Investigation of the influence of air guiding strips on the performance of multi-deck refrigerated display cabinets using CFD modelling

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Abstract: To decrease the cooling capacity of open-type display cabinets, air guiding strips are proposed to be used at the front face of shelves. A refrigerated food multi-deck display cabinet with a plug-in cooling unit is selected as a prototype, and a 3-D CFD transient model is developed in ANSYS-Fluent 14.5, to simulate the performance of the cabinet.

The air guiding strips were found to maintain the air velocity and the integrity of the air curtain, reducing turbulence and the entrainment of ambient air into the cabinet. For the same product temperature the cabinet with the air guiding strips was found to reduce the cooling load by up to 25% compared to the cabinet without the strips. These results need to be further validated against experimental tests at controlled conditions in the laboratory.

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

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. 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 (Chen, 2005). The penalty for the open-type refrigerated display cabinets is the lower energy efficiency due to infiltration from the warm store air to cold air at the air curtain. 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 (2015) for the chilled food application.

The air infiltration due to the open style cabinet can account for up to 67-77% of the total heat exchange from the ambient (Gaspar, 2010). The cabinets with doors are consuming less energy due to the glass door barrier. Fricke and Becker (2010) reported that the doored refrigerated cabinet had total electrical power consumption 1.71 kWh/day per feet and the open-type had 2.21 kWh/day per feet. Cao et al. (2011) pointed out that the air curtain losses and energy consumption can be reduced by 19.6% and 17.1% respectively by optimizing the air curtain. Navaz et. al. (2005) stated that the turbulence intensity, shape of the mean velocity profile at the discharge air grill and the Reynolds number affect the air entrainment. Gray et. al. (2008) reported 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.

The CFD simulation tool is a very practical way to investigate the air curtain and back panel mechanisms in the refrigerated display cabinets. Some investigations were carried out in 2D CFD model due to its simplification and less requirements of computer power and time (Navaz, 2002, Cortella, 2002, Gaspar, 2012, Ge, 2010). But, considering the absence of the cross flow of warm ambient air of 2D CFD model, 3D CFD model gives more precise results. D'Agaro et. al. (2006) compared the experimental results of a vertical display cabinet with both 2D and 3D CFD models and found 3D secondary vortices at the side walls due to the interaction of the side walls and the cross flow of warm ambient air, providing the most important mechanism for hot air entrainment.

In the present paper, flow guiding strips are used at the front face of the shelves of an open-type multi-shelves vertical refrigerated display cabinet. A transient 3D CFD model composed of the air circulation in and around the cabinet, food loads and cross flow of warm ambient air is developed and validated based on the experimental results. The display cabinet with/without flow guiding strips is simulated for 24 hours running time including both the defrosting periods and compressor on/off cycles. The aim of this paper is to investigate the impact of these flow guiding strips on the cooling capacity of the cabinet by analyzing the flow patterns of the air curtain, the entrainment of the warm ambient air and the food temperatures, giving an improved cabinet design with high energy efficiency.

2. CABINET DESCRIPTION

A refrigerated food multi-deck display cabinet with a plug-in cooling unit is selected as a prototype, as shown in Figure 1.

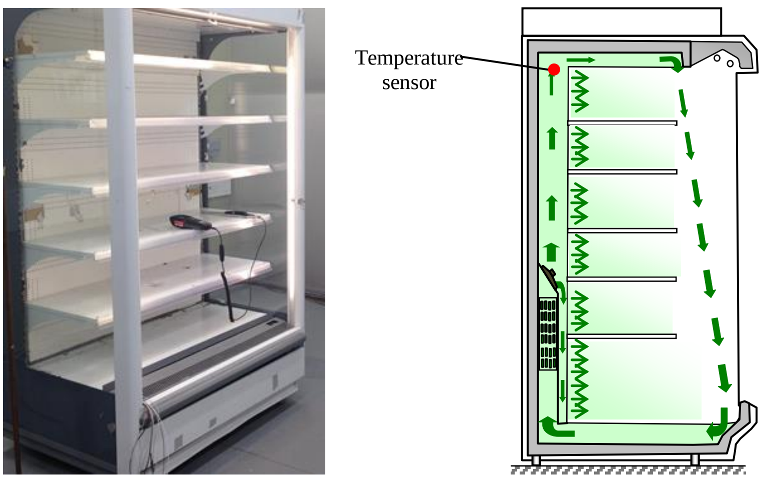

Figure 1: Prototype display cabinet

The prototype cabinet has dimensions of 1980 mm (H) x 880 mm (D) x 1250 mm (W) and is equipped with 5 shelves and a bottom panel for food storing and displaying. The air circulates in the cabinet through a bottom tunnel with an air-on grill as the air inlet, a back tunnel with perforated back panel and a top tunnel with an air-off honeycomb as the air outlet. The evaporator is located at the bottom of the cabinet back panel. Above the evaporator coils, a propeller fan is installed to facilitate the circulation of air flow in and around the cabinet. The other parts of the cooling unit are positioned underneath.

