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CFD comparisons of open-type refrigerated display cabinets with/without air guiding strips

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Abstract

Open-type vertical refrigerated display cabinets are used widely in supermarkets and grocery stores due to its attraction for customers and food merchandisers. These cabinets, however, are less energy efficient than cabinets with glass doors because of the interactions between the air curtain, that is used to provide an artificial barrier between the air in the cabinets, and the air in food premises. To improve the energy efficiency of open fronted refrigerated display cabinets, many types of air curtains have been designed, including single layer air curtains, multi-layer air curtains and shelf tip air curtains amongst others. An approach, considered in recent years to improve the efficiency of air curtains is the use of air guiding strips at the front face of the shelves of open-type vertical refrigerated display cabinets with single layer air curtains. This paper uses Computational Fluid Dynamics modelling to investigate the influence of air guiding strips on the performance of vertical multi-deck refrigerated display cabinets. The results showed that the air guiding strips accelerate the air curtain vertically; leading to a stronger and stiffer air curtain, consequently inhibit the infiltration of the ambient warm air into the cabinet. The average temperature of simulated food in the cabinet decreases by 4.9 °C compared to the cabinet without the strip due to the improved protection of the stiffer air curtain. The cooling capacity required to maintain the food chilled decreases by 34%.

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Keywords: display cabinet; air guiding strip; air curtain; energy efficiency; CFD

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1. Introduction

Open-type vertical refrigerated display cabinets are crucial parts in retailed food stores to ensure proper merchandise and safety of the food products. This type of cabinet is characterized by storing and displaying food for the customers at different levels of temperature within the food retail stores. The temperature level are characterized by the product temperature stored in the cabinet which varies between -1 °C to +7 °C as described in BS EN ISO 23953-2 [1] for the chilled food application. Different applications of the open-type vertical refrigerated display cabinets can be found in supermarkets stores including the stand-alone units or centralised systems. Stand-alone or remote units are self-contained refrigeration systems. For the centralised applications, the display cabinet evaporators in sales area are feed by the centralised refrigeration system which located in the machinery room. This application can supply from a very small number of cabinets to larger number based on the supermarket size.

The open-type refrigerated display cabinets are widely used in supermarket stores to attract the costumers and increase the sales. The absence of any physical obstacle like a glass door between the customer and product display area is preferred for commercial reasons. The main advantage of the open type refrigerated display cabinets is to allow consumers free access to food [2]. The penalty for this is the lower energy efficiency due to the energy intensive systems. In fact, there is no barrier between the warm ambient air in costumer sales area and the food products. The cold air exist the refrigerated display area allows warm air to infiltrate into the cabinet. The air infiltration due to the open style cabinet can account for up to 67-77% of the total heat exchange from the ambient [3]. The cabinets with doors are consuming less energy due to the glass door barrier. Fricke and Becker [4] compared a doored display cabinet with an open display cabinet type in terms of mean electrical energy consumption. The authors present the results by dividing the energy consumption into different categories including compressor, light, fans and anti-sweat heaters. The results show that the doored refrigerated cabinet has total electrical power consumption 1.71 kWh/day per feet and on the other hand the open display cabinet has 2.21 kWh/day per feet. Clearly, an increase in the energy efficiency of open refrigerated cabinet will result in significantly reduced energy consumption of the individual units and as an extension the operating and running costs of supermarkets.

