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Abstract

An experimental study was performed in order to investigate the effects of operating conditions, including door opening frequency, ambient air temperature and product-occupied volume, on the air and product temperature distributions inside a closed refrigerated display cabinet. The product position in the cabinet is a determining factor of its temperature: a high temperature was observed at the front, particularly at the top of the cabinet, and a low temperature was observed at the back. Air infiltration due to door openings caused a product temperature increase at the front and a temperature decrease at the back. At a higher door opening frequency (more than 60 openings per hour per door), the product temperature at the level of the front middle shelf was the most affected. Both the ambient temperature and occupied volume also affected product temperature variations in the closed display cabinet. In comparison to an open display cabinet, a closed display cabinet achieves lower product temperature and better temperature homogeneity, even with a high door-opening frequency. These findings indicate that the use of closed refrigerated display cabinets should be advocated in order to achieve better food preservation.

Keywords: Closed refrigerated display cabinet; Door-opening frequency; Experimental study; Thermal performance; Temperature

Nomenclature

A Area, m^{-2}

H Opening height, m

T Temperature, °C

$\overline{u}$ Mean air velocity, $m \cdot s^{-1}$

δ_c Characteristic time, s

θ Dimensionless temperature defined as $\theta = \frac{\overline{T} - \overline{T}_{th}}{T_e - \overline{T}_{th}}$

ρ Density, $kg \cdot m^{-3}$

Subscripts

a air

e external ambient

int initial

jet air curtain

p product/package

th thermostat

Abbreviations

DAG Discharge Air Grille

OPH Number of door Openings Per Hour

PBP Perforated Back Panel

RAG Return Air Grille

1. Introduction

Poor temperature control is often observed in open refrigerated display cabinets which are widely used in retail stores (ASHRAE, 2010). In open cabinets, a stable and homogeneous storage temperature is difficult to maintain since an air curtain alone is used to protect food products from the ambient surroundings, resulting in significant infiltration of warm and humid air (Gaspar et al., 2011). Air infiltration is frequently cited as one of the major factors causing temperature heterogeneity (Laguerre et al., 2012) and high energy consumption (Tassou et al., 2011). Temperature variations of up to 5°C between locations within the cabinet were observed (Willocx et al., 1994); the products in the front areas were usually exposed to a high temperature, whereas the products at the back were at lower temperatures (Evans et al., 2007). A great deal of research has been carried out using both experimental investigations (Chen and Yuan, 2005; Gray et al., 2008) and numerical simulations (Field and Loth, 2006; Moureh and Yataghene, 2016) in order to maximize the air curtain efficiency, thereby enhancing the overall performance of open display cabinets. In addition to efforts designed to improve the air curtain efficiency, a novel short air curtain design was proposed (Hammond et al., 2016). In this study, multiple short air curtains used for each shelf provided enclosure of the front of the cabinet, rather than a single long air curtain. The experimental results showed that beyond potential energy savings, a more uniform temperature distribution can be achieved. A review of the current usage situation and attempts to improve the performance of refrigerated display cabinets can be found in Chaomuang et al. (2017). Despite many improvements over the last few decades, higher display cabinet efficiency remains a necessary research topic for sustainable retail refrigeration (Al-Sahhaf, 2011).

Installation of doors on open-front display cabinets has become an alternative designed to address the air infiltration issue. It has been proven that the closed display cabinet achieves several favorable outcomes including energy savings of 20-70% (Faramarzi, 1999; Fricke and Becker, 2010; Kauffeld, 2015; Navigant Consulting Inc., 2009), reductions in internal temperature heterogeneity (Chaomuang et al., 2019; Evans and Swain, 2010; Lindberg et al., 2010), and improved food quality (Atilio de Frias et al., 2015). Moreover, doors can also provide better thermal comfort in retail stores due to less cold air spillage from the display cabinet (Lindberg et al., 2017). Given these benefits, doors have been installed to an increasing extent in various countries. An agreement between the French authorities and the major supermarket stakeholders aims to replace open display cabinets by closed display cabinets, and to ensure that by 2020, 75% of all display cabinets in use will be closed models (RPF, 2016).

In contrast to the energy consumption aspect, the temperature performance of closed refrigerated display cabinets is seldom investigated, particularly in terms of spatial and temporal temperature variations. A comparative investigation conducted by Evans and Swain (2010) revealed that the temperature variations within closed cabinets were lower than those within open cabinets. Lindberg et al. (2010) demonstrated that an overall air temperature reduction of at least 2°C was achieved when the display cabinet was retrofitted with doors. Atilio de Frias et al. (2015) observed a substantial decrease in the spatial temperature differences of almost 6°C and underscored the better visual quality and lower decay rate of minimally-processed vegetables achieved by the installation of doors on display cabinets.

An experimental analysis of heat transfer and airflow in a closed refrigerated display cabinet under closed conditions was performed in our previous study (Chaomuang et al., 2019). The knowledge acquired provides an insight into the thermal exchange mechanisms taking place in the equipment. It was found that convection and conduction were the predominant heat transfer modes, while radiation was rather weak due to the presence of low-emissivity coating materials on the glass doors. In addition, the main causes of air and product temperature variations in closed display cabinets are air infiltration through the door gaps and the proximity to the cabinet lighting. The authors highlighted that closed display cabinets can achieve better temperature performance in comparison with open cabinets.

As much greater air infiltration occurs during door openings than through the door gaps when the cabinets are closed, the opening frequency plays an important role in the performance of closed display cabinets. Lindberg et al. (2010) found that when the opening frequency increased from 10 to 30 openings per hour (OPH), the heat extraction rate of the heat exchanger increased by 16%, while the difference between the maximum and minimum product temperatures ($\Delta T = T_{\max} - T_{\min}$) increased from 2.7°C to 3.0°C. Orlandi et al. (2013) numerically highlighted the influence of this factor on the energy consumption of the closed display cabinet. Their results showed that this factor becomes the predominant factor determining the refrigeration load when an opening frequency of 60 OPH is applied. To the best of our knowledge, the influence of the door-opening frequency on the temperature distribution (spatial and temporal) had rarely been studied.

The present study aims to investigate the influence of operating conditions, i.e. the frequency of door openings, ambient temperature and percentage of occupied volumes, on the thermal performance of a closed refrigerated display cabinet. This performance was evaluated using air and product data for design improvements and the practical handling of closed refrigerated display cabinets in supermarkets.