The air guiding strips used in this paper are plane plates and are shown in Figure 2. The strips are 0.05 m in height and installed at the shelf fronts in pairs. The gap distance of the strips of each pair is 0.07 m, which is the same as the width of the air-off honeycomb. The thickness of the strips is neglected as modelling.

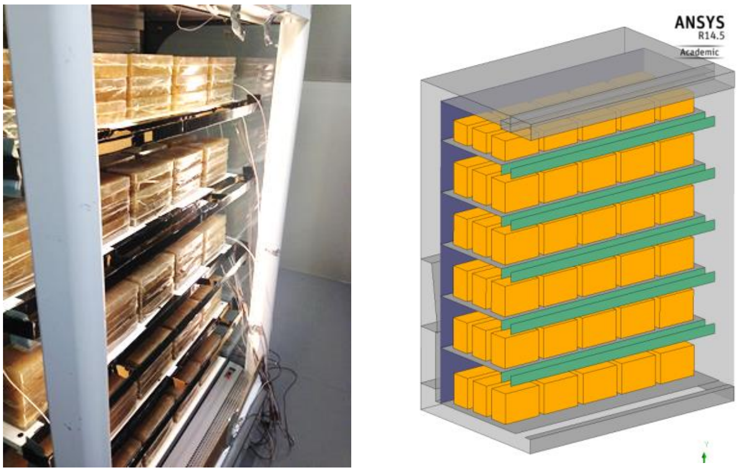

Figure 2: Air guiding strips

3. CFD MODEL SETUP AND VALIDATION

3.1. CFD model setup

In real cabinets, the defrosting process of the evaporator have to take place every 2 or 4 hours to keep the evaporator out of ice, and the compressor should be turned on or off once the air temperature is higher or lower than the upper or lower setting point to keep the food temperature not too high or too low. This means the air flow and heat transfer in the cabinet are always unsteady and the evaporator and the fan should be taken into account to simulate the transient air flow and heat transfer correctly.

To fulfil such a transient model, ANSYS-FLUENT R14.5 is used and a transient compressor controller programmed in UDF (User Defined Function) is applied to define the on/off status of the compressor according to the defrosting time and the air temperature in the back tunnel. The virtual temperature sensor is placed at the top of the back tunnel which is shown in Figure 1. In this paper, the upper and lower setting points are set at 5 °C and -3 °C based on the experimental test. Every 4 hours, the status of the compressor is set at “on” and keeps for 7 minutes, which is the same as the experimental test.

Apart from the aforementioned models, it is also necessary to activate the basic equations and models in to simulate the air flow and heat transfer in the cabinet, which are listed in Table 1 and not discussed in details.

Table 1: Activated basic equations and models in ANSYS-FLUENT

Simulation	Activated basic equations and models
Air flow	Mass & momentum conservative equation
Heat transfer	Energy conservative equation
Turbulence	Standard k-ε model
Humidity	Vapor mass fraction conservation equation
Radiation	S2S radiative model
Natural convection	Gravity & ideal gas model of air
Flow resistances of evaporator, honeycomb and back panel	Porous media model
Fan	Fan model

According to the BS EN ISO 23953-2 (2015) 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 (D) x 7 m (W) x 4m (H) where the warm room air comes from the right side of the cabinet and exits at the left side. The air velocity is set at 0.13 m/s. Temperature and humidity are kept constant at 25 °C and 60% respectively.

In this CFD model, the food samples are stacked consistent with the ISO 23953-2015 standard. Each refrigerated shelf area loaded in a way that they form rows of 200 mm width by the depth of the cabinet in the direction as the air flows inside the cabinet. The gap between the products was set to be 25 mm ± 5mm to have a minimum effect on the airflow of the cabinet. The loading height was equal to free height between the shelves minus 25 mm. The CFD model set to measure the product temperatures at the top, middle and bottom shelves (T/M/B). The product temperature monitored at the right and left part of the shelves (L/R) and the front and rear positions of the cabinet (F/R). For the food stacks of the food samples, the temperatures of the lower and upper samples (L/U) are recorded. The model extracts the temperature of the products by the middle of each product.

