the cold stores operation. Then, the specific operating parameters for cold stores that we obtain by stimulation in Chapter 2, including cold stores structure, goods storage mode, and refrigerator parameters, are input and the ambient temperature T_0 outside the cold stores. These parameters will affect the cost level function of energy consumption of the cold stores, thus affecting the operation and scheduling of the cold stores. Besides, input the set temperature T_c of the cold stores, which is obtained by solving the mathematical model of the periodic energy consumption of the cold stores. After that, The cold stores and set temperatures are judged in real-time. When the cold stores temperature is lower than the set temperature, the cold stores refrigeration system stops working. When the temperature in the cold stores is higher than the set temperature, the cold stores refrigeration system determines whether excessive cold stores is necessary. If this is a period of low electricity prices, the refrigeration system determines that excessive cold stores is carried out. The end of excessive cold stores indicates that the temperature in the cold stores reaches the set temperature. At this time, the cold stores maintains this set temperature until it enters a period of high electricity price. If this is a period of high electricity prices, the cold stores only needs to keep the temperature below the storage temperature of goods. If the temperature in

Period	Time
Peak period	9:00—11:30, 14:00—16:30, 19:00—21:00
Flat peak period	7:00—9:00, 11:30—14:00, 16:30—19:00, 21:00—23:00
Low peak period	23:00-7:00 the next day

Table 3: Time period of the differential electricity price

the cold stores is lower than this temperature, the cold stores refrigeration system will stop working immediately. Since the cold stores adjustment has a certain lag, the time interval for real-time reading of the specific parameters of the cold stores operation and the ambient temperature parameters outside the cold stores should not be too large; otherwise, it will lead to the lag of the cold stores adjustment, so that the temperature of the cold stores in some periods is higher than the storage temperature of the goods, thus affecting the quality of the stored goods. Here, the cold stores value is read once every minute. Hence, with one day, the maximum value of M is 1440, and the selection of the period can be changed according to the specific characteristics of different cold stores.

7. Experiments and Results

7.1. Determine the cold stores's optimal set temperature

In this section, we first analyze the cold stores operation situation in Harbin, a city in northern China, and the ambient temperature selection is based on Harbin's average temperature in June 2018. In order to consider the influence of diurnal temperature difference on the energy consumption optimization strategy, for 0 am to 6 am, the ambient temperature is set as the lowest temperature during this period; for 12 pm to 6 pm, the ambient temperature is set as the highest temperature during this period; for the rest of the day, the ambient temperature is set to the average temperature of the day.

The specific parameters of the cold stores is consistent with those in Chapter 2. Meanwhile, the switching frequency of the cold stores is set as once a day for a single time lasting 30 minutes. The time period of the differential electricity price model is shown in Table 3. The set temperature starts from -20°C, and at an interval of 0.1°C, the change curve of the energy consumption cost of cold stores is drawn under different set temperatures, as shown in Fig. 13. It can be seen that under the average environmental conditions in Harbin in June 2018, the optimal set temperature of the cold stores is -21.7°C, when the energy consumption cost is the lowest, proving the effectiveness of the strategy.

7.2. Energy-saving operation strategy under different cities

In the energy consumption optimization model, the ambient temperature, especially the diurnal temperature difference, is an important factor. Therefore, in this section, we select Harbin in the north, Shanghai in the middle, and Shenzhen in the south as experimental objects to explore the differences in energy-saving effects of this model on cold stores in different regions[4]. According to the data of the China Meteorological Administration (61), the monthly average diurnal temperature difference data of the three cities in 2018 is shown in Fig. 14. Similarly, we input the monthly average daily temperature of Harbin, Shenzhen, and Shanghai into the energy cost optimization model of the three cities, divided into three time periods: between midnight and 6 a.m., the ambient temperature is adjusted to the minimum value of that time frame; from noon until 6 p.m., the ambient temperature is adjusted to its peak value for that time slot; during all other hours, the ambient temperature is established at the day's mean value. With 0.1 °C as the interval, find the temperature that makes the energy consumption cost function minimum as the set temperature and make the best temperature of cold stores in different cities with changes in months, as shown in the Fig. 15.