Many investigations have been carried out in terms of energy savings and maintenance the required product temperatures [5, 6, 7]. Navaz et al [7] experimentally and numerically addressed all those parameters that have significant effects on the entrained warm air in open refrigerated cabinets. As they reported, the amount of warm air enters to open type refrigerated cabinets is due the turbulence intensity, shape of the mean velocity profile at the discharge air grill and the Reynolds number. Gray et al. [8] presents the experimental results on a remote refrigerated display cabinet by comparing different patterns on the rear duct panel to improve the air distribution of the display cabinet. The author reports that the 70% of the total air circulation needs to be delivered from the air curtain and the remaining 30% from the rear panel of the display cabinet. Chen [9] numerically assessed the parametric evaluation of refrigerated air curtains for thermal insulation. The length-width ratio, air curtain discharge angle, height-depth ratio of the cavity and the dimension and position of the inside shelve would greatly influence the air curtain performance as presented by the author. Cao et al. [10] presented the novel optimisation strategy for design of air curtains for open vertical refrigerated display cabinets. The results obtained from the authors showed that the air curtain losses and energy consumption can be reduced by 19.6% and 17.1% respectively by optimizing the air curtain. Therefore a proper design of air circulation ratio (air-off to air-on), air curtain shape, air flow and finally shelve structure can produce a stronger air curtain and minimize the infiltration rate. This could lead to higher performance of the cabinet and lower power consumptions.

In the present paper, flow guiding strips are used at the front face of the shelves of a conventional open-type multi-shelves vertical refrigerated display cabinet. The air flow and the heat transfer between the air and the food products in and around the cabinet are simulated with commercial CFD software ANSYS-Fluent R14.5. The aim of this paper is to investigate the impact of such flow guiding strips on the flow of the air curtain, the temperature of the food products and most importantly the energy consumption of the cabinet. The performance analysis of both the conventional and the proposed vertical display cabinets performed under controlled test conditions as specified by BS EN ISO 23953-2 [1]. For simulation purposes the room conditions set in Climate Class 3 (25 °C/60% RH). The air flow velocity across the cabinet was set at 0.2 m/s. The food products inside the cabinet located in the specified positions as the same standard required.

2. Model description

2.1. Cabinet and air flow strips description

A conventional commercial open-type vertical refrigerated display cabinet is used in this paper (conventional refrigerated cabinet) as shown in Fig. 1 (the left side panel is hidden to show clearly in Fig. 1(a)).

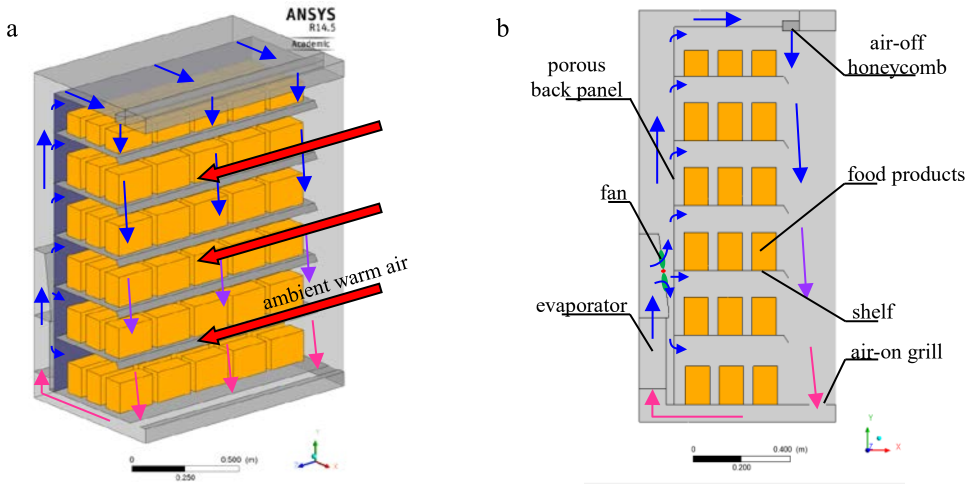

Fig. 1. Structure of the conventional refrigerated cabinet (a) 3D structure (b) 2D structure