The product temperatures are named in sequence of 4 letters based on each position. For example, TRRL means the food sample at the top (T) level, right(R) side, rare(R) side and lower (L) position.

The entrainment rate means how much of ambient warm air flows into the cabinet and is often used to evaluate the efficiency of air curtains, which is defined as follows.

$$\alpha = \frac{T_{on} - T_{off}}{T_{amb} - T_{off}} \tag{1}$$

where, T_{amb} is the temperature of the ambient warm air, and T_{on} and T_{off} are the temperatures at air-on and air-off respectively.

The evaporator cooling capacity is the cool used in the evaporator. It can be calculated by the enthalpy change of the air flow passing through, which is called sensible cooling capacity, and the enthalpy change of the vapor condensing, which is called latent cooling capacity.

$$Q_{sens} = \dot{m}C_{p,a}\left(T_{on} - T_{off}\right) \tag{2}$$

where, $\dot{m}$ is mass flow rate of the evaporator, and $C_{p,a}$ is the specific heat capacity of air.

$$Q_{lat} = \dot{m}\left(wf_{on} - wf_{off}\right)r \tag{3}$$

where, r is the latent heat of water vapor, and wf_{on} and wf_{off} are the water mass fraction in the air at air-on and air-off respectively.

3.2. CFD model validation

Figure 3 shows the air temperature history in 24 hours in the simulation. It can be seen that, the air temperature at the air-off honeycomb fluctuates due to the compressor on/off under control, as well as the air temperature at the air-on grill. The two temperatures fluctuate synchronously. Once the air-off temperature decreases to -3 °C, the compressor is turned off, causing the air-off and air-on temperatures increase. Once the air-off temperature increases to 5 °C, the compressor is turned on, and the air-off and air-on temperatures begin decreasing. The air-off temperature fluctuates between -3 °C ~ 6 °C, and the air-on temperature between 10 °C ~ 14 °C. The cycle number of the compressor on/off between every two defrosting processes is about 10. In the experiment test, the ranges of the air-off and the air-on temperature are also -3 °C ~ 6 °C and 10 °C ~ 14 °C, and the cycle number ranges between 9-11, which are the same as the simulating results.

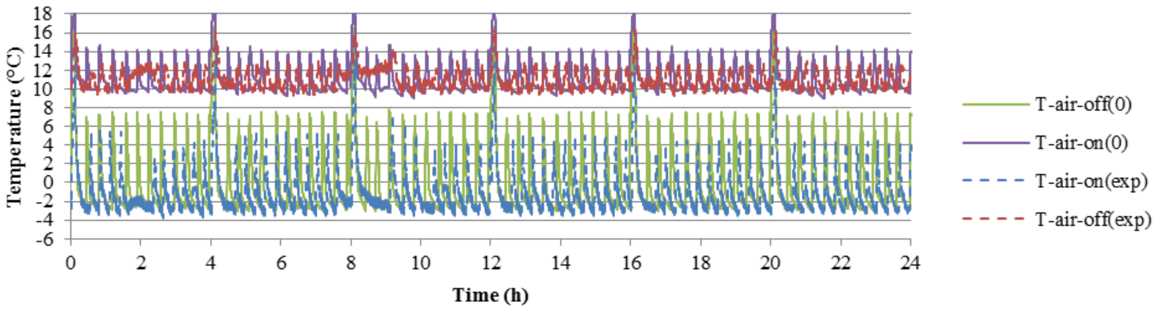

Figure 3: 24 hours history of the air temperatures at air-off and air-on in prototype cabinet

Figure 4 shows the variation temperatures of the food products in 24 hours in the simulation. Two virtual sensors are used at TRRL and BLFL, which are the positions with the minimum and maximum temperatures in the experimental tests respectively. It can be seen that, the TRRL varies in the temperature range of 1 °C ~ 2 °C and BLFL 7 °C ~ 8 °C, which are the same as the experimental data. Moreover, both these two temperatures increase just after each defrosting process and then decrease gradually, which is also consistent with the experimental tests.