It can be seen that the optimal set temperature of the cold stores in the three cities is higher in winter and lower in summer. The outdoor temperature has a great impact on the energy consumption model of the cold stores operation. When the outdoor temperature is high, a lower set temperature is needed to ensure that the cold stores has a longer cooling time and offset the influence of the indoor and outdoor temperature difference and heat

[4]The latitudes of the three cities are: (1) Harbin: 45.8°N; (2) Shanghai: 31.2°N; (3) Shenzhen: 22.5°N

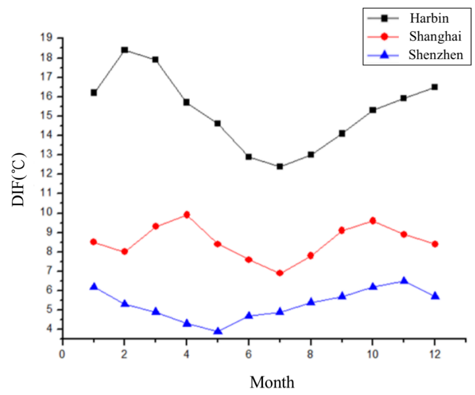


Figure 14: The diurnal temperature difference (DTF) in Harbin, Shenzhen and Shanghai

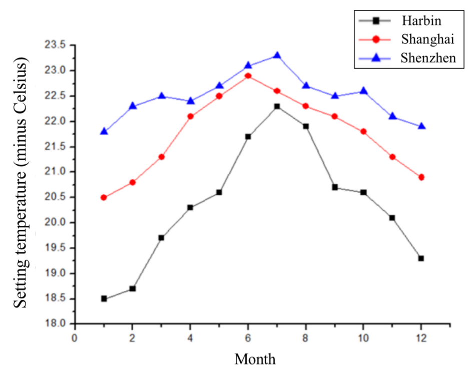


Figure 15: The monthly set temperature of cold stores in Harbin, Shenzhen and Shanghai (Unit: minus degrees Celsius)

City	Harbin	Shanghai	Shenzhen
Average energy consumption savings	16.1%	12.2%	5.2%
Average energy consumption cost savings	18.1%	15.8%	8.5%

Table 4: Annual energy consumption analysis of Harbin, Shanghai and Shenzhen

penetration caused by opening and closing doors. At the same time, the fluctuation of the optimal set temperature of the cold stores with month is the largest in Harbin and smallest in Shenzhen, indicating that the northern cities are more sensitive to the energy consumption optimization model than the southern cities.

7.3. Energy consumption optimization analysis considering diurnal temperature difference

The difference in ambient temperature will affect the choice of set temperature of cold stores and then affect the energy consumption of cold stores, which is the reason that we consider the daily temperature difference between day and night in the energy consumption optimization of Chapters 7.1 and 7.2 and set three different periods every day. In order to explore the energy-saving effect of considering the temperature difference between day and night, we consider the general situation and use the daily average temperature as the ambient temperature input for all periods.

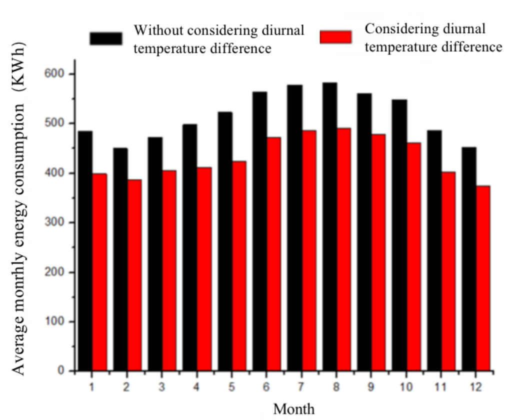


Figure 16: Energy consumption of cold stores in Harbin in each month under the two ambient temperature inputs