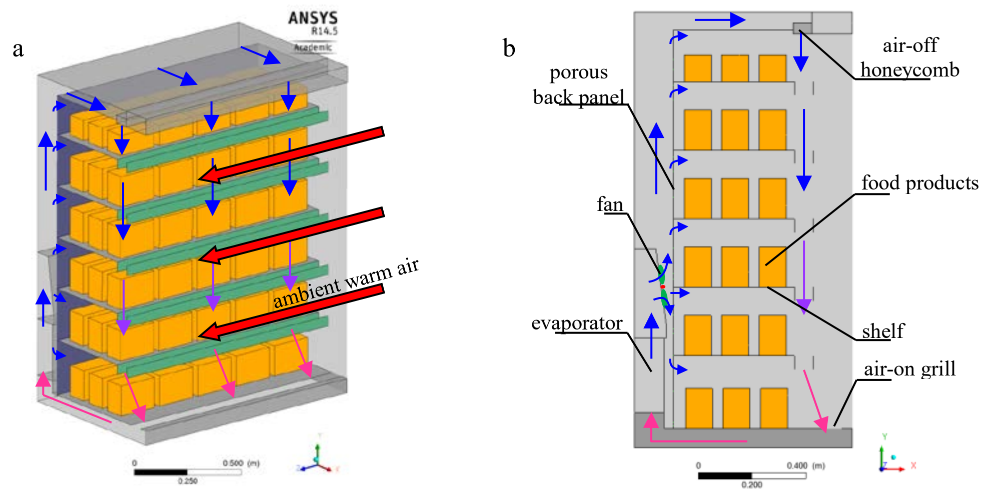

Fig. 2. the structure of the proposed refrigerated cabinet (a) 3D structure (b) 2D structure

The cabinet has 6 layers of food products, including 5 shelf layers and the bottom panel layer. The air enters the cabinet from the air-on grill at the front of the bottom panel and is cooled down as flowing through the evaporator. After that, the air is boosted by a fan to the top tunnel of the cabinet and flows straight down after passing through the air-off honeycomb at the front top of the cabinet, forming a cool air curtain between the display area and the ambient warm air to protect the chilled food products. Part of the cool air flows across the porous back panel into the display area and helps to maintain the required food temperature.

The overall dimensions of the cabinet are 2m of height (Y-direction in Fig. 1), 0.8m of depth (X-direction) and 1.2m of width (Z-direction). The vertical distance between the shelves is 0.25m. The air-off honeycomb dimension is 0.04 m height and 0.07 m width (X-direction). Dimensions including back panel, shelve, air path were defined by a real cabinet dimensions purposely measured for this work.

The proposed display cabinet with air guiding strips is shown in Fig. 2 (the left side panel is hidden to show clearly in Fig. 2(a)). This cabinet has exactly the same dimensions with the conventional cabinet, but the front face of each shelf is replaced by a pair of air guiding strips. The strips are thin plate planes with a height of 0.05 m and a gap distance (X-direction) of 0.07 m.

2.2. Mesh and simulation conditions

To simulate the air flow and heat transfer between the air and the food products, ANSYS-ICEMCFD is used to mesh the model and ANSYS-Fluent R14.5 is used to build up the simulation model.

Fig. 3 shows the mesh of the proposed cabinets. The total mesh number of each model is about four million. The mesh independent investigation shows that when the mesh number increases to about twelve million, the results are remaining similar, which means that the results are the mesh independent.

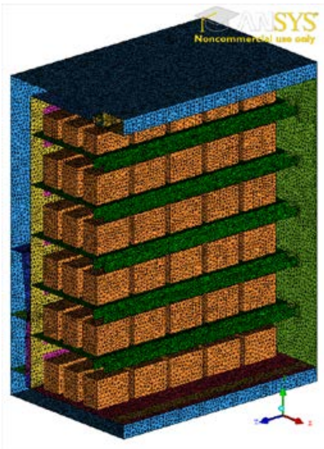

Fig. 3. the mesh of the two cabinet models

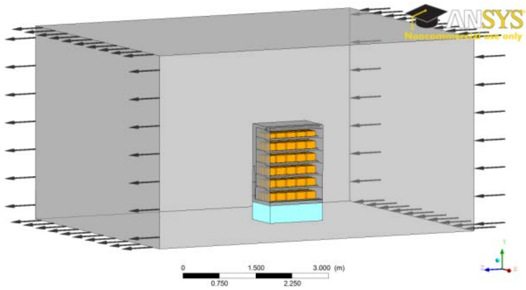

Fig. 4. the testing room and ambient air flow direction

In the ANSYS-Fluent models, the fan is simulated with a fan model, of which the pressure jump is set at 0.025 kPa. Porous material model is used to model the evaporator and the honeycomb. In the evaporator, the air flow along the Z-direction is strictly stopped and in the honeycomb only vertical air flow is permitted.