2. Material and methods

2.1. Closed refrigerated display cabinet

The closed refrigerated display cabinet was placed in a test room in which the ambient temperature was controlled at 19.4°C (with a standard deviation of 0.5°C) and the air humidity varied between 0.007 and 0.009 kg water/kg dry air. As shown in **Fig. 1a**, the test room was equipped with two fans to homogenize the room temperature; more details were presented in Chaomuang et al (2019). The rear of the display cabinet was in front of these fans to minimize the influence of airflow in the room on the measured value inside the cabinet. **Fig. 1b** depicts the closed refrigerated display cabinet (Offlip 2 Eco 125S, Costan) used in the study, which had external dimensions (width × length × height) of 650 mm × 1310 mm × 1980 mm and internal dimensions of 525 mm × 1250 mm × 1345 mm. The cabinet is an integral-type cabinet which is designed to meet the requirements of cabinet class M1 and climate class 3, i.e. product temperature varies between -1°C and +5°C for an ambient temperature of 25°C and a relative humidity of 60% (EN ISO 23953-2, 2015). Two hinged doors (620 mm × 1330 mm) and the lateral walls are made of a double-glazed window with 22-mm thickness in which a 14-mm air gap filled with 90% argon gas is sandwiched between two panes of 4-mm tempered glass. The glass panes are also coated with a low-emissivity material to avoid the transmission of infrared radiation. There are 8-mm gaps between the door and the lateral wall of the cabinet to assist door openings.

There are five shelves from the top (Shelf 1) to bottom (Shelf 5) in the display cabinet. The space above Shelves 1 to 4 (350 mm in width × 1250 mm in length) is 225 mm, while that above Shelf 5 (475 mm × 1250 mm) is 345 mm (**Fig. 1b**). These spaces between shelves represent a total storage volume of about 0.60 m^3 in the display cabinet.

Different perforation patterns and percentages of the perforated back panel (PBP) are allocated to each shelf as illustrated **Fig. 1b**. The percentage of perforated area (PA) over Shelf 1 is the lowest (2.3%) as there is no perforation in the center. For the intermediate shelves (Shelves 2-4), the same percentage of 3.8% is applied, while more refined perforation is applied Shelf 5 with the highest percentage, 8.3%.

Air is cooled down and flows upwards along the vertical rear duct after flowing through a finned-tube heat exchanger by means of two propeller fans underneath the bottom shelf as schematically illustrated in **Fig. 1b**. Because of the different percentages of the PBP on each shelf, different air flow rates into the shelves-storage space were observed (Chaomuang et al., 2019). Another part of the air flows upward until it reaches a discharge air grille (DAG). Here, an air curtain homogenized using a honeycomb is established, providing protection of products located at the front of the cabinet. Some of the air flowing from the PBP mixes with the air curtain and flows downward to a return air grille (RAG) to be cooled down and returned to the display cabinet.

2.2. Temperature measurement

Test packages made of methylcellulose (width × length × height: 100 × 50 × 200 mm) were loaded in the display cabinet of which the total storage volume was 60% occupied (**Fig. 1b**). Calibrated T-type thermocouples (200 µm diameter, uncertainty of ±0.2°C) were installed at various positions in the cabinet for the air temperature measurements. Some of them were inserted into the geometric center and/or attached onto the surface of the test packages using aluminum tape for product temperature measurements. Air and product temperatures were recorded using a data acquisition system (Agilent 34970A) at an interval of 10 seconds after the beginning of testing. The time-averaged temperature of both air and products was then calculated over a 5-hour (quasi)-steady state period in which the defrosting period was excluded from the calculation.

2.3. Door-opening regime

2.3.1. Automatic door opening

Two cabinet doors are assigned to an automatic 12-hour door-opening regime by using a programmable apparatus to control the frequency of door openings. The baseline of the door-opening experiment consists in opening each door for three minutes to simulate stocking and replenishing activities as illustrated in **Fig. 2**. Each door is then open in sequence with respect to a frequency of 10 openings per hour (OPH) with a full opening angle of 90° for a duration of 15 seconds (one second to open the door, 13 seconds holding time and one second to close the door). According to this defined frequency, the door opening takes place every 3 minutes, i.e. at 0 min. the right door is open, at 3 min. the left door is open, at 6 min. the right door is open, at 12 min. the left door is open and so on (see **Fig. 2**). It is important to note that this door-opening regime is programmed as prescribed in the standard test (EN ISO 23953-2, 2015).

2.3.2. Experimental procedure

After temperature stabilization, the closed display cabinet operated for three periods, each of a duration of 12 h. The display cabinet lighting and the room lighting were switched off for the first period. The lighting was then switched on and the automatic door-opening system was started for the second period. After the end of the door-opening experiment, the doors were closed while the lighting remained on. Air and product temperatures were recorded throughout the three periods, and the time-averaged values were calculated as described in Section 2.2.

2.4. Variations in operating conditions

Air and product temperature measurements were carried out in the closed refrigerated display cabinet. The operating conditions of these measurements are summarized in **Table 1**. The experiment carried out at an ambient temperature of 19.4°C, with a door-opening frequency of 10 OPH, and 60% total occupied volume (considered as full load) was then assigned to be a baseline for analysis of the influence of operating conditions on the thermal performance of the closed refrigerated display cabinet. It should be emphasized that when the influence of one factor was studied (e.g. door-opening frequency), the other factors were fixed (ambient temperature 19.4°C and 60% of total occupied volume).

2.4.1. Door-opening frequency

In addition to the permanently closed doors and permanently open doors (door-opening frequency of 0 and ∞ respectively), the frequency of 10, 20, 40 and 60 OPH was programmed to study its influence on the air and product temperature distributions inside the closed refrigerated display cabinet. The duration of 15 s with the full opening angle of 90° was applied for all door-opening frequencies and the same experimental procedure (Section 2.3.2) was applied to all experiments. Based on data available in the literature (Fricke and Becker, 2010) and information provided by a display cabinet manufacturer, the average frequency of door openings is, respectively 6.3 and 12.1 OPH. The frequency of 60 OPH was therefore set as an extreme condition as it is rarely encountered in reality. Note that the doors were completely removed from the display cabinet for the permanently open condition.

2.4.2. Ambient temperature

In addition to the room temperature of 19.4°C considered as a baseline, the test room was controlled at different temperatures of 14.6°C, 24.3°C and 28.2°C (with a standard deviation of less than 0.5°C for all temperatures) to investigate its influence on the air and product temperatures in the display cabinet. The water content of the air in the test room varied from 0.008 to 0.013 kg water/kg dry air, corresponding to the variation in the relative air humidity of 50% and 75%, respectively. This small variation in water content in the air exerted little influence on the temperature performance, but it does affect the energy performance because of frost formation on the evaporator (Chen and Yuan, 2005). The same experimental procedure (Section 2.3.2) was applied in all experiments.