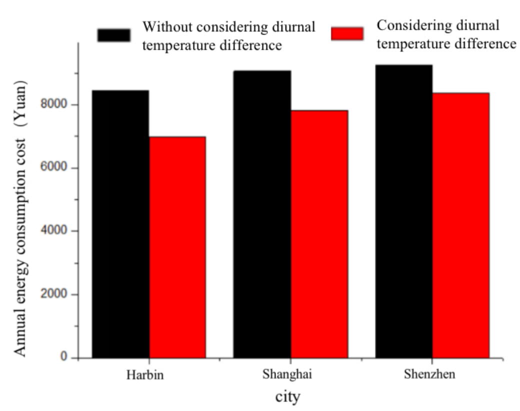


Figure 17: The annual energy consumption cost of cold stores in Harbin, Shanghai, and Shenzhen under two ambient temperature inputs

Taking Harbin as an example, the comparison of energy consumption of cold stores in each month under the two ambient temperature inputs of diurnal temperature difference and not considering diurnal temperature difference is made, as shown in the Fig. 16. It can be seen that the ambient temperature input, considering the temperature difference between day and night, can help the energy consumption optimization model obtain lower energy consumption. At the same time, we calculate the total annual energy consumption cost of cold stores in Harbin, Shanghai, and Shenzhen under two ambient temperature inputs, as shown in the Fig. 17, and summarize the optimization of the energy consumption cost of cold stores in the three cities considering the temperature difference between day and night in Table 4. It can be seen that the average energy consumption cost-saving degree of the three cities is above 8%, among which Harbin is the highest, which can save 18% of cold stores energy consumption, indicating that the energy consumption model has a more significant optimization effect on northern cities with larger diurnal temperature difference.

8. Conclusions

This study focuses on energy consumption analysis and optimization of cold stores considering differential electricity prices. Initially, we employ computational fluid dynamics to simulate cold stores operations and establish the best boundary conditions. Next, we conduct a more holistic method for calculating cold stores energy consumption, accounting for heat conduction from the enclosure and air leakage energy costs. Furthermore, we segment cold stores operations into four states and design an energy consumption optimization model for the entire operation cycle, aligned with differential electricity pricing. Finally, we select three typical cities to test the effect of the energy consumption optimization model. The conclusions of this study are summarized as follows.

1. For the cold stores we study, the optimal boundary conditions for the refrigerator and cargo placement mode based on computational fluid dynamics simulation are: the refrigerator should be positioned opposite the cold stores door with an optimal wind speed of 9.3m/s; and goods should be arranged in a layer-gap manner, facing the refrigerator.
2. The permeability obtained by calculating energy consumption accounting for air seepage caused by hot pressure using the simulation method is close to the empirical formula, especially that proposed by Pham (49).
3. The optimal setting temperature of cold stores varies with seasons and regions, lower in summer and higher in winter. The optimal set temperature of cold stores also fluctuates more in Harbin due to the larger diurnal temperature difference. Considering the diurnal temperature difference, the daily multi-period ambient temperature input can achieve a better energy-saving effect than the single ambient temperature input with the daily average temperature, especially in Harbin, which can save almost 18% of the energy cost.

In the future, we can further consider energy consumption sources in different periods, and the energy consumption model can also be calculated and analyzed from the perspective of carbon emission reduction.

References

[1] Jisung Lee, Sangkwon Jeong, Young Hee Han, and Byung Jun Park. Concept of cold energy storage for superconducting flywheel energy storage system. *IEEE Transactions on applied superconductivity*, 21(3):2221–2224, 2010.

[2] JA Evans, EC Hammond, AJ Gigiel, AM Fostera, L Reinholdt, K Fikiin, and C Zilio. Assessment of methods to reduce the energy consumption of food cold stores. *Applied Thermal Engineering*, 62(2):697–705, 2014.

[3] TANG Youliang, YANG Xue, and HU Shunbao. Analysis of the current situation and development trend of domestic cold storage construction. *Science and Technology Outlook*, 15, 2016.