A source UDF is activated to simulate the cooling process in evaporator and calculate the total cooling capacity consumption. The coil temperature of the evaporator is set at -7 °C based on the measurement of the real cabinet and the heat transfer coefficient between the evaporator and the air is estimated based on the traditional empirical equation of convective heat transfer in round tubes with turbulent flow.

The air curtain is cool and the ambient air is warm, resulting in strong natural convection due to the density difference between the cool air and the ambient warm air. To simulate this natural convection, the gravity is activated in the models and the density of the air is calculated based on the idea gas fomular.

The heat conductivity of the food products used in the model is set at 1.0 W/m^{3}K. The material of the shelves is steel, as well as the internal panels, i.e., the back panel, bottom panel and top panel, through which heat transfer occurs. So these panels and shelves are modelled as steel thin wall with a thickness of 0.003m.

According to the BS EN ISO 23953-2 [1] standard, a refrigerated display cabinet should be tested in an controlled environment of 25 °C, 60% RH and air flow at 0.1 - 0.2 m/s for climate class 3. For simulation purposes the cabinets is placed in an environmental testing room with dimensions of 5 m (X-direction) x 7 m (Z-direction) x 4m(Y-direction) where the warm room air comes from the right side and exits at the left side as shown in Fig. 4. The air velocity is set at maximum of 0.2 m/s. Temperature and humidity are kept constant at 25 °C and 60% respectively.

To solve the air flow and heat transfer in ANSYS-Fluent, the finite volume method is applied to discretize the governing equations and a second-order upwind discretization scheme is used to calculate the convection terms. A convergence criterion of $1 \cdot 10^{-3}$ is specified for the relative error of the successive iterations.

3. Model results & discussion

3.1. Conventional Refrigerated Cabinet Results

Fig. 5 and 6 show the air velocity in the conventional display cabinet at the middle plane. In Fig. 5, it can be seen that the cool air flows out of the air-off honeycomb with the highest velocity of 1.5 m/s. While going straight down vertically under gravity due to its higher density, the cool air behaves like a jet flow, mixing with the surrounding static (or almost static) air and consequently slowing down. The air velocity reduces to about 0.75 m/s near the air-on slot at the bottom of the cabinet, only half of the injection velocity near the air-off honeycomb.

Fig. 6 shows the 3D air curtain through the isothermal surface of 15 °C. It can be seen that the air curtain stands in front of the cabinet and works as an artificial "door" protecting the chilled products from the warm environment by inhibiting the infiltration of the ambient warm air. At the beginning top, the air curtain goes down straightly because of its highest air velocity as shown in Fig. 5. As it goes down to the second shelf, the air curtain declines from the straight down flow and flow away the cabinet at the right hand which is the upstream of the ambient air cross flow. This phenomenon increases as the air flows to the bottom part of the cabinet. .

