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Experimental study of the performance of open–type refrigerated display cabinet

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Abstract

This paper presents experimental investigations of the efficiency of an open-type refrigerated display cabinet used to store food at temperatures between –1 and +7 °C. The purpose of the study was to increase the efficiency of the open-type cabinet by improving its design. The cabinet has five shelves for food products with lengths of 350-600 mm. The spacing between the base and the first shelf is 280 mm, and between the other shelves it is 250 mm. The air enters the cabinet from the return air grille (RAG) at the bottom of the front panel, fans blow air through the evaporator, and the cooled air travels through a tunnel to the top of the refrigerator. The perforated distributor at the top distributes the cooled air, and part of the air is blown through the perforated back panel and the other part passes through the air-off honeycomb (dimensions (W×H) are 120×20 mm) at the front top of the cabinet, thus forming an air curtain between the inside of the refrigerator and the ambient warm air to protect the chilled food products. The cooled air entering through the perforated back panel into the display area helps maintain the required food temperature. In this study, two versions of the refrigerated cabinet were analyzed. The first version is the standard refrigeration cabinet and the second version is the same cabinet but with a change in the angle of inclination of the honeycomb and a reduction in the depth of the shelves. Air and test product temperatures were measured with thermocouples, and electrical energy consumption was measured with the Carel MT300W1100 energy meter. The experimental results show that the infiltration ratio decreases from 38.7 to 27.7%, and the 24-hour electrical consumption decreases from 24.91 to 19.22 kWh in the case of the modified cabinet. The average air temperature in the return air grille (RAG) decreased from 7.5 to 6.52 °C with the same temperature settings. The average temperature of the M packages decreased by 0.2-2.2 °C depending on the position in the refrigerator.

Keywords: air curtain, air temperature, energy consumption, heat transfer, honeycomb, open-type refrigerated display cabinet.

1. INTRODUCTION

Open-type refrigerated display cabinets are often used in retail food stores to attract customers because they do not have a physical barrier between the customer and the products. Within supermarkets, the primary concern when choosing retail display cabinets has always been to maximize sales, often at the expense of energy consumption. Open-front refrigerated cabinets are known to be less energy effective than closed refrigerated cabinets. Many researchers have conducted numerical and experimental investigations to improve the efficiency of open-type refrigerators. Although many studies have been conducted on the performance of refrigerated cabinets (Amin, Dabiri, & Navaz 2009; Cao, Han, & Gu 2011; Fricke & Becker 2010; Hammond, Quarini, & Foster 2011; Tsamos et al. 2019; Yuan et al. 2021), most of them only emphasize a few aspects by performing experiments or computational fluid dynamics (CFD) software simulations. As a result, few studies have presented systemic strategies for performance optimization by investigating the relationship between multiple parameters. Amin et al. (2009)

developed a new technique that combines analytical and experimental methods to find the infiltration rate of outside air into open-type refrigerated display cabinets. The method is based on direct measurement and is stated to be more reliable and accurate than conventional techniques. A tracer gas is released into the air inside the channel of a display cabinet and after mixing, the mixture is discharged into the display area and environment through the air curtain and the perforated back panel of the cabinet (Amin et al. 2009). This technique is based on the measurements of the concentrations of the tracer gas at three locations: the return duct, the discharge duct, and the environment. Cao et al. (2011) applied a two-fluid cooling loss (CLTF) model and a support vector machine (SVM) algorithm, which successfully gained a better prediction of cooling loss. In this simulation, the cooling loss was reduced by 19.6 %. After being validated using experimental data, the TEC/TDA of the cabinet was reduced by 17.1%. The SVM algorithm developed was trained to optimize the design parameters with minimum cooling loss. Tsamos et al. (2019) used air guiding strips and cold shelves to achieve low ambient air infiltration and the correct temperature of test products with less energy consumption. Hammond et al. (2011) introduced a design guide which would enable cabinet designers with limited fluid flow expertise to rapidly identify the most efficient air curtain design to seal any given cavity from fundamental measurements without any need for intensive computation.