[4] JA Evans, AM Foster, J-M Huet, L Reinholdt, K Fikiin, C Zilio, M Houska, A Landfeld, C Bond, M Scheurs, et al. Specific energy consumption values for various refrigerated food cold stores. *Energy and Buildings*, 74:141–151, 2014.

[5] Hongxia Zhao, Sheng Liu, Changqing Tian, Gang Yan, and Da Wang. An overview of current status of cold chain in china. *International journal of refrigeration*, 88:483–495, 2018.

[6] Song Pan, Xinru Wang, Yixuan Wei, Xingxing Zhang, Csilla Gal, Guangying Ren, Da Yan, Yong Shi, Jinshun Wu, Liang Xia, et al. Cluster analysis for occupant-behavior based electricity load patterns in buildings: A case study in shanghai residences. In *Building simulation*, volume 10, pages 889–898. Springer, 2017.

[7] Michael Lanahan, Sarah Engert, Taewoo Kim, and Paulo Cesar Tabares-Velasco. Rapid visualization of the potential residential cost savings from energy storage under time-of-use electric rates. *Journal of Building Performance Simulation*, 12(1):68–81, 2019.

[8] Ruan Wenjun, Wang Beibei, Li Yang, and Yang Shengchun. Research on user response behavior under peak-valley time-of-use electricity price [j]. *Power System Technology*, 7:86–93, 2012.

[9] Mesut Avci, Murat Erkoc, Amir Rahmani, and Shihab Asfour. Model predictive hvac load control in buildings using real-time electricity pricing. *Energy and Buildings*, 60:199–209, 2013.

[10] Xueling Liu, Jianxiao Zhu, Jiansheng Wang, Yuguo Fu, Huipeng Zhang, and Jintao Niu. Zero fluctuation: Electric-fluctuation-elimination heat pump system with water storage tank based on time-of-use tax. *Energy and Buildings*, 279:112703, 2023.

[11] Kenichi Tanaka, Kosuke Uchida, Kazuki Ogimi, Tomonori Goya, Atsushi Yona, Tomonobu Senjyu, Toshihisa Funabashi, and Chul-Hwan Kim. Optimal operation by controllable loads based on smart grid topology considering insolation forecasted error. *IEEE transactions on smart grid*, 2(3):438–444, 2011.

[12] Yi Li, Jinqing Peng, He Jia, Bin Zou, Bin Hao, Tao Ma, and Xiaoyang Wang. Optimal battery schedule for grid-connected photovoltaic-battery systems of office buildings based on a dynamic programming algorithm. *Journal of Energy Storage*, 50:104557, 2022.

[13] Hai Tao Yue, Kun Chen, Li Tong Dong, Wen Xu Tian, and Zhong Fu Tan. The decision-making model of air-conditioning options based on time-of-use electric policy. In *Applied Mechanics and Materials*, volume 291, pages 1839–1846. Trans Tech Publ, 2013.

[14] Hongkai Chen, Zeyu Li, and Yongrui Xu. Assessment and parametric analysis of solar trigeneration system integrating photovoltaic thermal collectors with thermal energy storage under time-of-use electricity pricing. *Solar Energy*, 206:875–899, 2020.

[15] Farhad Kamyab and Shahab Bahrami. Efficient operation of energy hubs in time-of-use and dynamic pricing electricity markets. *Energy*, 106:343–355, 2016.

[16] Doyun Lee, Ryozo Ooka, Shintaro Ikeda, Wonjun Choi, and Younghoon Kwak. Model predictive control of building energy systems with thermal energy storage in response to occupancy variations and time-variant electricity prices. *Energy and Buildings*, 225:110291, 2020.

[17] ZX Pi, XH Li, YM Ding, M Zhao, and ZX Liu. Demand response scheduling algorithm of the economic energy consumption in buildings for considering comfortable working time and user target price. *Energy and Buildings*, 250:111252, 2021.

[18] Liu Haibo. *Energy consumption analysis and energy saving study of refrigeration system for large reserve meat*. PhD thesis, Beijing University of Technology, 2018.

[19] Zhao Yue. Analysis and optimization of energy saving operation of a cold storage refrigeration system in harbin. Master's thesis, Harbin University of Commerce, 2016.