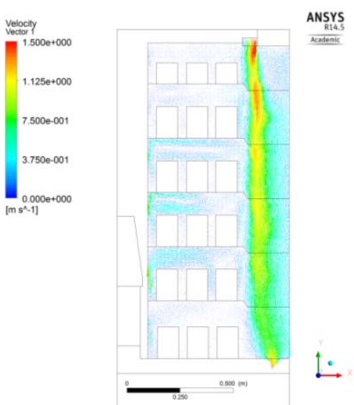

Fig. 5. Air velocity at the middle plane of the conventional cabinet

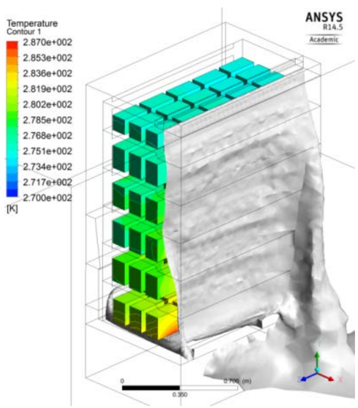

Fig. 6. Air curtain of the conventional cabinet

The declination of the air curtain actually is the result of the interaction of the air curtain and the ambient air cross flow as shown in Fig. 7.

It can be seen in Fig. 7 that the ambient warm air cross flow passing the cabinet is actually a kind of flow around a blocker. The ambient air cross flow comes from the right of the cabinet and turns at the cabinet right panel, inducing a detaching vertex between the main cross flow and the air curtain. After the vertex, the cross flow reattaches the air curtain and flows downstream. This detaching vertex pulls the cool air from the air curtain, causing loss of cool air at the right part of the air curtain, and pushes the ambient warm air to the air curtain, causing infiltration of warm air at the left part of the air curtain. The declination of the air curtain is formed by the outflow of the cool air and related to the loss of the cool air and energy efficiency, and determines the protecting ability of the air curtain and the temperature profiles of the cabinet as shown in Fig. 8 and 9.

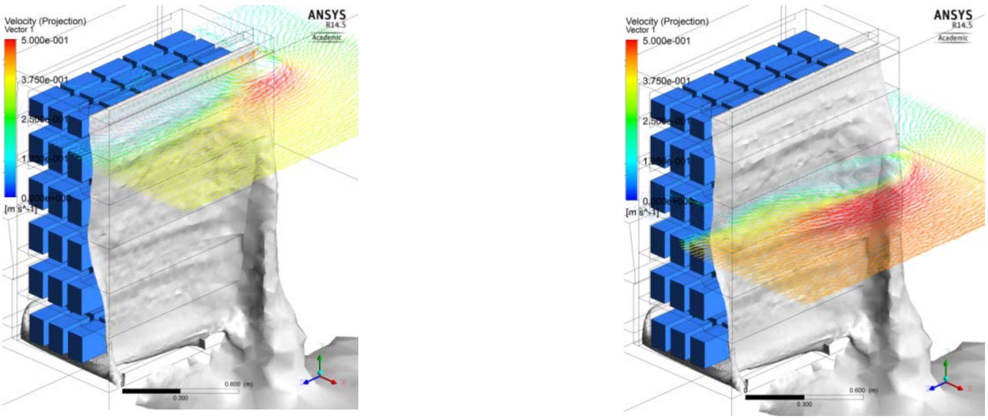

Fig. 7. Vertex between the air curtain and the ambient warm air cross flow (a) top level (b) middle level

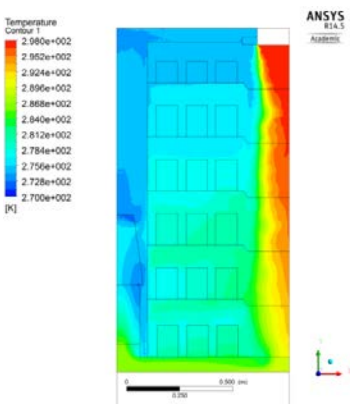

Fig. 8. Temperature at the middle plan of the conventional cabinet

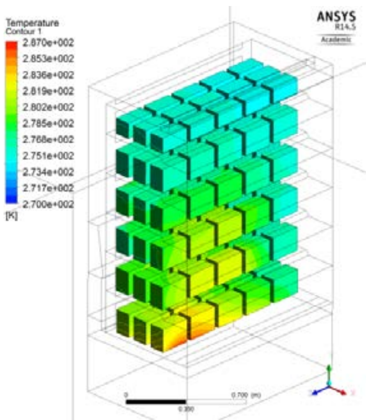

Fig. 9. Food temperature of the conventional cabinet

In Fig. 8, it can be noticed that the air temperature in the back tunnel is the much lower comparing to the bottom tunnel. This is due to the heat transfer in the evaporator which cools down the air passing through. In the chilled product area, the lower product temperature can be found at the higher shelves. The reason of such a temperature profile is that the protection of the air curtain is worse at the lower layer than the upper layer due to more loss of cool air and more infiltration of warm air across the air curtain as explained earlier.