2.4.3. Occupied volume

Two occupied volumes were used in the experiments: 30% (considered as half load) and 60% (considered as full load). The difference in these occupied volumes concerns the number of layers of test packages in height only, while the arrangement remained the same (6 columns in width and 3 columns in depth, see **Fig. 1b**). The same experimental procedure (Section 2.3.2) was applied to all experiments.

3. Results and discussion

3.1. Evolution of air and product temperatures

Fig. 3 shows the evolution of the air and product (core and surface) temperatures in the center plane (520 mm from the left wall) of the closed refrigerated display cabinet over the 36-h operation comprising 12 h of closed-door and lights off conditions, 12 h of door openings with a frequency of 10

OPH and lights on, and 12 h of closed-door and lights on conditions. During the closed-door periods, the air temperature fluctuation was almost identical and followed the on/off regulation of the compressor (with a duration of about 10 min.) and the defrosting operation (every 6 h with a duration of about 25 min.) as shown in **Fig. 3a**. During the door openings, a larger amplitude of fluctuation in the air temperature was observed at the front of the cabinet (A1, A3 and A5).

The product temperature fluctuations during the closed-door periods were also subject to the on/off compressor and defrost operations; however, their amplitudes were much lower than that of the air (**Fig. 3b**). During the door openings, the product surface temperature fluctuations became more pronounced on the top and middle shelves (S1 and S3). The surface temperature fluctuations on the bottom shelf (S5) and those of the core at the front (F1, F3 and F5) were less obvious despite a slight temperature increase. The door-opening frequency (10 OPH) exerted an insignificant effect on the average temperatures and the temperature fluctuations of the products at the back (B1, B3 and B5).

To ascertain the thermal phenomena during the door openings, additional air temperatures at the A1, A3 and A5 positions were recorded with more frequent data acquisition (a time interval of 1 s). After 24 h of temperature stabilization, recording of the door-opening cycles with a frequency of 10 OPH was undertaken for 12 h.

Figures 4a and **4b** show the air temperature evolution during 6 door openings (3 openings for the right and left doors sequentially) with 15 s and 30 s opening durations, respectively. The effect of door openings can be observed during the second part of compressor "off" periods (240<t<420s and 780<t<960s in **Fig. 4**) since the air temperature is rather constant when the door is closed. For both opening durations, the air temperature increased (from its initial value T_{int}) as soon as the door was opened, and then dropped gradually to the normal state (variation with the on/off compressor operation) when the door was closed. The magnitude of temperature increase ($\Delta T_{max} = T_{peak} - T_{int}$) and time to reach the peak (T_{peak}) vary with the position. On the top shelf (A1, **Figures 4a** and **4b**), after the door was opened, the air temperature rapidly reached a peak within a few seconds ($\Delta T_{max} \cong 6.5°C$), then decreased to the normal state even though the door remained open. The air curtain is destabilized when the door is being opened, then it tends to stabilize immediately while the door is completely open (13 s in **Fig. 4a** and 28 s in **Fig. 4b**). The characteristic time (δ_c) required for air curtain stabilization for this display cabinet was approximately 2.2 s where $\delta_c = \frac{H}{\overline{u}_{jet}}$, H is the opening height of the cabinet (1.3 m) and $\overline{u}_{jet}$is the mean air velocity at the DAG (0.6 m·s^{-1}, Chaomuang et al. 2019).

Several temperature changes during the door openings were observed for the air temperature on the middle shelf (A3, **Figures 4a** and **4b**). After the left door was opened, the air temperature increased rapidly to the peak ($\Delta T_{max} \cong$ 6.3℃) over a relatively longer time interval compared with the air at the level of the upper shelf (A1, closer to the DAG), then dropped towards the normal state. Nonetheless, after the door was closed, the air temperature increased again, and it took at least 10 s to reach equilibrium. The second temperature increase can be explained by the door closure movement which forces warm external air into the cabinet. Smooth door closings could reduce this temperature increase. A different air temperature evolution at this position (A3) was observed when the right door was opened. Based on the opening procedure of 15 s and 30 s, the air temperature tended to increase gradually and seemed not to decrease until the door was closed.

A gradual increase in the air temperature on the bottom shelf (A5, **Figures 4a** and **4b**) was always observed ($\Delta T_{max} \cong$ 3.2°C), regardless of the door (left or right) which was opened. The air temperature decreased and reached the normal state only after the door had been closed. The longer the duration of the door opening (30 s, **Fig. 4b**), the higher the air temperature at this position.

Time-averaged air and product (core and surface) temperatures were calculated over 5 h in the quasi-steady state (excluding the defrost period) of each operating period (closed door-lights off, open door with a frequency of 10 OPH-lights on, and closed door-lights on) and reported in **Fig. 5**. It is noteworthy that the time-averaged temperatures during the door openings were calculated over 5 hours between two defrost cycles to respect the quasi-steady state condition (temperature during defrost cycles was excluded from the calculation).

On the whole, the average air and product temperatures at most positions were not significantly different between lights on and off conditions when the doors were closed (**Figures 5a** and **5c**). The illumination effect is only significant at the front of the top shelf due to the proximity to the cabinet lighting.

During the door-opening period (**Fig. 5b**), the average air temperature was slightly lower in the rear duct (about 0.1°C) and higher at the front (up to 0.9°C). External warm air infiltration into the cabinet during the door openings explained an increase in the air temperature at the front. According to the air temperature increase, the compressor working cycles became more frequent, thereby lowering the air temperature in the rear duct. Compared with the closed-door periods, the number of compressor working cycles during the door openings was approximately 18% greater. Each door opening caused an increase in product temperatures at the front and a decrease in those at the back (**Fig. 5b**). This resulted in a greater temperature difference between the front and the back products on the shelf. Overall, the product temperature distribution in the closed display cabinet was consistent for every period. The highest temperature position was at the front of the top shelf and the lowest temperature position was at the back of the bottom shelf. The top shelf was also the position at which the front and the back products had the maximum temperature difference.

Because there were additional heat losses through the lateral glass walls, the product core temperature at the sides was higher than that at the center (**Table 2**). It should be emphasized that the measurement of product core temperatures at the side was taken at a distance of 100 mm from the lateral wall since 1-kg test packages were used in the study. There will be a tendency to observe higher temperatures at the sides in the EN23953 test because 500-g test packages (width × length × height: 100 × 50 × 100 mm) are usually used and the measurement is performed at a distance of 50 mm from the wall.