[20] Yang Lei and Wang Xiaomin. Numerical simulation and experimental study on temperature field during precooling process of cold storage. *Journal of Northwest A F University (Natural Science Edition)*, 36(9):219–223, 2008.

[21] John David Anderson and John Wendt. *Computational fluid dynamics*, volume 206. Springer, 1995.

[22] My Lan Hoang, Pieter Verboven, Josse De Baerdemaeker, and BM Nicolaı. Analysis of the air flow in a cold store by means of computational fluid dynamics. *International Journal of Refrigeration*, 23(2):127–140, 2000.

[23] XIE Jing, QU Xiaohua, and XU Shiqiong. Numerical simulation and verification of gas flow field in cold storage. *Transactions of the Chinese Society of Agricultural Engineering*, 21(2):11–16, 2005.

[24] XIE Jing, TANG Yi, WANG Jinfeng, HOU Weifeng, and ZHU Junwei. Three-dimensional fluid dynamics predicts the influence of different fan arrangements on the airflow of cold storage. *Science and Technology of Food Industry*, 32(11):349–351, 2011.

[25] SA Tassou and W Xiang. Modelling the environment within a wet air-cooled vegetable store. *Journal of Food Engineering*, 38(2):169–187, 1998.

[26] HU Yaohua, JIANG Guozhen, and XIONG Laiyi. Cfd simulation of flow field in kiwifruit cold storage. *Journal of Agricultural Mechanization Research*, (5):155–159, 2012.

[27] TANG Yi, XIE Jing, and WANG Jinfeng. Predicts the influence of fan furnishing form on cold storage by cfd. *Food and Machinery*, (1):124–128, 2012.

[28] SUN Haiting. Research on airflow distribution characteristics of apple crates under different stacking methods in cold storage using cfd. Master's thesis, Northwest A F University, 2014.

[29] Miao Chen and Xie Jing. Unsteady state numerical simulation and verification of air curtain flow field in cold storage. *Transactions of the Chinese Society of Agricultural Engineering*, 29(7):246–253, 2013.

[30] Wang Jun. Experimental study and numerical simulation of air curtain in cold storage. Master's thesis, Shanghai Ocean University, 2016.

[31] Li Yizhe and Xie Jing. Numerical simulation and optimization of temperature field in cold storage. *Food and machinery*, 33(6):139–142, 2017.

[32] RobertE Paull. Effect of temperature and relative humidity on fresh commodity quality. *Postharvest biology and technology*, 15(3):263–277, 1999.

[33] H Wang and S Touber. Distributed and non-steady-state modelling of an air cooler. *International Journal of Refrigeration*, 14(2):98–111, 1991.

[34] HB Nahor, ML Hoang, Pieter Verboven, Martine Baelmans, and BM Nicolai. Cfd model of the airflow, heat and mass transfer in cool stores. *International Journal of Refrigeration*, 28(3):368–380, 2005.

[35] NJ Smale, Jean Moureh, and G Cortella. A review of numerical models of airflow in refrigerated food applications. *International Journal of Refrigeration*, 29(6):911–930, 2006.

[36] MK Chourasia and TK Goswami. Simulation of effect of stack dimensions and stacking arrangement on cool-down characteristics of potato in a cold store by computational fluid dynamics. *Biosystems Engineering*, 96(4):503–515, 2007.

[37] MK Chourasia and TK Goswami. Steady state cfd modeling of airflow, heat transfer and moisture loss in a commercial potato cold store. *International Journal of Refrigeration*, 30(4):672–689, 2007.

[38] Alemayehu Ambaw, Niels Bessemans, Willem Gruyters, Sunny George Gwanpua, Ann Schenk, Ans De Roeck, Mulugeta A Delele, Pieter Verboven, and Bart M Nicolai. *International Journal of Refrigeration*, 66:156–168, 2016.

[39] Tian Shen. Research on energy consumption analysis and ammonia leakage safety detection of cold storage. Master's thesis, University of Chinese Academy of Sciences, 2017.