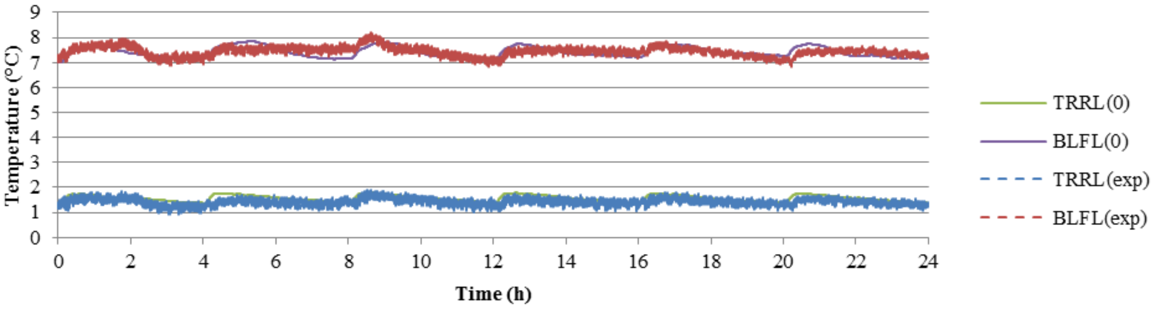

Figure 4: 24 hours history of the food temperatures in prototype cabinet

The consistency of the history of these critical temperatures in the simulation and the test shows that this CFD model can simulate correctly the flow and heat transfer process in and around this open-type refrigerated display cabinet and is reliable.

4. MODEL RESULTS AN|D DISCUSSION

4.1. Air flow and entrainment rate

Figure 5 shows the mass flow rates and compressor cycle history of the prototype cabinet (referred by '0'). It can be seen that the mass flow rate of the evaporator is about 0.2 kg/s. The mass flow rate of the air-off is 0.138 kg/s, accounting for about 70% of the mass flow rate of the evaporator. It can also be seen that the flow rates fluctuate consistent with the air temperature history. As the air temperature increases, the mass flow rates of both the evaporator and the air-off decrease, and vice versa.

This fluctuation of mass flow rate as well as air temperature is the direct result of the compressor on/off history. When the air temperature in the back tunnel is higher than the upper setting point, the compressor is on, with decreasing air temperatures and increasing air density, causing the air flow rates increase. When the air temperature in the back tunnel is lower than the lower setting point, the compressor is then off and the air temperatures increase with increasing air density and air flow rates.

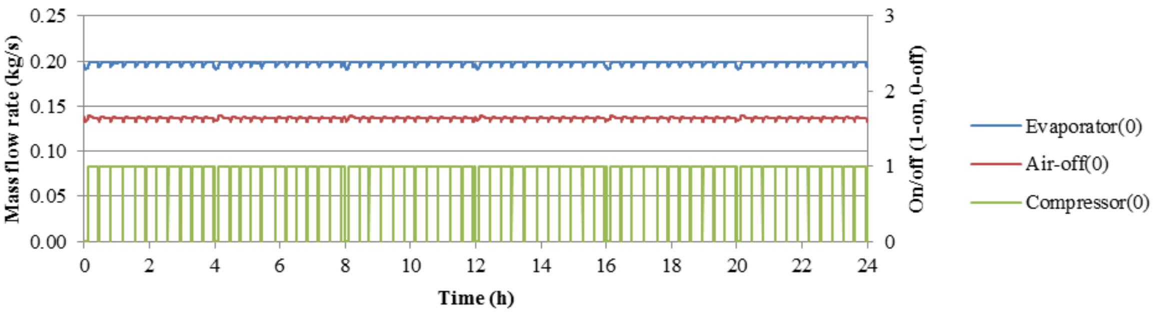

Figure 5: Mass flow rates and compressor cycle history of the prototype cabinet

Figure 6 shows the mass flow rates and compressor cycle history of the strip cabinet (referred by '1'). It can be seen that the mass flow rates of the evaporator and the air-off are almost the same as the prototype cabinet, indicating that the installation of the air guiding strips at the shelf fronts does not change the mass flow rates of the cabinet. However it could be noticed easily that the fluctuation frequency of the mass flow rates in the strip cabinet is much higher than the prototype, meaning the compressor in the strip cabinet is turned on/off more frequently. The cycle number between two defrosting processes is about 26 in the strip cabinet, which is much higher than the 10 cycles in the prototype cabinet, meaning the air-off temperature decreases to the lower setting point much quicker in the strip cabinet than in the prototype cabinet.

