Research Article

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Experimental and numerical study of heat transfer and flow characteristics with different placement of the multi-deck display cabinet in supermarket<https://doi.org/10.1515/phys-2021-0023>

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Abstract: This work focuses on the heat transfer and flow characteristics with the different placement of the multi-deck display cabinet and tries to optimize the placement position of refrigerated display cabinet. First, the temperature distribution in a refrigerated display cabinet was experimentally investigated. The result showed that the food temperature in front is 3.6–4.8°C higher than back row of the same layer, and temperature fluctuation of 0.3–0.7°C less than the back row. Then, a three-dimensional numerical model of the display cabinet was established, and the k - ε model is employed to compare and analyze the heat transfer and air curtain characteristics. The results show that the placement methods have great influence on the performance of the display cabinet. The face-to-back placement method can acquire a better food refrigeration performance, and the food temperature of the face-to-back placement method is 0.3–0.5°C lower than that of the face-to-face placement method.

Keywords: multi-deck display cabinet, food temperature, placement, CFD

1 Introduction

With the improvement of people's living standards, consumers have a higher and higher request about fresh, frozen, and refrigerated food in quantity, variety, and quality. To ensure that the customers have a high-quality

food supply, the cold chain is rapidly developed to cater to the production storage, transportation, sales, and other links. The display cabinet is a terminal device in cold chain, and it is an important sales platform in supermarkets. Not only it can display chill food but also has a good impact on beautiful display and convenient food selection for the customer, so it is a widely used in shopping malls and supermarkets. However, the refrigerated display cabinet has the problems of high energy consumption and uneven food temperature distribution [1]; it was indicated that 70% of energy consumption in a supermarket was by the display cabinet [2]. There existed about a 5°C food temperature difference between shelves in the refrigerated display cabinet, and 90% of the higher temperature food is located near the air curtain side [3,4]. This greatly improves the deterioration rate of refrigerated food, resulting in a large amount of refrigerated food waste. So, the efficiency of the display cabinet and food storage integrity is critical to the economic viability of the supermarket.

A lot of research work have been carried out to improve the system operation efficiency and refrigerated food storage performance of the refrigerated display cabinet. This work includes air flow organization optimizations of air curtain [5,6], refrigerant system improvement [7–9], optimized design of cabinet structure [10,11], and the influence of environmental factors [12–14]. Wu et al. [15] used pure paraffin as phase change materials (PCM) in the food shelf of the display cabinet to improve its performance. The results show that the improved shelves can decrease the food temperature and temperature fluctuation during the defrosting period. Hammond et al. [16] developed a multi-layer short air curtain to optimize the performance of display cabinet. The experimental results show that compared with the traditional display cabinet, the power consumption is reduced by 35.9%, and the maximum temperature difference of food is reduced by 67%. Tutuncu and Ozcan [17] applied the embedded fuzzy logic control system (EFLCS) in the closed refrigerated display cabinet to meet the storage conditions. The results show that compared with traditional systems, the developed EFLCS can stabilize the temperature of the cabinet in a shorter period. Tsamos et al. [18] combined

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the single-layer shelf air supply and guide strip to form a new shelf and experiment and numerical simulation to study the performance of the display cabinet with the new shelf. The results show that the power consumption is reduced by 16.7 kW h/24 h. Ben-Abdallah et al. [19] added PCM to improve the performance of the display cabinet. The results show that PCM has important potential in maintaining air and product temperature when the compressor is turned off for up to 2 h.