3.2. Effect of door-opening frequency

Different door-opening frequencies were applied to the closed display cabinet to investigate their effects on the time-averaged temperatures at different locations in the cabinet. The air and product temperatures at any given position inside the display cabinet are influenced by the operating conditions. Theoretically, these temperatures should be high when the ambient temperature and the door opening frequency are high. However, in practice, under such conditions (high ambient temperature and high door opening frequency), the compressor operates at a greater frequency (shorter "off" cycle) to compensate for thermal loads in the cabinet to a greater extent. Thus, the time-averaged air temperature after the heat exchanger (where the thermostat sensor is located: $\overline{T}_{th}$) is lower, and this leads to lower air/product temperatures at the back and higher temperatures at the front. To overcome this complexity and to enable comparison of temperatures obtained from different operating conditions, the dimensionless temperature (θ_i) was defined (**Eq. (1)**) by taking the time-averaged temperatures of external ambient air ($\overline{T}_e$) and of supply air just after the heat exchanger ($\overline{T}_{th}$) as references. In this manner, the dimensionless temperature at a given position was not influenced by the ambient temperature and the supply air temperature which decreased when the door-opening frequency increased.

$$\theta_i = \frac{\overline{T}_i - \overline{T}_{th}}{\overline{T}_e - \overline{T}_{th}} \quad (1)$$

Fig. 6 shows the dimensionless product core temperatures (θ_p) at the front and the back of the closed display cabinet for door-opening frequencies of 0, 10, 20, 40 and 60 OPH. The value ∞ represents the permanently open condition in which the doors were completely removed. As shown in **Fig. 6a**, it was observed that θ_p at the front of all shelves increased with an increase in the door-opening frequency. When the door-opening frequency was less than 40 OPH, θ_p was the highest at the level of the top shelf (F1) and it was the lowest at the bottom (F5). Beyond this frequency, the door opening resulted in a relatively smaller increase in θ_p at the top shelf (F1), as compared to its effect on the product at the level of the lower shelves (F2 and F3) for which θ_p became the highest. This can be explained by the fact that the products at these positions (F2 and F3) are the most influenced by the introduction of external warm air when the door is open as observed in the open display cabinet (Laguerre et al., 2012). Warm air infiltration during door openings is enhanced by the vortices which form in the mixing layer of the air curtain. At the level of the lower shelves (F4 and F5), θ_p remained relatively lower (**Fig. 6a**) because there was more cold air flowing from the back through the PBP into these shelves.

The small effect of the door-opening frequency on θ_p was observed at the back **(Fig. 6b)**. When the door-opening frequency varied from 0 to 40 OPH, θ_p at the back of all shelves increased slightly and was steady when the door-opening frequency increased from 40 to 60 OPH. However, when the doors were permanently open, θ_p at the back of Shelves 1-3 (B1, B2 and B3) tended to increase, while it seemed to change only slightly for the product at the level of the lower shelves (B4 and B5). This is because the back product mainly exchanges heat with the air flowing through the PBP, of which the temperature is practically uninfluenced by the external ambient temperature.

Despite a very high door-opening frequency (60 OPH), the closed refrigerated display cabinet achieves somewhat better temperature homogeneity compared with the cabinet without doors (**Table 3**): the average product core temperatures both at the front and the back of the display cabinet where a door-opening frequency of 60 OPH was applied remained lower than those under permanently open conditions. This difference was more pronounced when the surface temperature was considered, particularly at the front of Shelf 3 (5.1°C for 60 OPH and 8.7°C for permanently open). Regarding the field investigation by Fricke and Becker (2010), it was found that the daily mean door-opening frequency was only 6.3 OPH with a mean opening duration of 12 s (the most frequent duration was 5 s). Based on these findings, food preserved in closed refrigerated display cabinets would be maintained under better temperature conditions, thereby prolonging the shelf life and reducing food loss.

In addition to the temperature performance, the closed refrigerated display cabinet also shows energy saving potential. Based on the total period of a complete compressor working cycle, the time fraction during the compressor "on" period increased from 23% for the closed-door condition to 25%, 32%, 37% and 44% for the door-opening frequencies of 10, 20, 40 and 60 OPH, respectively. The time fraction was 63% in the case of the cabinet without doors.

3.3. Effect of ambient temperature

Air and product temperature measurements in the closed refrigerated display cabinet were conducted for four different ambient temperatures (see **Table 1**) while a door-opening frequency of 10 OPH and an occupied volume of 60% were applied in all experiments. The same dimensionless temperature (θ_p) defined in the previous section was used, and the results are reported in **Fig. 7**. It was observed that θ_p was almost independent of $\overline{T}_e - \overline{T}_{th}$ for the products at the front of the cabinet (**Fig. 7a**), while it decreased a little for most products at the back (Shelf 2-5) when $\overline{T}_e - \overline{T}_{th}$ increased. This result is in agreement with that observed in our previous study (Chaomuang et al., 2019). Despite door openings, forced convection and conduction, which are linear phenomena, heat transfer modes remain predominant in the closed display cabinet. Free convection and radiation from the external walls, which are non-linear phenomena, can explain the slight influence of $\overline{T}_e - \overline{T}_{th}$ on the dimension temperature. As reported in **Table 4**, when $\overline{T}_e - \overline{T}_{th}$ rose from 15.0°C to 30.4°C, on the average $\overline{T}_p - \overline{T}_{th}$ at the front and the back positions increased from 1.5°C to 3.1°C and from 0.5°C to 0.9°C, respectively. Under a door opening frequency of 10 OPH, the highest temperature position was at the front of the top shelf where $\overline{T}_{pf} - \overline{T}_{th}$ was approximately 14% of $\overline{T}_e - \overline{T}_{th}$. The lowest temperature occurred across the back of Shelf 3-5 where $\overline{T}_{pb} - \overline{T}_{th}$ was approximately 3% of $\overline{T}_e - \overline{T}_{th}$. These results highlight that the product temperature in a closed display cabinet is directly influenced by the external ambient temperature, and the front area is the position at which the products are the most exposed to a high temperature.

3.4. Effect of occupied volume

Two percentages of occupied volume in the closed display cabinet were studied: 30% and 60%. A door-opening frequency of 10 OPH and an ambient temperature of 19.4°C were applied to both experiments. The same dimensionless temperature (θ_p) defined in Section 3.2 was also used for analysis so that the variation in the air temperature after the heat exchanger ($\overline{T}_{th}$) due to different thermal loads was eliminated. As shown in **Fig. 8**, **a** higher percentage of occupied volume leads to a decrease in product temperature at all positions. When the cabinet volume was occupied to a greater extent, the space above the product top surface became smaller, resulting in higher air velocity flowing from the back. Cold exchange between the air and the products was therefore enhanced. By knowing the air mass flow rate ($\dot{m}_{a,i}$, Chaomuang et al., 2019) and the area above the product for each shelf (A_i), the mean air velocity flowing from the back ($\overline{u}_{a,i}$) was estimated by

$$\overline{u}_{a,i} = \frac{\dot{m}_{a,i}}{\rho_a A_i} \quad (2)$$

where i is the number of the shelf ranging from 1 (top) to 5 (bottom) and ρ_a is the air density (1.28 kg·m^{-3} at 0°C). As shown in **Fig. 9**, the air velocity above the products on Shelves 1-4 in the display cabinet with a 60% occupied volume could be about 5 times higher than that with a 30% occupied volume. It was about 1.7-fold in the case of the bottom shelf. It should be borne in mind that the air velocity presented in **Fig. 9** was an average value supposing plug flow which is seldom observed in a real cabinet (Chaomuang et al. 2019).