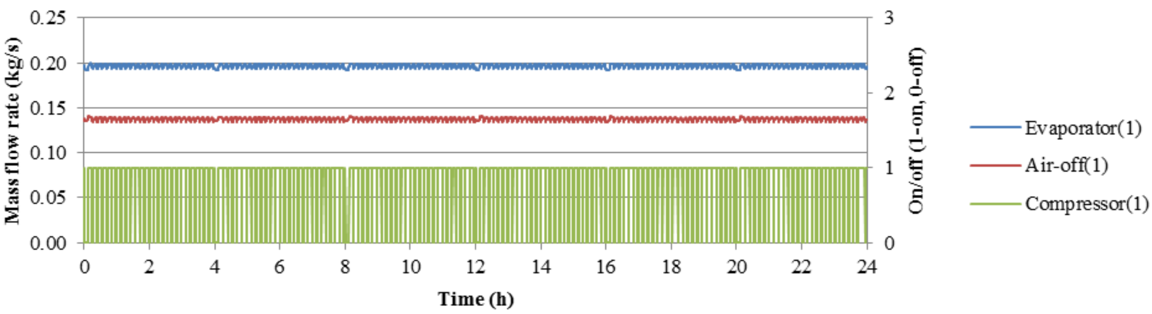

Figure 6: Mass flow rates and compressor cycle history of the strip cabinet

Figure 7 shows the air-on and air-off temperature histories in the strip cabinet. It can be seen that the air-off temperature fluctuates between -3 °C ~ 6 °C, which is the same as the prototype (see Figure 7) because of the same control rule as the prototype cabinet applied. However the air-on temperature varies between 7 °C ~ 12 °C, which is much lower than the range of 10 °C ~ 14 °C in the prototype cabinet (see Figure 7). This lower air-on temperature means lower entrainment rate according to Eq. (1).

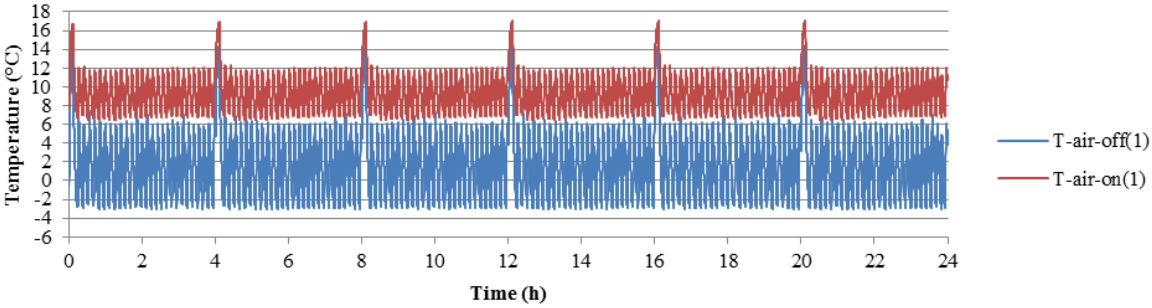

Figure 7: 24 hours history of the air temperatures at air-off and air-on in strip cabinet

The average air-off and air-on temperatures in the prototype cabinet are 0.15 °C and 11.1 °C respectively, resulting in an entrainment rate of 0.438. In the strip cabinet the average air-off and air-on temperatures are 1.71 °C and 9.36 °C and the entrainment rate is 0.328. The lower entrainment rate means less warm ambient air is entrained into the cabinet, and consequently less cooling capacity is required for cooling down the air flow. This lower entrainment rate in the strip cabinet comes from the improved flow pattern of the air curtain, which is shown in Figure 8 to Figure 11.