Numerical study provides a great convenience for investigating the air flow and heat transfer in the refrigerated display cabinet, and several numerical studies on the display cabinet have been carried out. Ge and Tassou [20] used the semi-empirical jet model to simulate the heat transfer of air curtain in the refrigerated display cabinet. The results show that the semi-empirical jet model can show the performance of air curtain well. Lv et al. [21] introduced the mathematical model of turbulent buoyancy jet to study the performance of the air curtain of the refrigerated display cabinet, and the simulation results show that the mathematical model could more accurately study the performance of the air curtain of the display cabinet. Wu et al. [22] adopted the multi-scale method to establish a coupling model of supermarket, freezers, and shelves and studied the influence of supermarket heating ventilation and air conditioning (HVAC) coupling system on the performance of the display cabinet. The simulation results show that the air supply temperature of the air conditioning system drops from 19 to 16°C, and the display cabinet energy consumption system decreases by 6.36%. Chaomuang et al. [23] used particle image velocimetry technology to the airflow velocity of refrigerated display cabinet experimental measurements and established a two-dimensional refrigerated cabinet computational fluid dynamics (CFD) model, and the results showed that the model can reproduce the main flow observed in the experiment phenomenon and predicted the temperature distribution trend is consistent with the experimental value. Sun et al. [24] installed air guide strips at the front edge of the food shelf to improve the efficiency of the air curtain and used commercial software to establish a three-dimensional model of the display cabinet. The simulation results showed that the average temperature of the food in the display cabinet with the guide strip was reduced by 4.9°C, and the operating energy consumption was reduced by 34%. Cao et al. [25] introduced the MTF model and the ASVM algorithm in cabinet to optimization design and validated with experimental data, and the results showed that the total energy consumption was found to be reduced by 19.3%. D'Agaro et al. [26] have proved that the three-dimensional model can more accurately simulate the flow heat

transfer of refrigerated display cases. Yu et al. [27] adopted the standard $k-\varepsilon$ turbulence model to simulate the flow and heat transfer characteristics of the air curtain in the display cabinet. The results show that the standard $k-\varepsilon$ two-equation turbulent model can reproduce the heat transfer and flow characteristics of air curtain well.

In summary, most of the work cited above focus on improving the performance of the multi-deck display cabinet, such as air curtain characteristics and food temperature stability, but very few work investigated the influence of different placement methods. The objectives of this study were to analyze the air flow and heat transfer characteristics of the display cabinet in different placement method. First, the temperature distribution in the refrigerated display cabinet was experimentally investigated. Then, the three-dimensional numerical model of the display cabinet was established, and the $k-\varepsilon$ model is employed to compare the heat transfer and air curtain characteristics of the display cabinet in different placement method and find out the best placement method of the refrigerated display cabinet.

2 Experimental setup

2.1 Refrigerated display cabinet

A multi-deck display cabinet was placed in an environmental test chamber. And the test product packages (made of methylcellulose) were fully loaded up in the

Figure 1: The display cabinet with full food.

display cabinet as shown in Figure 1. For a multi-deck display cabinet, two axial fans under the bottom shelf provide air circulation in the display cabinet. After the air is cooled by the evaporator, it flows into two parts along the vertical back air duct, a portion of the air flow is emitted from the discharge air grille (DAG) to form an air curtain, and a portion of the air flow is emitted from perforated back panel (PBP) to form a horizontal air flow for refrigerating the food, which is eventually added to the air curtain at the front. At the bottom of the display cabinet, the air is driven into the evaporator through the return air grille (RAG) to complete the airflow circuit. The characteristics of the cabinet and its components are given

in Table 1. The ambient condition in the test room was 25°C and the relative humidity was 60% to simulate the environmental conditions in the supermarket in summer.

2.2 Temperature measurement

Figure 2 shows the temperature measuring points of the display cabinet. There were 12 temperature points in food, and 2 points were in the DAG and RAG. Temperature point measuring tools were used by calibrated T type thermocouples (accuracy of ±0.2°C).