4. Conclusions

Closed refrigerated display cabinets are increasingly used in retail stores because of their numerous advantages, particularly a considerable reduction in warm and humid air infiltration, compared with open cabinets. In this study, air and product temperature measurements in the closed display cabinet were carried out under various operating conditions to evaluate the thermal performance of the cabinet including door-opening frequency, ambient air temperature and product-occupied volume. The product position in the cabinet is a determining factor of its temperature. The product at the front always had a higher temperature than that at the back, whatever the operating conditions, and that on the top shelf most often had the highest temperature. Higher door-opening frequency and/or higher ambient temperature result in a substantial increase in the product temperature at the front. The product temperature on the front middle shelf was the most affected when the door-opening frequency exceeded 60 OPH. On the other hand, each door opening causes a slight decrease in product temperature at the back because more refrigeration capacity was required to withstand higher thermal loads. Product-occupied volume also causes product temperature variations. A lower product temperature was observed at all positions when the cabinet volume was occupied to a greater extent. Overall, the closed refrigerated display cabinet fitted with doors provides better thermal performance, i.e. lower product temperature and more temperature homogeneity, as compared to the cabinet without doors despite a very high door opening frequency. Based on the time fraction of periods during which the compressor was operating, the closed refrigerated display cabinet also shows energy saving potential.

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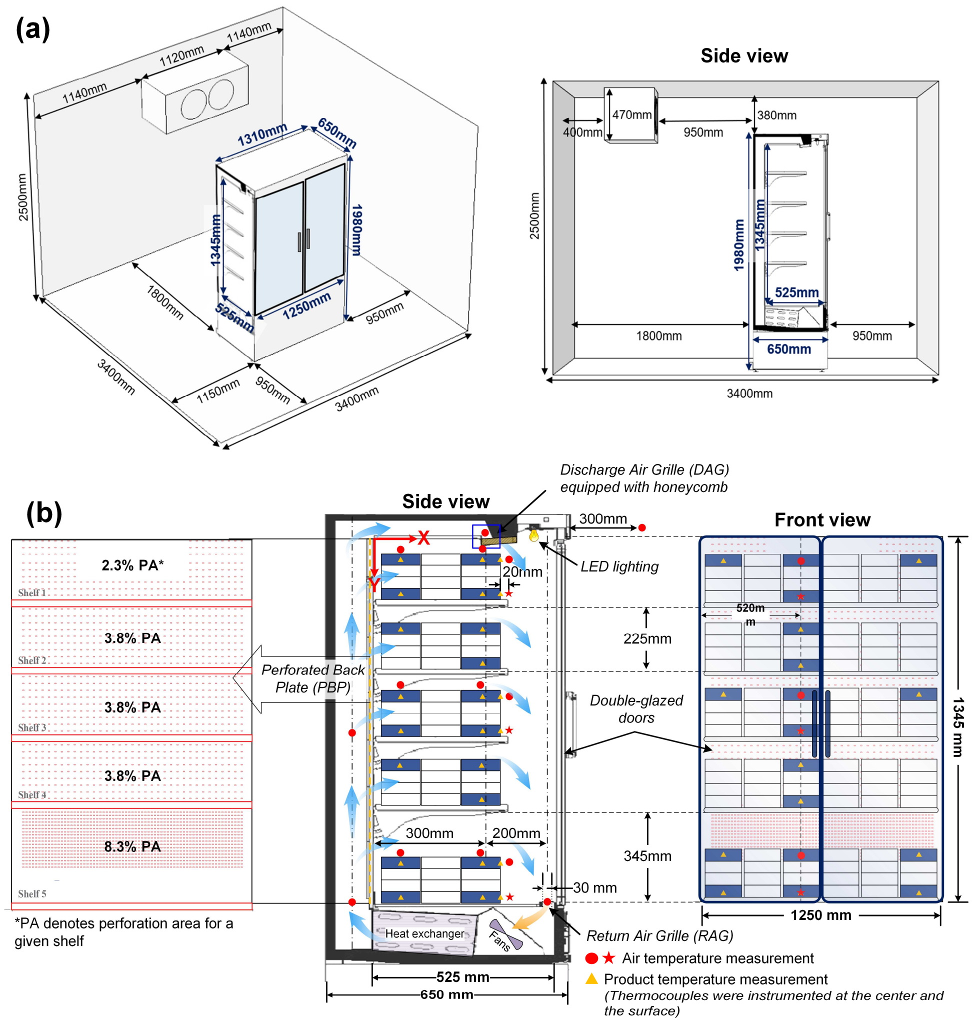

Fig. 1 (a) Closed refrigerated display cabinet in the climate-controlled room (b) diagram showing the experimental setup for air and product temperature measurements inside the display cabinet