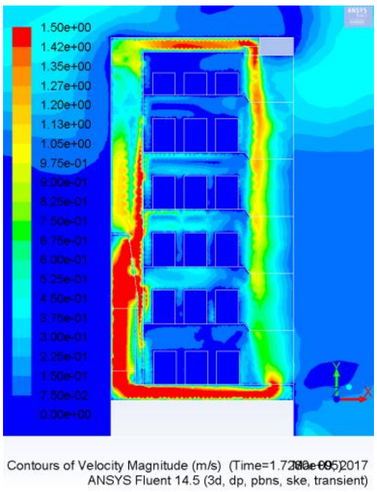

Figure 8: Air velocity profile in the prototype

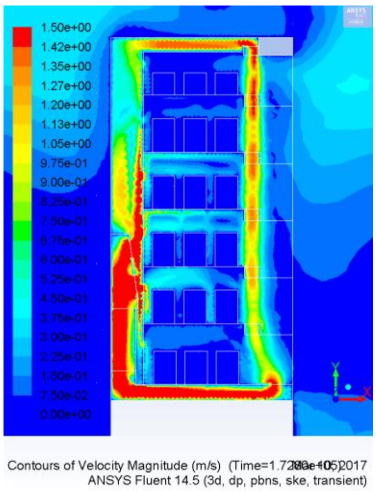

Figure 9: Air velocity profile in the strip cabinet

Figure 8 and Figure 9 show the air velocity profiles at the middle cross section of the prototype and strip cabinets. It can be see that the air velocity at the air-off honeycomb of the prototype cabinet is about 1.5 m/s. As the cooling air flows down, the ambient air is infiltrated into the cooling air stream along the air curtain and flows down together with the cool air, causing the vertical velocity of the air curtain slow down continuously. The air velocity decreases to about 0.9 m/s as the 5th layer front. In the strip cabinet the air flow keeps straight down and the air velocity is about 1.1 m/s at the 5th layer front, much higher than the prototype. Therefore, the air guiding strips can guide the air down and increase the air curtain velocity.

Figure 10 shows the turbulent kinetic energy in the prototype cabinet. It can be found that the turbulent kinetic energy in the prototype cabinet increases along the stream wise of the air curtain. This is because in the prototype cabinet the air curtain flows down in an open space and the turbulent vortex could develop along the stream easily without any limitation, causing strong turbulence along the air curtain and intensive mixture of the cool air and the warm ambient air.

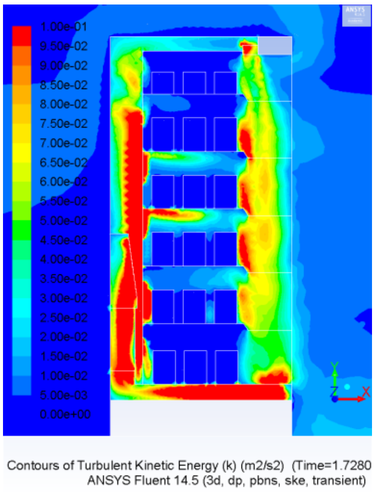

Figure 10: Turbulent kinetic energy profile in the prototype

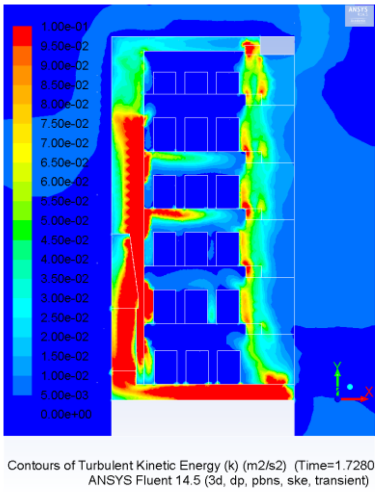

Figure 11: Turbulent kinetic energy profile in the strip cabinet

But in the strip cabinet the turbulent kinetic energy is much smaller along the air curtain (see Figure 11). Once the turbulent kinetic energy flows down to the strips, it decreases to a very low value and increases again as flowing down. Here the strips work like a grid which splits big turbulent vortices into small vortices, limiting the mixture of the cooling air and the ambient air and causing smaller entrainment rate.

4.2. Food temperatures

Figure 12 shows the 24 hours history of the food samples of TRRL and BLFL, which are the minimum and maximum food temperatures respectively. It can be seen that the minimum temperature varies between 2 °C ~ 3 °C and maximum temperature 8 °C ~ 9 °C. Compared with the food temperatures in the prototype cabinet (see Figure 4), it can be found that the food temperatures in the strip cabinet are higher by about 1 °C.