Table 1: Characteristics of the experimental display cabinet

Instrument	Range
Dimensions of the storage space (width × height × depth)	2,500 mm × 2,048 mm × 765 mm
Dimensions of shelves	
• Shelves 1–5	2,500 mm × 25 mm × 400 mm
Distance between 1 and 5 shelves	300 mm
• Shelf 6	2,500 mm × 25 mm × 470 mm
Distance between 5 and 6 shelves	320 mm
Dimensions of a test product package	200 mm × 50 mm × 100 mm
DAG width	100 mm
RAG width	70 mm
Dimensions of the PBP (width × height × thickness)	2,500 mm × 2,048 mm × 3 mm
Number of propeller fans	2

Figure 2: Measuring point location. (a) measurement points left view, (b) measurement points main view.

3 Experimental results

3.1 Evolution of air temperatures

Figure 3 shows the evolution of the air temperatures of DAG and RAG in the center plane (1,250 mm from the left wall) of the refrigerated display cabinet over the 24 h operation conditions. The air temperature curve provided information on the compressor working cycle and defrost cycles. Two air temperature fluctuation cycles in DAG were observed: small fluctuations (0–5°C) and large fluctuations (0–13.2°C). The former (during the quasi-steady state) was due to the regulation of the on/off compressor working cycle, which was automatically conducted by the thermostat sensor. The latter was due to defrosting, which occurred every 3 h with the duration of about 20 min. The compressor was switched off during defrosting and warm air heated by the electric strip heater was blown over the evaporator by the fans, which explains a rapid increase in the air temperature in DAG with a peak of 13.2°C.

3.2 Evolution of food temperatures

Figure 4 shows the evolution of food core temperatures in the middle plane ($Z = 1,250$ mm) of the display cabinet over the 24 h operation conditions. There were 12 food core temperature measurements represented under different names of three letters, each depending on the food location in the cabinet. The first letters F and R represent front and rear, respectively; the second letters 1, 3, and 5 represent the number of different shelves; the third letters T and B represent top and bottom, respectively. For example, R1B represented the food at the first

Figure 3: Air temperature variations of DAG and RAG with time during periods of 24 h for the cabinet.

Figure 4: Food temperature variations with time during periods of 24 h for cabinet.

shelf, bottom, rear portion of the cabinet. It can be seen that food temperature can be maintained at 0–7°C, but it has obvious non-uniform distribution and periodic fluctuations phenomenon.

Figure 5 presents the average and standard deviations of food core temperatures on the middle plane ($Z = 1,250$ mm) of the cabinet during 24 h steady state. It can be noted that the food temperature in front is 3.6–4.8°C higher than that in rear; meanwhile, the food temperature in front has less temperature fluctuation of 0.3–0.7°C than that in rear. This is mainly because the food in front is more susceptible to the impact of the warm and humid air environment.

4 CFD model

Usually, the display cabinet in the supermarket is often placed in several rows, which is shown in Figure 6, and they were named face-to-back and face-to-face placement method. A three-dimensional CFD model of the display cabinet was set up to further study the heat transfer and air curtain characteristics of the multi-deck display cabinet in different placement method and find the best placement method of the refrigerated display cabinet to chill food.

4.1 Geometry and mesh details

Figure 7 shows the face-to-back placement method and the face-to-face placement method. The three-dimensional CFD model calculated area includes test room, the display cabinet, and food. It is defined that x is the

Figure 5: The average and standard deviations of food core temperatures on the middle plane ($Z = 1,250$ mm) of the cabinet during 24 h steady state.

width coordinate, y is the height coordinate, and z is the length coordinate. And the calculated area is expanded until the influence of the air curtain can be ignored. The food package in the cabinet was rectangular and stacked uniformly; in this way, the solid area cannot be considered as a boundary but can be treated as fluid whose viscosity is infinite. The characteristics of the display cabinet's geometric structure calculating process are relatively complex, and one side of the flow field is wide open.

The standard k - ε two-equation turbulent model is used to simulate the airflow in the domain by comprehensive consideration of accuracy of simulation, computer requirements, and computational model established by previous researchers. To simplify numerical simulation and keep the basic characteristics of the process, the following assumptions are made in the present simulations:

- (1) The thermal properties of the fluid are constant and the processes are in steady state.