The influence of the surrounding air is an important factor that must be taken into account to achieve a well-designed air curtain. Fricke and Becker (2010) compared a typical open-type refrigerated display cabinet line-up to a typical glass-doored refrigerated display cabinet line-up with the aim of quantifying the difference in overall energy consumption for each type. The open-type display cabinet line-up was obtained to consume approximately 1.3 times more energy (per unit length of the cabinet line-up) than the doored display cabinet line-up. A Coriolis mass flow meter was used to measure the refrigerant mass flow rate, electrical energy consumption was measured using kilowatt meters, the temperature was measured by thermocouples, and the relative humidity was measured with a humidity sensor. Yuan et al. (2021) compared different placements of multi-deck display cabinets in a supermarket to understand the influence of the environment. The results show that the face-to-back placement method exhibits better food refrigeration performance, and the food temperature is 0.3-0.5 °C lower than that of the face-to-face placement method.

In this paper, an experimental study of energy efficiency and temperatures inside an open-type semi-vertical refrigerated cabinet is reported. This study continues the previous research (Vengalis & Mokšin 2022) that developed and validated the Computational Fluid Dynamics (CFD) models of unmodified and modified refrigerated cabinets. This experimental study aims to compare the performance of open-type display cabinets with different honeycomb angles in terms of return air temperature and energy consumption.

2. MATERIALS AND METHODS

The scheme of an open-type semi-vertical refrigerated display cabinet is presented in Figure 1. This cabinet is used to store food at temperatures between –1 and +7 °C. The cabinet has five shelves for food products, including 4 wall shelves and the bottom panel. The dimensions of the cabinet are presented in Figure 1. The spaces between the shelves are as follows: between the base and the first shelf, 280 mm, and between the wall shelves 250 mm. Other properties of the cabinet are given in Figure 1 and Table 1.

The required temperature inside the refrigerated display cabinet is maintained by two cooled air streams. The first air stream descends from a discharge air grille (DAG) or honeycomb (Figure 1, top) placed at the top of the display cabinet and creates an air curtain. The second cold air stream penetrates from the back through the perforated back panel (PBP, Figure 1, top) and moves toward the front where these two air streams are mixed. The air is directed to a return air grille (RAG) by 4 fans (Figure 1, top), then passes through the cooling coils to decrease the temperature and returns to the display cabinet. The arrangement of the test packages and test packages with thermocouples attached is shown in Figure 1.

The experimental study consists of three phases. First, it took 24 hours to chill the refrigerated cabinet after it was on. Second, after 24 hours, the chilled products (+1 °C) were loaded into the refrigerated cabinet that was left to work for 24 hours again. After 48 hours, the measurements were started. The measurements were split into data logging and the calculation of the time-averaged values collected during the measurements. The data logger collected data from temperature sensors, the compressor relay, and the energy consumption meter within 24 hours. The time-averaged air temperature values were calculated over a quasi-steady state during which the defrosting period was excluded. In the experiment, the refrigerated cabinet works all the time in day mode without night blinds. The defrosting process runs automatically after 5.5 hours of work, and the defrosting process takes about 30 minutes. During the defrosting process, the 4 fans work, and the evaporator ice is melted with electrical heating wires. The defrosting process is seen