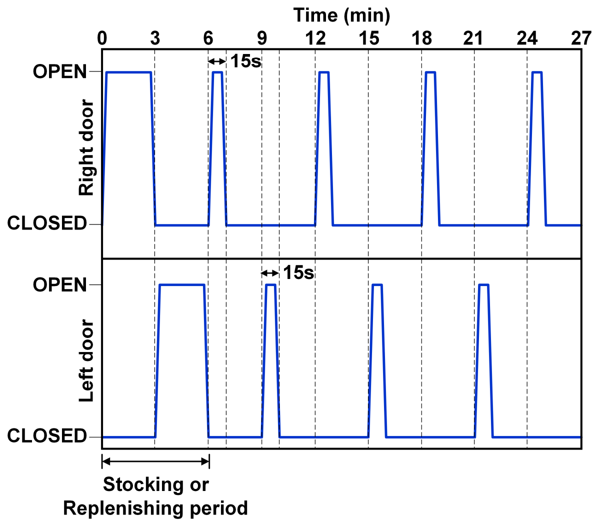

Fig. 2 Algorithm of automatic door openings

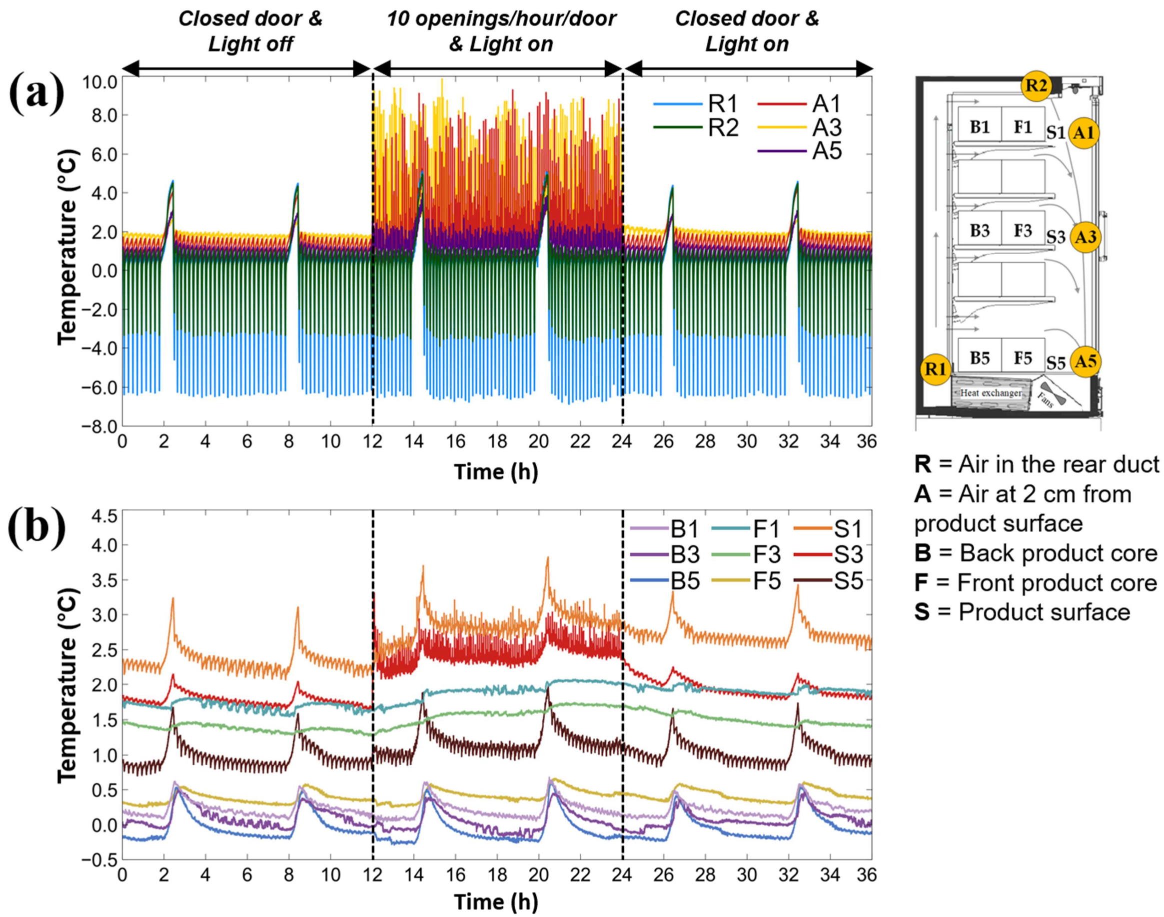

Fig. 3 Evolution of (a) air, and (b) product (core and surface) temperatures on the center plane of a closed refrigerated display cabinet over 36-hour operation for an ambient temperature of 19.4°C.

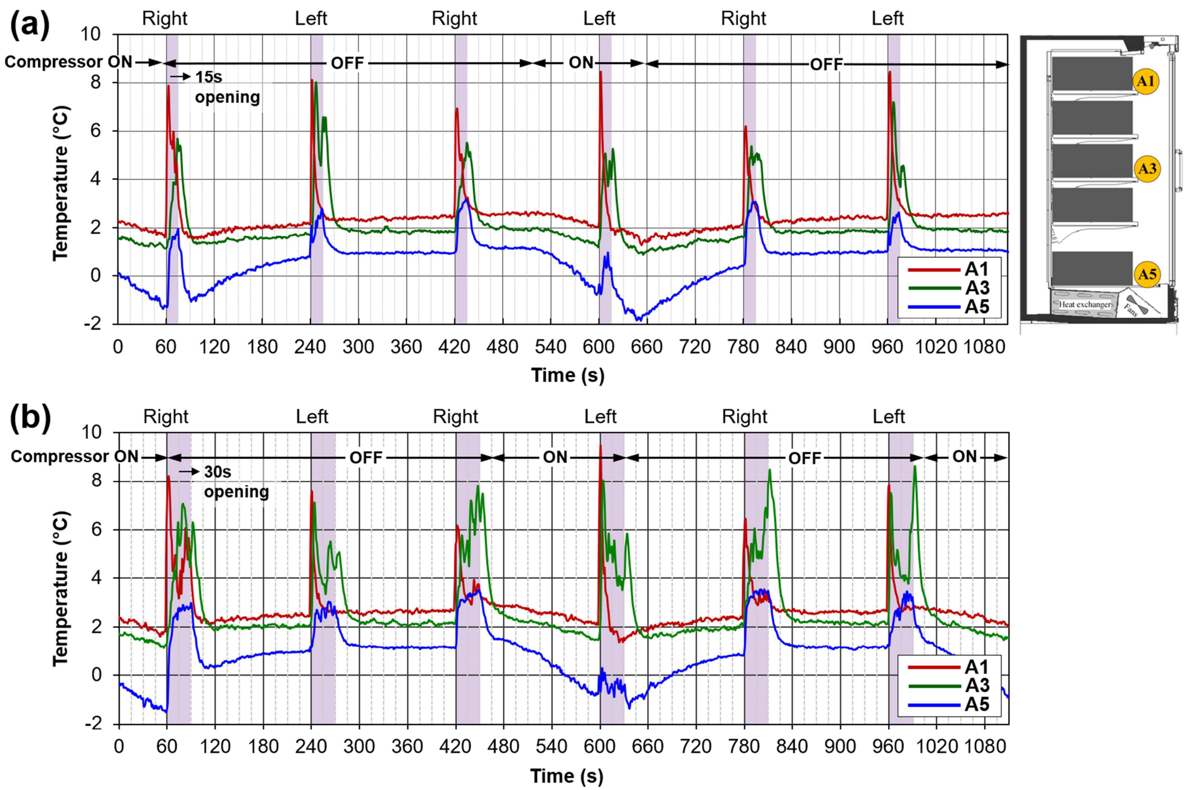

Fig. 4 Air temperature evolution at 2 cm from the front product surface on the center plane of the closed display cabinet during 6 door openings (10 OPH frequency) with (a) 15 s and (b) 30 s opening durations (acquisition interval of 1 s)