Figure 6: Different placement method. (a) Face-to-back placement method, (b) face-to-face placement method.

- (2) Mass transfer from the load to air (weight loss) is not considered.
- (3) Only packaged frozen food is loaded in the open vertical display cabinet.

The governing equations for the mass, momentum, and energy equation are similar to those in ref. [28].

The general governing equation is as follows:

$$\frac{\partial(\rho u \Phi)}{\partial x} + \frac{\partial(\rho v \Phi)}{\partial y} + \frac{\partial(\rho w \Phi)}{\partial z} = \frac{\partial}{\partial x} \left(\Gamma \frac{\partial \Phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\Gamma \frac{\partial \Phi}{\partial y} \right) + \frac{\partial}{\partial z} \left(\Gamma \frac{\partial \Phi}{\partial z} \right) + S,$$

where u , v , and w represent velocity in the x , y , and z direction (m/s); Φ , S , and Γ , respectively, represent the generic variable, source, and the generalized diffusion coefficient.

The convergence criterion of the simulation is that the root mean square of the variable residuals is lower than 1.0×10^{-5} , and the mass flow unbalance between the outlet and inlet is less than 1.0×10^{-3} . It is worth noting that the iterative solution process in ANSYS CFX is implemented by the transient solution process

Figure 7: Geometry periodicity unit. (a) Face-to-back periodicity unit, (b) face-to-face periodicity unit.

because of the equivalence between these two processes. Therefore, the number of time steps can be regarded as the number of outer iterations.

4.2 Boundary conditions

The boundary condition solves the variable of the edge of the area or its derivative with the changing rule of the place and time, so the numerical boundary conditions of any problem must be given. The boundaries of refrigerated cabinet and three-dimensional environment space are, respectively, shown in Tables 2 and 3. The translational periodicity interface boundary is used for the interface. The adiabatic wall boundary is adapted to simulate the supermarket roof wall, food package, multi-shelves, and floor. The average static pressure boundary condition is used for the outlet, fluid–solid coupling boundary for fluid and solid interface regions.

4.3 Mesh independence

Mesh quality has a larger impact on precision and convergence for numerical calculation. The less or more meshing will make the result divergence or computer memory requirement increase. Neither is favorable for simulation. Although mesh may not always be sparse or dense for the whole model, it can be divided according to the part of the model, such as at the place of the large temperature gradient, large velocity gradient, air supply channel, discharge grille, and return grille, in which the grid should be dense while another is sparse. Following this principle, the hexahedral grid is used, and simulating space geometry is divided into 389,386 grids. And the implementation of the grid independence test is to guarantee that the choice of grid number is reasonable. Figure 8 shows the meshing scheme of the display cabinet in the environmental chamber.

Table 2: Refrigerated cabinet's boundary

Boundary	Inlet boundary	Outlet boundary	Food package boundary	Aside frame boundary
Condition	Mass flow inlet boundary, set to 0.108 kg/s	Outlet boundary	The initial temperature is set to 30°C	The initial temperature is set to 0°C

Table 3: Three-dimensional environment space's boundary

Boundary	The around boundary	The ceiling boundary	The ground boundary	Fluorescent lamp boundary
Condition	Moving boundary	Fixed temperature boundary	The adiabatic boundary	Fixed heat flux boundary, set to 15 W/m ²

Figure 8: Meshing scheme of the display cabinet in the environmental chamber.

4.4 Model validation

Figure 9 shows the comparison between the experimental results and the simulation results of the six food temperatures in the front row. By the experiment data and simulation data of the model for calculation, there is a certain error of $\pm 10\%$. In the range of allowable error, the model is suitable to simulate the display characteristics.

Figure 9: Comparison of food temperature distribution by CFD and experiment.