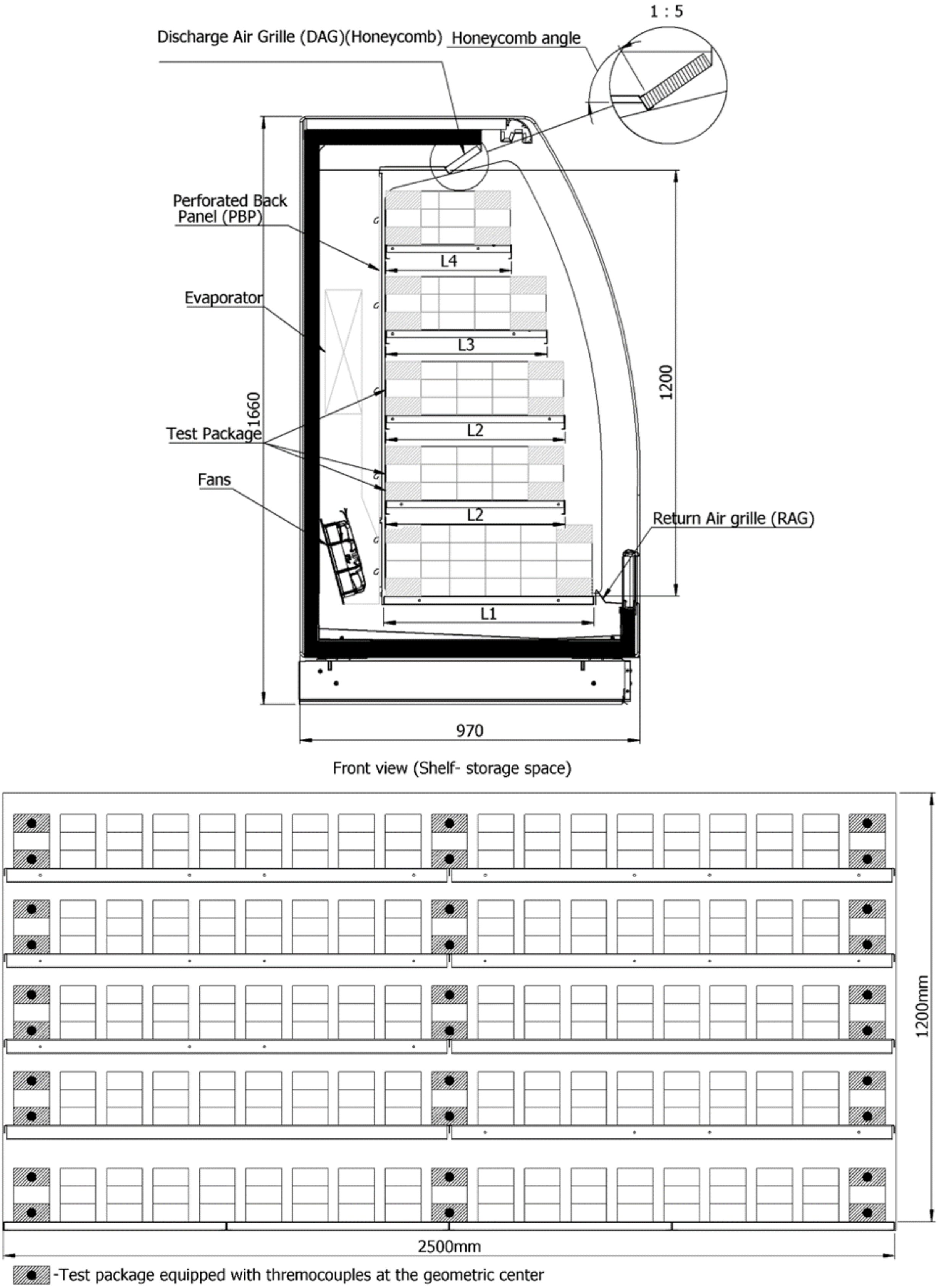

Figure 1. Scheme of the open-type refrigerated display cabinet: a) side view; b) front view.

Table 1. Geometrical and other properties of open-type display cabinet Figure (1) .

Parameter	Unmodified version	Modified version
Volume, m^3	1.8	1.8
Exposition space, m^2	6	5.375
Honeycomb angle, °	40	55
Shelf depth L1, mm	600	600
Shelf depth L2, mm	500	450
Shelf depth L3, mm	500	450
Shelf depth L4, mm	450	400
Shelf depth L5, mm	350	250
Dimensions of test product package, mm	100´100´50	100´100´50
Dimensions of DAG, mm	2500´120´20	2500´120´20
Dimensions of RAG, mm	2500´70	2500´70
Number of propeller fans	4	4
Propeller fan rpm and flowrate, m^3/h (back flow pressure 12Pa)	1300; 400	1300; 400
Connection type	Hydroloop	Hydroloop

in the temperature versus time graphs. In the electrical consumption graphs, the defrosting process cannot be distinguished because the energy power of the heating wires is the same as the electrical power needed for the compressor to cool the cabinet. According to the BS EN ISO 23953-2 standard, a refrigerated display cabinet was tested in a controlled environment of 25 °C temperature, 60% RH and airflow velocity of 0.1-0.2 m/s for climate class 3.