In Fig. 9, the left hand side products temperature is higher comparing to right hand side products. It is because that the cool air in the chilled area flows out at the right part of the air curtain, making the food in this area to cool down. On the other hand, the infiltration of the ambient warm air occurs at the left part due to the reattaching of the ambient air cross flow, reducing the protecting ability of the air curtain and resulting in a higher food products temperature.

3.2. Proposed Refrigerated Cabinet Results

Fig. 10 shows the velocity of the cool air flowing down the cabinet after the air-off honeycomb. The highest air velocity at the outlet of the honeycomb is 1.5 m/s, which is the same as the conventional cabinet in Fig. 5. As the cooled air flows down to shelves, it is still in high velocity comparing to the conventional cabinet.

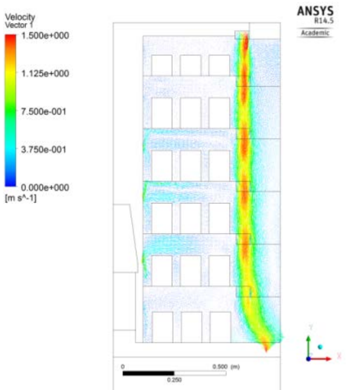

Fig. 10. air velocity at the middle plane of the proposed cabinet

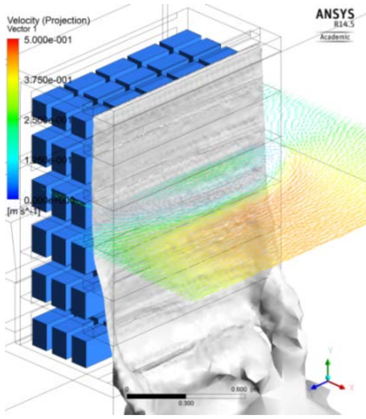

Fig. 11. air curtain of the proposed cabinet

Comparing the air curtains of the conventional (see Fig. 6) and the proposed cabinet (see Fig. 11), it is very easy to notice the much smaller declination of the air curtain at the very low position of the proposed cabinet. Actually, the air flow rate at the air-off honeycomb is found to be 0.114 kg/s for both the conventional and proposed refrigerated cabinets, as well as the backflow across the back panel, which is 0.013 kg/s, meaning the cool air flowrate of the air curtain and the back panel are not influenced by the air guiding strips. From the viewpoint of fluid dynamics, the air velocity of the air curtain is the only difference between the two cabinets. For the conventional cabinet, the air velocity is found to be equal to 1.00 m/s in the fourth shelf and 0.75 m/s at the fifth shelf; on the other hand, for the proposed cabinets, the air velocity is found to be 1.3 m/s and 1.1 m/s at the same positions.

The higher velocity of the air curtain in the proposed refrigerated cabinet is induced by the strips. As widely known, in tunnel flows, the velocity profile has always higher velocity in the centre and almost zero near the wall. In this paper, the air guiding strips in the path of the cool air curtain behave like a kind of short tunnels. When the cooled air jet flows down, the air at the centre of the gap of the strips accelerates to a higher velocity than the average air velocity of the cool air, strengthening the air curtain and promoting the protecting ability of the air curtain. It can be seen in Fig. 11 that the detaching vertex between the air curtain and the ambient warm air cross flow is much weaker and smaller than the conventional cabinet as shown in Fig. 7(b). At the same time, the flow direction of the air curtain is restricted vertical, promoting the protecting ability of the air curtain further. However, in the conventional cabinet, the cool air flows down without any acceleration and limitation, causing a relatively weak and disordered air curtain which is affected by the ambient air cross flow easily.