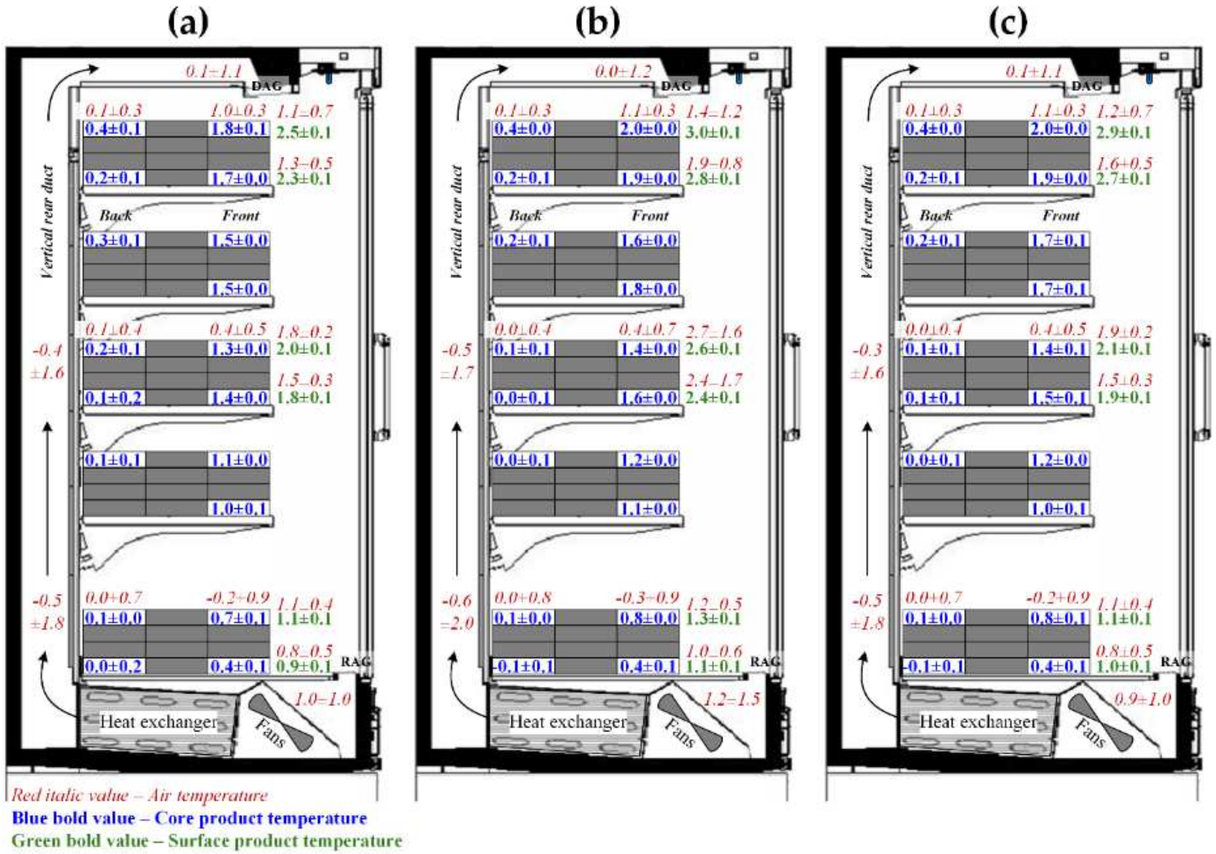

Fig. 5 Time-averaged (± standard deviation in °C) air and product temperatures in the closed refrigerated display cabinet for an ambient temperature of 19.4°C during (a) closed door – light off, (b) open door with a frequency of 10 OPH – light on, and (c) closed door – light on conditions. Values are the average over 5 hours of quasi-steady state

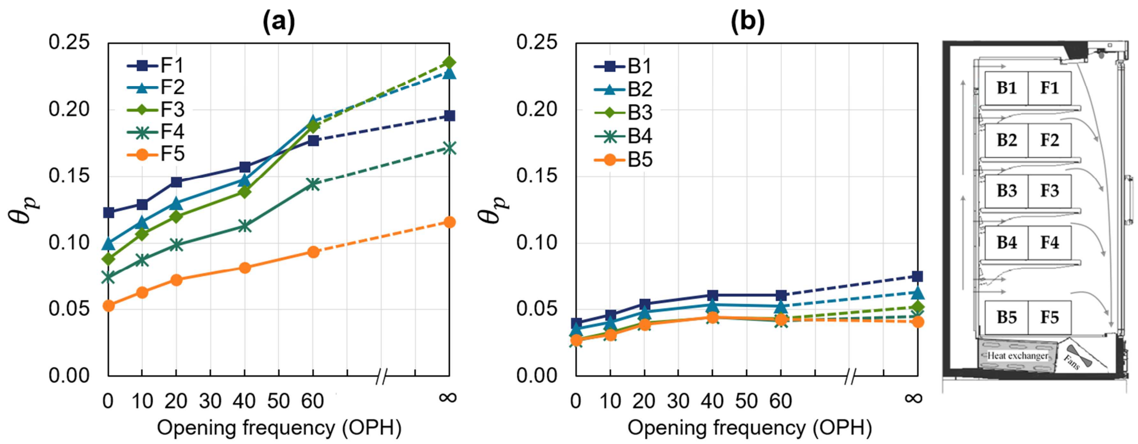

Fig. 6 Effect of door-opening frequency on the dimensionless product core temperature (a) at the front, and (b) at the back of the five shelves

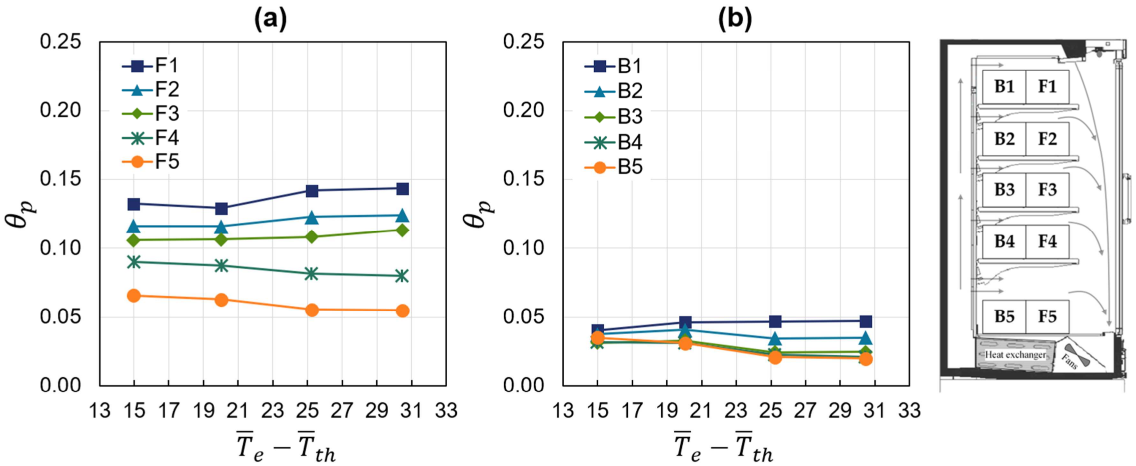

Fig. 7 Variation of dimensionless product core temperature (θ_p) with the difference between the average of ambient air temperature $\overline{T}_e$ and of air temperature after the heat exchanger $\overline{T}_{th}$: (a) front products (b) back products (opening frequency of 10 OPH and occupied volume of 60%)