The air temperature measuring scheme is depicted in Figure 2. A hot wire anemometer (Testo 405-V1) attached to a height-adjustable stand and T-type thermocouples were used for the measurements. Each thermocouple was calibrated in the temperature range from –5 to 20 °C in the water bath (Lauda ECO Silver RE1050S filled with Kryo 30 heat transfer liquid) and the precision of ±0.2 °C was determined. The refrigeration cabinet was sliced into three planes: $Z = 0$ m (middle plane), $Z = -1$ m (left plane) and $Z = +1$ m (right plane). In each plane, thermocouples were installed in the honeycomb and return air grille (RAG) and the air temperature was measured with an anemometer according to the scheme shown in Figure 2. Two data loggers (Carel EasyPJEZC00000 with 3 probes) were used with thermocouples that recorded temperature values every 300 s. The average values were then calculated at each measurement point during the quasi-steady state.

Another part of the experiment was carried out with the open-type display cabinet loaded with test product packages (50% of the total storage volume). The M packages were made of oxyethylmethylcellulose (dimension in width×height×length: 100×50×100 mm according to ISO 15502, ISO 5155, ISO 7371, ISO 8187, ISO 8561 standards). The M package freezing point is –1 °C and the thermal conditions are similar to lean beef. The thermocouples were placed at the geometric centers of the test product packages (Figure 1, bottom). Carel Easy controllers with 3 probes were used in this study. The controllers were connected to the computer with Carel PlantVisor PRO monitoring software. The temperature averages were calculated over a 6-hour cycle.

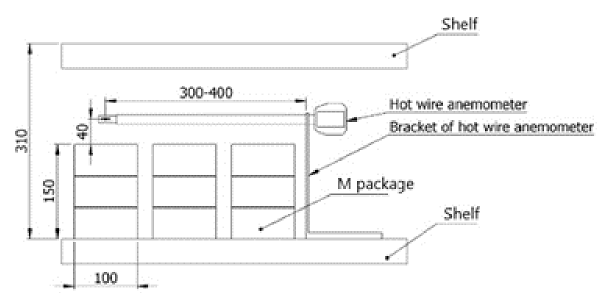

Figure 2. Scheme of temperature measurement with a hot wire anemometer.

The Carel MT300W1100 energy meter was used to measure electrical energy consumption. It was connected to the computer with Carel PlantVisor PRO software. After 72 hours, the refrigerated cabinet was on and the experimental measurement was started. During the energy consumption test, the cabinet was left alone in the test room to increase the accuracy of the measurements and eliminate the influence of the test room environment. The main components that use energy in the refrigerated cabinet are 4 V-type fans, a 3-phase compressor, an electronic expansion valve, evaporator defrosting wires, and a controller. It should be mentioned that the electrical energy consumption test was carried out without the canopy and shelf lights and the results do not describe all the electrical energy consumption of the refrigerated cabinet. This test was carried out to evaluate the impact of design modifications on electrical energy consumption and compressor working time.

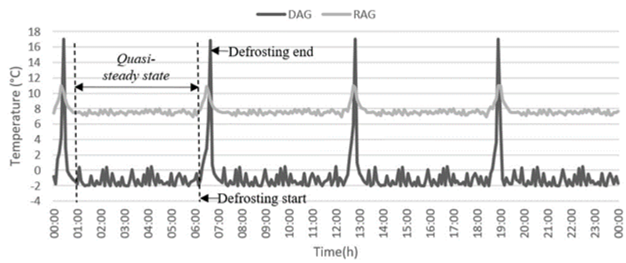

Figure 3. Air temperature measured in DAG and RAG as a function of time (unmodified cabinet, average of measurements in three planes).