[40] Paulo Brito, Pedro Lopes, Paula Reis, and Octávio Alves. Simulation and optimization of energy consumption in cold storage chambers from the horticultural industry. *International Journal of Energy and Environmental Engineering*, 5:1–15, 2014.

[41] GONG Haihui, XIE Jing, and ZHANG Qing. Current status of cold storage structure and insulation materials. *Logistics Science and Technology*, (2):121–123, 2010.

[42] LIU Bin, YANG Zhao, and TAN Jingying. Study on the influence of enclosure structure characteristics on cooling performance of micro cold storage. *Transactions of the Chinese Society of Agricultural Engineering*, (z1):235–237, 2005.

[43] Zhou Dan. Energy-saving design analysis of automatic cold storage insulation structure. *Refrigeration Technology*, 36(1):71–76, 2016.

[44] AM Foster, MJ Swain, R Barrett, and SJ James. Experimental verification of analytical and cfd predictions of infiltration through cold store entrances. *International Journal of Refrigeration*, 26(8):918–925, 2003.

[45] WG Brown and KR Solvason. Natural convection in openings through partitions-1, vertical partitions. *Int. J. Heat Mass Tran*, 5:859–868, 1963.

[46] W Tamm. Kalterveluste durch kuhlraumoffnungen. *Kaltetechnik-Klimatisierung*, 18:142–144, 1966.

[47] C Fritzsche and W Lilienblum. Neue messengun zur bestimmung der kalterluste an kuhlraumturen. *Kaltetechnik-Klimatiserung*, 20:279–286, 1968.

[48] WB Gosney and QLAMA HAL. Heat and enthalpy gains through cold room doorways. 1976.

[49] BW Jones, BT Beck, and JP Steele. Latent loads in low-humidity rooms due to moisture. *ASHRAE Trans.;(United States)*, 89(1A), 1983.

[50] Yang Yanbin. Numerical study on air curtain performance of cold storage door under hot pressing and wind pressure coupling. Master's thesis, Xi'an University of Architecture and Technology, 2009.

[51] HE Yuan. Numerical study on the running performance of air curtain of cold storage gate. Master's thesis, Xi'an University of Architecture and Technology, 2008.

[52] Tianrun Yang, Changjiang Wang, Qie Sun, and Ronald Wennersten. Study on the application of latent heat cold storage in a refrigerated warehouse. *Energy Procedia*, 142:3546–3552, 2017.

[53] Omid Ghahramani Zarajabad and Rouhollah Ahmadi. Numerical investigation of different pcm volume on cold thermal energy storage system. *Journal of Energy Storage*, 17:515–524, 2018.

[54] Nor Azwadi Che Sidik, Tung Hao Kean, Hoong Kee Chow, Aravinthan Rajaandra, Saidur Rahman, and Jesbains Kaur. Performance enhancement of cold thermal energy storage system using nanofluid phase change materials: a review. *International Communications in Heat and Mass Transfer*, 94:85–95, 2018.

[55] Rami Zeinelabdein, Siddig Omer, and Guohui Gan. Critical review of latent heat storage systems for free cooling in buildings. *Renewable and Sustainable Energy Reviews*, 82:2843–2868, 2018.

[56] Siemens plm software. [Online]. Available: https://plm.sw.siemens.com/en-US/nx/.

[57] Ansys fluent. [Online]. Available: https://www.ansys.com/products/fluids/ansys-fluent.

[58] Abdullatif E Ben-Nakhi and Mohamed A Mahmoud. Cooling load prediction for buildings using general regression neural networks. *Energy Conversion and Management*, 45(13-14):2127–2141, 2004.

[59] Michael Kintner-Meyer and Ashley F Emery. Optimal control of an hvac system using cold storage and building thermal capacitance. *Energy and Buildings*, 23(1):19–31, 1995.

[60] Shuangquan Shao Shen Tian, Hongbo Xu. Cold storage building energy consumption status and evaluation methods. *Refrigeration Air-Conditioning*, 15(12):52–56, 2015.