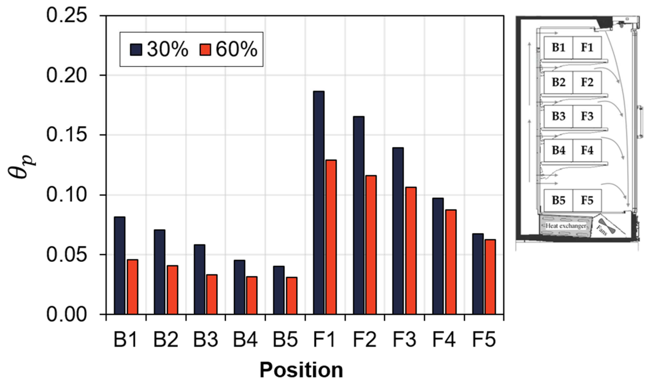

Fig. 8 Effect of occupied volume on the product temperature in the closed display cabinet (opening frequency of 10 OPH and ambient temperature of 19.4°C)

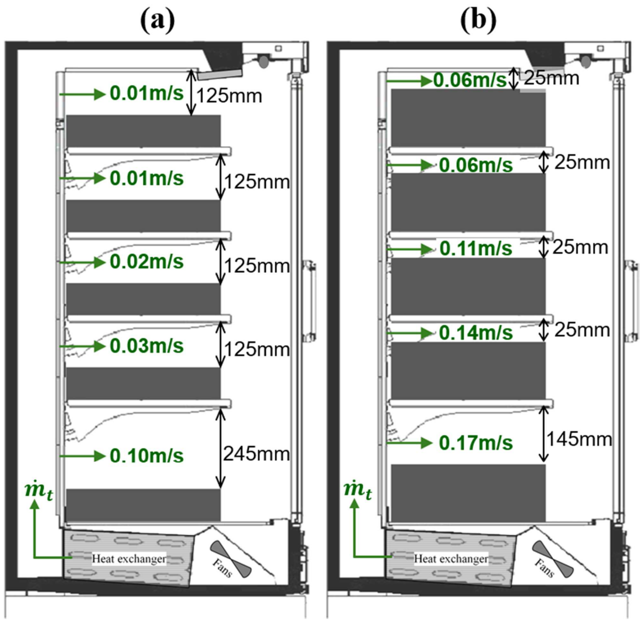

Fig. 9 Variation in air velocity above the products on different shelves in the closed display cabinet (1.25 m in length) for two occupied volumes: (a) 30%, (b) 60%

Table 1 Operating conditions in a closed refrigerated display cabinet

Experiment	Door-opening frequency [OPH[d]]	Ambient temperature (Standard deviation) [°C]	Percentage of occupied volume [%]
1[a]	10	19.4 (0.5)	60
2[b]	0		
3	20		
4	40		
5	60		
6[c]	∞		
7	10	14.6 (0.5)	60
8		24.3 (0.3)	
9		29.2 (0.3)	
10	10	19.4 (0.5)	30

a: Baseline. b: Permanently closed. c: Permanently open. d: Number of openings per hour per door

Table 2 Effect of lateral glass wall on the product core temperature in the closed display cabinet

Plane	**Time-averaged product core temperature[†] [°C]**		
	F1	**F3**	**F5**
Left	3.0	2.3	1.5
Center	2.0	1.4	0.8
Right	3.6	3.5	3.3

[†]*Average (top package on the stack) over 5 h of quasi-steady state excluding the defrost period.*

Table 3 Time-averaged product temperature[†] (in °C) at the back and front of the display cabinet with a door-opening frequency of 60 OPH and permanently open (without doors) condition for an ambient temperature of 19.4°C and occupied volume of 60%.

Shelf no.	**60 OPH**			**Permanently open**		
	Back	**Front**		**Back**	**Front**	
	Core	**Core**	**Surface**	**Core**	**Core**	**Surface**
1 (top)	0.0	2.4	3.6	0.2	2.7	4.7
2	-0.2	2.7	-	0.0	3.4	-
3	-0.4	2.6	5.1	-0.3	3.6	8.7
4	-0.4	1.7	-	-0.4	2.2	-
5 (bottom)	-0.4	0.7	1.6	-0.5	1.1	2.0

[†]*Average (top and bottom packages on the stack) over 5 h of quasi-steady state excluding the defrost period; the standard deviation was 0.1°C for all positions under both conditions.*

Table 4 Effect of external ambient temperature ($\overline{T}_e$) on the product core temperature ($\overline{T}_p$) in the closed display cabinet.

Temperature difference	$\overline{T}_e - \overline{T}_{th}$	[°C]	15.0	20.0	25.2	30.4	Average
Front product (pf)							
Shelf 1			2.0	2.6	3.6	4.4	3.1
Shelf 2			1.7	2.3	3.1	3.8	2.7
Shelf 3	$\overline{T}_{pf} - \overline{T}_{th}$	[°C]	1.6	2.1	2.7	3.4	2.5
Shelf 4			1.3	1.7	2.1	2.4	1.9
Shelf 5			1.0	1.3	1.4	1.7	1.3
	Average		**1.5**	**2.0**	**2.6**	**3.1**	**2.3**
Back product (pb)							
Shelf 1			0.6	0.9	1.2	1.4	1.0
Shelf 2			0.6	0.8	0.9	1.1	0.8
Shelf 3	$\overline{T}_{pb} - \overline{T}_{th}$	[°C]	0.5	0.7	0.6	0.8	0.6
Shelf 4			0.5	0.6	0.6	0.6	0.6
Shelf 5			0.5	0.6	0.5	0.6	0.6
	Average		**0.5**	**0.7**	**0.8**	**0.9**	**0.7**

The cabinet doors were periodically opened with a frequency of 10 OPH and with 60% occupied volume.