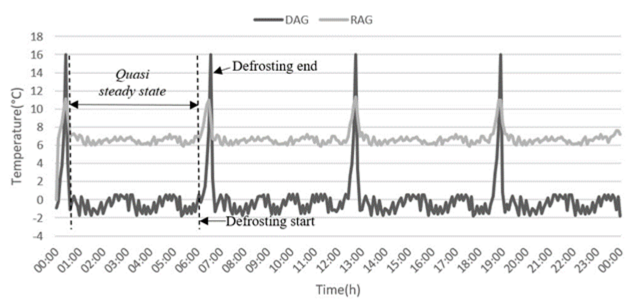

Figure 4. Air temperature measured in DAG and RAG as a function of time (modified cabinet, average of measurements in three planes).

3. RESULTS AND DISCUSSION

The air temperature versus time graph obtained for the unmodified cabinet is presented in Figure 3. It can be seen from Figure 3 that the average air temperature measured in the discharge air grille (DAG) in a quasi-steady state is –1.36 °C. In the return air grille (RAG), the average air temperature is +7.50 °C, respectively. The maximum temperature measured in DAG during the defrosting process was +17.00 °C, in the RAG it was +11.00 °C, respectively. In the quasi-steady state temperature in the DAG varied between –1.90 and 0.50 °C and in the RAG between +7.00 and +8.00 °C (Figure 3).

The temperature versus time graph obtained for the modified refrigerated cabinet is presented in Figure 4. The average air temperature measured in the discharge air grille (DAG) in the quasi-steady state is –0.58 °C and the temperature in the return air grille (RAG) is +6.52 °C. The maximum air temperature in the DAG recorded at the end of the defrosting process was +16 °C, it was +11.1 °C in the RAG. In a quasi-steady state, the DAG temperature varied from –1.7 to +0.5 °C and the RAG from +5.90 to +6.90 °C.

Both refrigerated cabinets use hot wires for faster defrosting; therefore, in the defrosting process, the DAG temperature is higher than the RAG temperature. It was established by comparing the temperatures inside the unmodified and modified refrigerated cabinets that the average temperature measured in the DAG was 0.78 °C higher for the modified version of the cabinet. The average air temperature in the RAG in the modified cabinet was 0.98 °C lower than in the unmodified cabinet. In all cases, the controller temperature set point was set at –2 °C. In the unmodified version, the return air was warmer and needed to cool with more cooling power. In this case, the operation of the evaporator is inert and accumulates cool in the metal parts, which means more cooling power to the air, and the air was cooler in the unmodified version.

The infiltration ratio shows how effectively the air curtain works in the open-type refrigerated cabinet. It was calculated according to the formula presented in (Vengalis & Mokšin 2022). For an unmodified cabinet, the infiltration ratio is 38.7% and in the case of the modified design, the infiltration ratio decreases to 27.7%. The difference is 11%; therefore, the modified refrigerator works more efficiently using less energy. The main consumer of electricity in this case is the compressor. Lower energy consumption also means a shorter operating time and a longer service life.

Figure 5 presents the temperatures of the M packages in the unmodified and modified refrigerated cabinets. It can be seen from Figure 5 that the temperatures of the M packages in the modified version are always lower than or at least equal to the temperatures of the M packages in the unmodified refrigerated cabinet. The position F10(M) fully represents the optimized air curtain; the average temperature at this position decreases by 2.1 °C compared to the unmodified version. In the other positions of the M packages, the average temperature decreases by 0.2-2.2 °C depending on the position of the M package.