As a result of the stronger air curtain, the both the food and the air temperatures in the proposed refrigerated cabinet are much lower than the conventional one (see Figs 12 and 13).

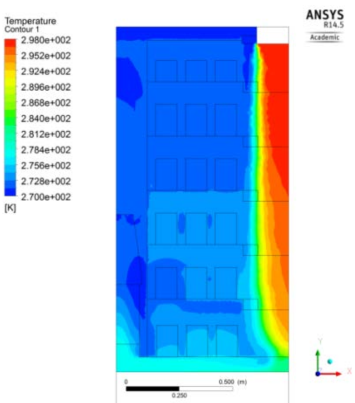

Fig. 12. Temperature of the middle plane of the proposed cabinet

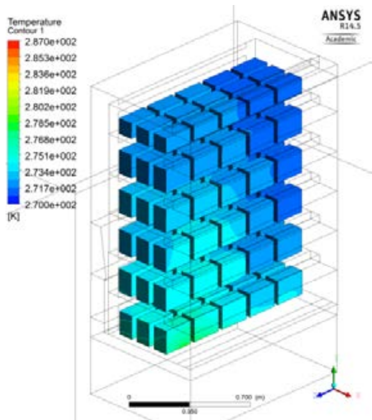

Fig. 13. Food temperature of the proposed cabinet

In Figs 12 and 13, it can be seen that the temperature profile of the proposed refrigerated cabinet is similar to the conventional one. The upper level has lower temperature than the lower level and the temperature at the right hand side is lower than the left.

However, by comparing Fig. 13 and Fig. 9, it can be found that the temperature of the proposed refrigerated cabinet is much lower than the conventional one. The results show that the average food temperature decreases from 4.7 °C in the conventional refrigerated cabinet to -0.2 °C in the proposed cabinet, by 4.9 °C.

This lower temperature is a direct result of the less infiltration of the ambient warm air. From the viewpoint of convectional heat transfer, the less infiltration of the ambient warm air makes the cabinet more of a closed cycling air system like cabinets with glass doors. The cool air curtain is less affected by the ambient warm air cross flow and returns through the air-on grill into the bottom tunnel of the cabinet at lower temperature (see Fig. 12), reducing the temperature difference between the cool air and the evaporator and resulting in less cooling capacity consumption. This less the cooling capacity consumption reduces the compressor operation, leading to power consumption savings. The consumed cooling capacity decreases from 890W in the conventional refrigerated cabinet to 586W in the proposed one, by 34%, meaning a potential energy saving of up to 34%.

4. Conclusion

An open-type vertical refrigerated display cabinet is proposed using air guiding strips at the front face of shelves of a conventional commercial open-type vertical refrigerated display cabinet. Both the conventional and proposed refrigerated cabinets are modeled and meshed in ANSYS-ICEMCFD together with the food products, and the air flow and heat transfer between the air and the food products are solved in ANSYS-Fluent R14.5. A testing condition consistent with BS EN ISO 23953-2 standard is built in the CFD model.

- The results show that the air guiding strips decrease both the temperature of the chilled food products and the cooling capacity consumption.
- The average food temperature decreases from 4.7 °C in the conventional cabinet to -0.2 °C in the proposed cabinet by 4.9 °C.
- The cooling capacity consumption decreases from 890 W to 586 W by 34%. This improvement comes from the strengthening of the air curtain.
- The air guiding strips in this paper accelerate the cool air at their gap centers and restrict the air flow vertical, causing a stronger air curtain which is impacted less by the ambient warm air cross flow.
- The loss of the cool air and the infiltration of the warm air are less in the proposed refrigerated cabinet, leading to the lower food temperature and less cooling capacity consumption.

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