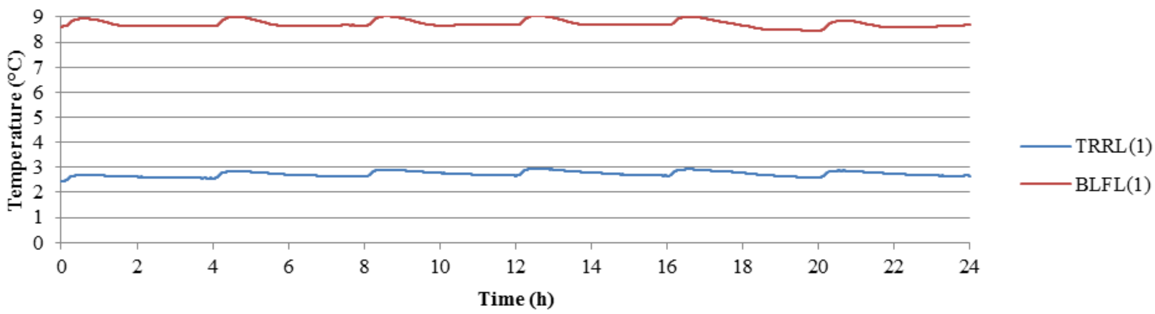

Figure 12: 24 hours history of the food temperatures

This is because of the higher air-off temperature in the strip cabinet which is shown in Figure 13. It can be seen clearly in this 2 hours air temperature history that during each compressor-on period the air temperatures in the prototype decrease quickly, because the air-on temperature is high at the beginning, causing high temperature difference as well as heat transfer between the air and the evaporator. As the air-on temperature drops down, the temperature difference and heat transfer rate decrease, causing the air-off temperature decrease slowly.

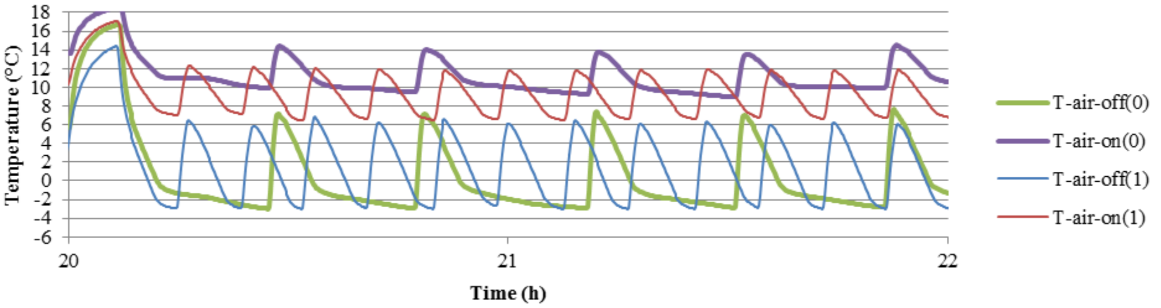

Figure 13: 2 hours history of the air temperatures at air-off and air-on in the prototype and strip cabinets

However, for the strip cabinet, the air-on temperature is much lower than the prototype cabinet by about 2 °C, indicating that it is easy for the air-off temperature to decrease to the lower setting point, causing the average air-off temperature in the strip cabinet, 1.71 °C, higher than the prototype cabinet, 0.15 °C, and resulting in less protection of the air curtain and higher food temperature.

4.3. Results with the lower setting point of -4 °C

To tackle the problem of the higher food temperature in the strip cabinet, the control rule is improved by setting the lower setting point to -4 °C, which is lower than the previous setting of -3 °C by 1 °C. This run is named as the No.2 strip cabinet in this paper.

Figure 14 shows the 24 hours history of the air temperatures in the No.2 strip cabinet (referred as '2'). It can be seen that the air-off temperature changes between -4 °C ~ 6 °C, which is the direct result of the -4 °C lower setting point. The average air-off temperature of the No.2 strip cabinet is -0.25 °C, lower than the strip cabinet by about 2 °C. The air-on temperature of the No.2 strip cabinet decreases to the range of 6 °C ~ 12 °C, also lower than the strip cabinet, 7 °C ~ 12 °C. The average of the air-on temperature of the No.2 strip cabinet is 8.1 °C, lower than the strip cabinet by 1.2 °C.