Figure 6 presents the temperature distribution inside the unmodified and modified refrigerated cabinets in the steady state. The DAG temperature is –1.3±1 °C in the unmodified version and –0.6±1 °C in the modified version. The difference is 0.7 °C, which means that in the unmodified version the compressor works for a much longer period of time than in the modified version. In the return air grille (RAG) the air temperature is 7.5 °C (unmodified version) and 6.5 °C (modified version). This difference shows the efficient working of the air curtain and the temperature does not make much sense here because the DAG temperature was 0.7 °C higher in the modified version. The higher temperature of intake influences the temperatures of the M packages placed on the bottom shelf. The main reason is conduction between the warm intake air and the bottom shelf made of steel, and in this case, the shelf acts as a heat exchanger with negative consequences.

Electrical consumption was measured by an energy meter during a 24-hour work cycle. In the unmodified version, energy consumption was 24.91 kWh, and in the modified version it was decreased to 19.22 kWh per 24 hours. The difference can be seen in Figures 7 and 8. It

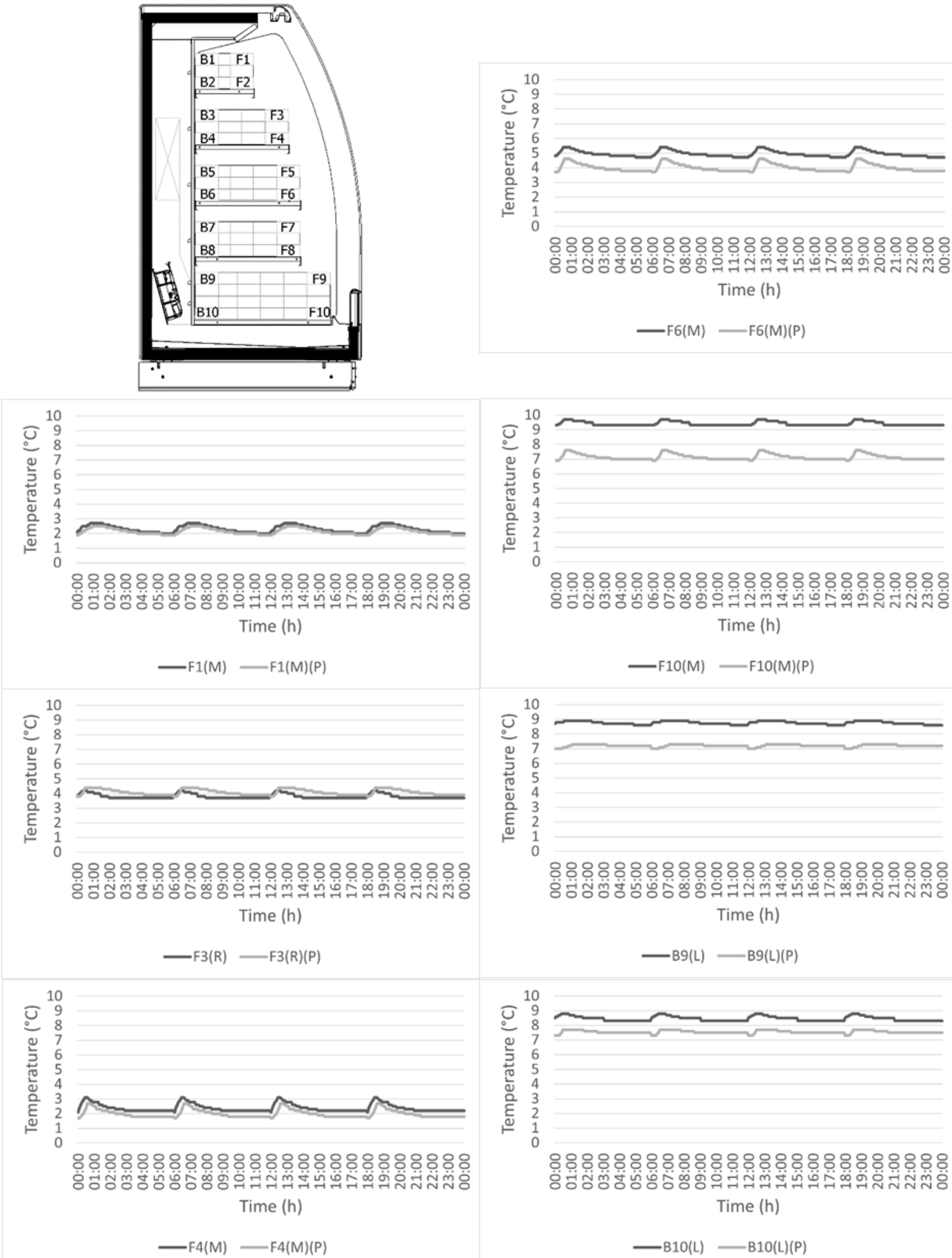

Figure 5. Distribution of the temperatures of the M packages in the left (L), middle (M), and right(R) planes of the unmodified and modified (P) refrigerated cabinets: F(i) – position of the M package seen in the side view in the upper left corner.

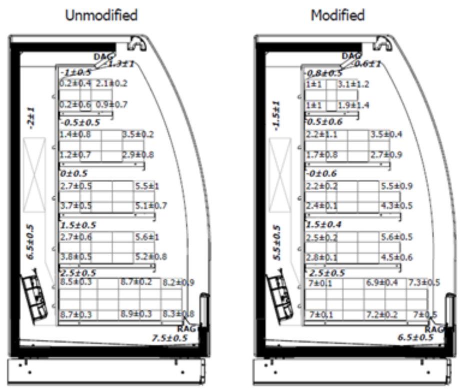

Figure 6. M package and air temperature distribution in quasi-stable state (middle plane).

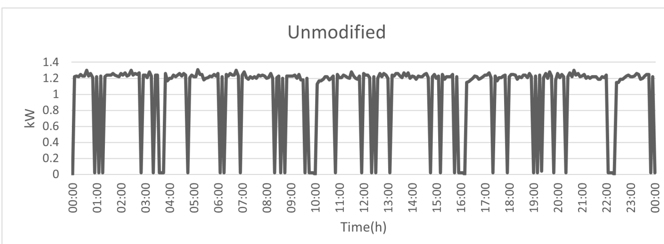