[61] Data of china meteorological administration. [Online]. Available: http://data.cma.cn/.

Appendix A. The mathematical model of cold stores

We consider the flow field distribution in the cold stores as a turbulent flow field, and the mathematical model is shown as follows.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k \mu_i)=\frac{\partial}{\partial x_i}(\Gamma_k \frac{\partial k}{\partial x_j})+G_k+G_b-\rho\varepsilon-Y_m+S_k \tag{A.1}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon \mu_i)=\frac{\partial}{\partial x_i}(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x_j})+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{A.2}$$

$$\mu_t=\rho C_u\frac{k^2}{\varepsilon} \tag{A.3}$$

$$G_k=\mu_t(\frac{\partial \mu_i}{\partial x_j}+\frac{\partial \mu_j}{\partial x_i})\frac{\partial \mu_i}{\partial x_j} \tag{A.4}$$

$$G_b=\beta g_i\frac{\mu_i}{Pr_t}\frac{\partial T}{\partial x_i} \tag{A.5}$$

$$\beta=-\frac{1}{\rho}\frac{\partial \rho}{\partial T} \tag{A.6}$$

$$Y_m=2\rho\varepsilon M_t^2 \tag{A.7}$$

$$M_t=\sqrt{\frac{k}{a^2}} \tag{A.8}$$

$$a=\sqrt{rRT} \tag{A.9}$$

$$\Gamma_k=\mu+\frac{\mu_t}{\sigma_k} \tag{A.10}$$

$$\Gamma_\varepsilon=\mu+\frac{\mu_t}{\sigma_\varepsilon} \tag{A.11}$$

In the model, G_k represents the turbulent flow energy due to the speed difference between each laminar flow, G_b represents the turbulent flow energy generated by buoyancy between each laminar flow, Γ_k and Γ_ε respectively represent the diffusivity of the relative parameters, Y_m is turbulence caused by the fluid flow between each laminar flow, $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants, S_k and S_ε are the standard terms selected in the simulation model. Table 1 shows the common model coefficient values. Based on the above assumption

Coefficients	$C_{3\varepsilon}$	$C_{1\varepsilon}$	$C_{2\varepsilon}$	σ_k	σ_ε	Pr_t
Values	0.09	1.44	1.92	1.0	1.3	0.9-1.0

Table A.5: Coefficients in the k-ε model

that the fluid in the cold stores is a turbulent fluid and the characterization of the mathematical model of turbulence, we can obtain the equation of motion and energy of the fluid in the cold stores in three directions. After the standard terms in the simulation model are selected and the corresponding parameters are set, the specific mathematical expressions of the above equations can be obtained, as shown in Table 2. In the

Equation	Φ	Γ	S
Continuity equation	1	0	0
Momentum equation in the X direction	u	n_{eff}	$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}(n_{eff}\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(n_{eff}\frac{\partial v}{\partial x})+\frac{\partial}{\partial z}(n_{eff}\frac{\partial W}{\partial x})+S_u$
Momentum equation in the Y direction	v	n_{eff}	$-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}(n_{eff}\frac{\partial u}{\partial y})+\frac{\partial}{\partial y}(n_{eff}\frac{\partial v}{\partial y})+\frac{\partial}{\partial z}(n_{eff}\frac{\partial W}{\partial y})+S_v$
Momentum equation in the Z direction	W	n_{eff}	$-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}(n_{eff}\frac{\partial u}{\partial z})+\frac{\partial}{\partial y}(n_{eff}\frac{\partial v}{\partial z})+\frac{\partial}{\partial z}(n_{eff}\frac{\partial W}{\partial z})+S_w$
Energy equation	T	$\frac{\eta}{P_r}+\frac{\eta_t}{\sigma_T}$	S_T

Table A.6: Equations of motion and energy of turbulent fluids

above equation, $\eta_t=\frac{\rho C_\mu k^2}{\varepsilon}$, $\eta_{eff}=\eta+\eta_t$, and S_μ, S_v, S_w and S_T are the standard terms selected in the simulation model.