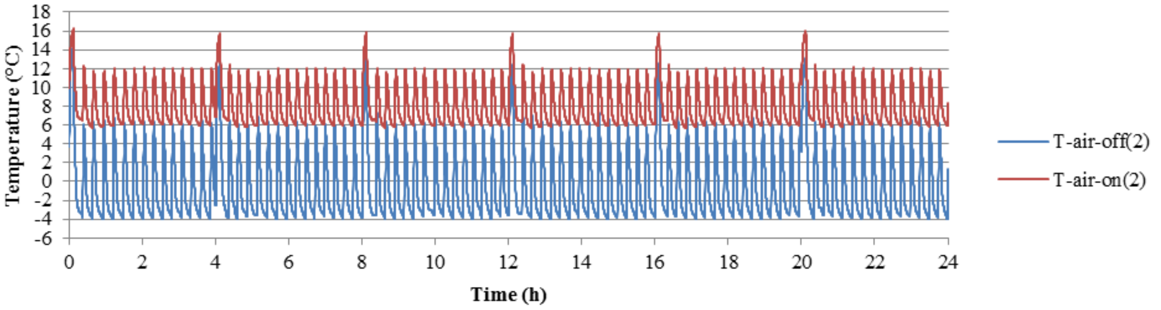

Figure 14: Air temperature history in the No.2 strip cabinet

It can be seen in Figure 15 that the maximum food temperature fluctuates between 7 °C ~ 8 °C, which is lower than the strip cabinet by 1 °C and the same as the prototype cabinet. The minimum food temperature changes between 0.5 °C ~ 1.5 °C, which is slightly lower than both the strip cabinet and the prototype cabinet by 1.5 °C and 0.5 °C respectively.

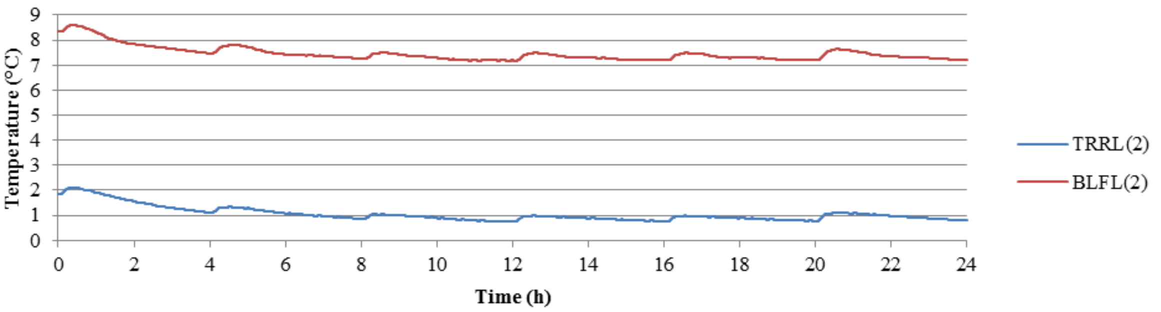

Figure 15: Food temperature history in the No.2 strip cabinet

4.4. Cooling capacity

According to equation (2) and (3), the cooling capacity of these 3 cabinets are calculated and listed in Table 2.

Table 2: the cooling capacity

Cabinets	Mass flow rate (kg/s)	T-on (°C)	T-off (°C)	Specific heat (kJ/kg·K)	Sensitive cooling capacity (kW)	Wf-on	Wf-off	Latent heat (kJ/kg)	Latent cooling capacity (kW)	Total cooling capacity (kW)
Prototype cabinet	0.2	0.15	11.1	1.006	2.20	0.0039	0.0072	2484	1.66	3.86
Strip cabinet	0.2	1.7	9.4	1.006	1.54	0.0046	0.0068	2484	1.09	2.63
No2. strip cabinet	0.2	-0.25	8.1	1.006	1.69	0.0040	0.0064	2484	1.20	2.89

Both of the two strip cabinets have a cooling capacity which is lower than the prototype cabinet. The prototype cabinet has a total cooling capacity of 3.86 kW. The total cooling capacity of the No.2 strip cabinet 2.89 kW. So the total cooling capacity of the No.2 strip cabinet is 75% of the prototype.

5. CONCLUSIONS

To decrease the cooling capacity of open-type display cabinets, air guiding strips are proposed to be used at the front face of the shelves of the cabinets. An integral refrigerated food multi-deck display cabinet was used to investigate the effect of the guiding strips. The transient performance of the cabinet was modeled using CFD modelling. The CFD model was validated against experimental results.

It was identified that the air guiding strips at the shelf fronts help to straighten the air flow from the discharge grille as it descends towards the suction grille, reducing turbulence and ambient air entrainment into the cabinet. For the same product temperatures the cabinet with the strips was found to reduce the cooling load of the cabinet by 25%. This figure needs to be validated experimentally through tests at controlled conditions in the laboratory.

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