Figure 7. The 24-hour electrical energy consumption graph of the unmodified refrigerated cabinet.

can be seen from Figure 7 that in the case of the unmodified cabinet, the compressor works with short shutdowns. The stops were usually about 5 minutes. In Figure 8 obtained for the modified cabinet, the compressor does not work all the time; the shutdown time was usually about 20 minutes.

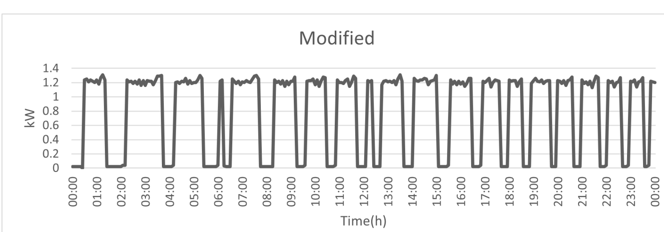

Figure 8. 24-hour electrical energy consumption graph of the modified refrigerated cabinet .

4. CONCLUSIONS

The results of the experimental study of energy efficiency and heat transfer characteristics in open-type refrigerated display cabinets show that the new shelf configuration and the changed honeycomb angle increase the efficiency of air curtain work. The results of experimental investigations show the following:

- The infiltration ratio decreases from 38.7 to 27.7 % in the modified version.
- The 24-hour electrical consumption decreases 1.3 times in the modified version.
- The average temperature in the RAG decreases from 7.50 to 6.52 °C in the modified version with the same temperature settings. The average temperature in the DAG shows that the modified version requires less cooling energy to maintain the temperature in the refrigerated cabinet.
- The average temperature of M packages decreases by 0.2-2.2 °C in the modified version depending on the position of the package inside the cabinet.

NOTE

This article was originally presented as an abstract at the EEM2023 conference. The findings and conclusions have been expanded upon in this full article, which provides a more comprehensive and in-depth analysis of the research.

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