5 Numerical results

The results from modeling the supermarket in winter and summer are presented. Suppose the environmental temperature is 18 and 26°C for winter and summer, respectively. In our investigation, the roof wall temperature is 18 and 26°C for winter and summer, respectively. The inlet air temperature and mass flows are 0°C and 0.3 kg/m²s, respectively, which come from testing a real multi-deck display cabinet. According to the results of the CFD simulation, the computer can display temperature and velocity diagram under different temperatures of the cabinet.

Figure 10 shows the temperature contours at $Z = 1,250$ mm slice for both models in winter and summer. It can be seen that temperature variation is not evident in winter and summer. But upon comparing face-to-back and face-to-face placement methods, it can be seen that the face-to-back placement method can make the ambient air temperature lower, which shows the stronger coupling with environmental and more availability to prevent the hot air of the back-to-face placement method. At the same time, the isotherm distribution difference of display cabinet above and below. In face-to-back placement method, the isotherm distribution density above the cabinet and near the top is large and even closed while it is dense but not closed near the ground, and the closed isotherm also appears at the center of the symmetry plane. In the face-to-face placement method, the isotherm distribution above the cabinet is uniform even almost parallel while it is sparse near the ground, and the isotherm at the center of the symmetry plane is dense but not closed.

Figure 11 shows velocity streamlines at $Z = 1,250$ mm slice for the inlet mass flow rate of 0.3 kg/m²s. In the face-to-back placement method, there are two regular large air eddy flows on the back and front of the display case, respectively, and the outside air flow is relatively uniform and air velocity distribution has no significant difference between summer and winter. In the face-to-face placement method, the air velocity distribution is related to environmental temperature. Although in both there are three eddies, one of them is in another location. The small eddy is close to the top of the center of the symmetry plane, while another is close to the top of the second display cabinet when the temperature is $T = 18^\circ\text{C}$, $T = 26^\circ\text{C}$, and velocity distribution intensity around the eddy is not the same. In general, the velocity distribution of the back-to-face placement method is more uniform, stable, and orderly than that of the face-to-face placement method.

Figure 12 shows the temperature distribution in the isothermal surface temperature of 3°C, and it is vividly described in the form of three dimensions which show the

Figure 10: Temperature (K) contours at $Z = 1,250$ mm slice. (a) Face-to-back placement method, (b) Face-to-face placement method.

Figure 11: Velocity streamline at $Z = 1,250$ mm slice. (a) Face-to-back placement method, (b) Face-to-face placement method.

flow of the air curtain in two placement methods. It can be concluded that the floor had only a very small effect on the air curtain flow of the face-to-back placement method than that of the face-to-face placement method. At the

same time, it can be found that the isothermal surface temperature of 3°C is similar for two placement methods when the environmental temperature is $T = 18^{\circ}\text{C}$ and $T = 26^{\circ}\text{C}$, respectively.

Figure 12: Isotherm surface of 3°C. (a) Face-to-back placement method, (b) Face-to-face placement method.

Figure 13 shows a comparison of the temperature of food products in winter. It can be seen that the food

Figure 13: Average temperature of food in different positions.

temperature is lower in the face-to-back placement method of the refrigerated food display cabinet, and the food temperature in the front is 0.3–0.5°C lower than that in the front of face-to-face placement method. So, it can be concluded that the face-to-back placement method is better than the face-to-face placement method for food storage.

6 Conclusion

In this article, the heat transfer and flow characteristics in a refrigerated display cabinet are experimentally studied. And the exhaustive comparison of the heat transfer and airflow characteristics in the multi-deck display cabinet with different placement method was numerically investigated. The major findings are as follows:

1. The result showed that the food temperature in front is 3.6–4.8°C higher than that of the back row, and temperature fluctuation of 0.3–0.7°C less than that of the back row.
2. In winter and summer, the supermarket environment has a similar influence effect on air curtain characteristics of the display cabinet.
3. Upon comparison between the placement methods, the face-to-back placement method can acquire a better food refrigeration performance, and the food temperature is 0.3–0.5°C lower than that of the face-to-face placement method.

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