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Energy Savings Potential in Using Cold-shelves Innovation for Multi-deck Open Front Refrigerated Cabinets

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Abstract

An approach considered in recent years to improve the efficiency of open-type refrigerated display cabinets is to install air guiding strips at the front face of the shelves with a single layer air curtain. This paper presents experimental results comparing a conventional open-type vertical refrigerated cabinet and a cold shelf innovation, which integrates both air-guiding strips and air supply at the front of individual shelves. In addition, a comprehensive and detailed Computational Fluid Dynamics model using ANSYS Fluent has been created to further investigate the influence of the cold shelve innovation on the performance of vertical multi-deck refrigerated display cabinets. The experimental results showed energy savings of 16.7 kWh/24 hrs for the guiding strips and cold shelf innovation compared to the conventional cabinet due to the more efficient air curtain and lower air temperature entering the evaporator coil.

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Keywords: Open front refrigerated cabinet; air guiding strips, cold shelf, CFD, ANSYS Fluent.

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1. Introduction

Refrigerated display cabinets contain about half of the food presented in the store. It is the last stage in the cold chain before the food is purchased by the customers [1]. Although being high consumers of energy, vertical display cabinets are still preferred for storing chilled products due to the limited space available in stores [2]. In retail stores, vertical refrigerated display cabinets are used to store and display food products in a way to increase the food shelf life as well as ensuring food safety [3].

In order to maintain proper food storage conditions, supermarkets and retail store refrigeration systems must be running continuously. This continuous operation results in a higher energy consumption which accounts for about 50% of the total electrical energy consumption in a typical retail store [3]. Clearly, looking to improve the efficiency of the cabinets would significantly reduce the energy consumption and operating cost of retail stores/supermarkets. One of the main techniques to decrease the energy consumption is to install glass doors. This would reduce the energy consumption by 50% [4]. The installation of glass doors would prevent any interaction between the cold air inside the cabinet and the warm ambient air within the supermarket premises. This air interaction, also known as air infiltration, accounts to about 67-77% of the heat gain in open refrigerated display cases [5]. Moreover, there are other contributions to the refrigeration load which include heat gain from lighting, conduction, fans etc.

Fricke et al. [3] compared the performance between a doored vertical display cabinet and an open display cabinet type. They found that the total electrical energy consumption for the doored refrigerated cabinet (1.71 kWh/day per foot length) was lower than the open display cabinet (2.21 kWh/day per foot).Although the doored display cabinet has a higher efficiency, the open display cabinet is always preferred by the customers. The absence of the glass doors, attracts customers and makes it easier for them to reach the food products in the display cabinets; hence, increasing the sales in the supermarket. In February 2013, a survey was carried out in England for one week in three leading supermarkets in Cheltenham and Gloucester area [6]. The survey found that 50.3% of the interviewed customers prefer to shop from an open refrigerated cabinet compared to just 12% who would go for glass doored cabinets. On the other hand, Fricke et al. [3] declared that the use of either cabinet types had no effect on sales in the USA.

Despite having higher energy consumption, open front refrigerated cabinets (OFRCs) are the most commonly used cabinet types. The optimisation of such cabinets is necessary to reduce their energy consumption. Several researchers have numerically and experimentally investigated the key factors to improve the performance of the OFRCs. Such factors include operating and ambient conditions, as well as design parameters [2]. A good design of air curtain is essential to reduce the energy consumption.

Many researchers carried out various investigations to improve the efficiency of open vertical display cabinets. Investigations included experimental and numerical studies by addressing the parameters that have major effects in keeping the product temperatures within the correct range [4, 5,7].

Jining et al. [5] carried out a numerical investigation of a conventional vertical mutli-deck open refrigerated cabinet where a flow guiding strips were installed at the front face of each shelf. The results showed an acceleration in the air curtain by making it stronger and stiffer. This has led to lower air infiltration of the warm air into the cabinet. Such effects reflected positively on the average food temperature inside the cabinet which was reduced by 4.9 °C compared to a cabinet without air flow guiding strips. Consequently, the energy consumption was reduced by 34%.

In this paper, an experimental study of the heat transfer and airflow behaviour within an open front vertical multi-deck refrigerated display cabinet is reported. The innovation is the integration of air guiding strips along with the use of cold shelves as a new technology for maintaining a product temperature below 5 °C and above -1 °C for M1 classification described by BS EN ISO 23953-2 [8]. The paper will also present a preliminary CFD model using ANSYS Fluent. The model will be used at a later stage as a tool for further optimisation of the display case.

2. Test facility and operational procedure

The prototype under investigation is a vertical multi-deck open-front refrigerated cabinet with a plug-in cooling unit. The cabinet is 2.5m in height and consists of 5 shelves and one bottom panel where food can be displayed and stored (see Fig. 1).

Fig. 1. Tested cabinet.

Fig. 2 is a side-view schematic diagram of the tested cabinet, which shows the air flow circulation within the cabinet. Air is drawn by a propeller fan and enters the bottom tunnel through the grill (Air-ON). Below the bottom panel, the air circulates over the evaporator coils losing thermal energy to the refrigerant, hence decreasing its temperature. The cold air is then pushed by the fan to a back tunnel which have three ways. Part of the cold air travels through the vertical back tunnel straight to the exit (air-OFF). The second part of the air enters each shelf in a U-shape while exiting through holes located at the bottom of it, which comes the cold shelf innovation. In this way, the cold air circulating inside the shelves will keep the shelves at low temperature as well as adding more thickness to the air curtain. The last part of the air will travel all the way up and exiting a honeycomb type structure located at the top of the cabinet, known as air-OFF. Both air-ON and air-OFF locations are shown in Fig. 1. The remaining components of the cooling unit are located underneath the cabinet.

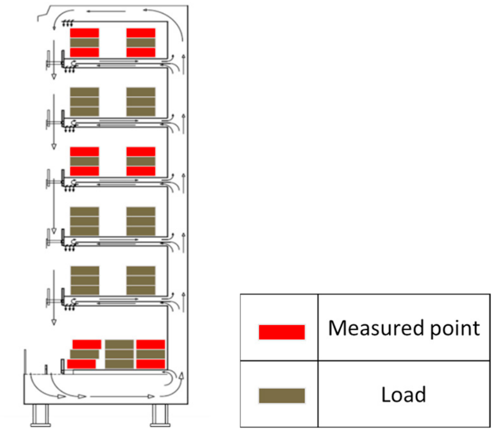

Fig. 2. Schematic of the air flow circulation inside the tested cabinet (side-view).

The cabinet was loaded with M-packages (Fig. 1). M-packages at selected positions had a calibrated K-type thermocouple inserted into their geometric centre. A total of 36 thermocouples were installed at various locations within the cabinet. The position of the product measurement points in the cabinet can be seen in Fig. 2 and Fig. 3. For the air-ON / air-OFF, 9 thermocouples in total were used as shown in Fig. 1.

Fig. 3. Tested cabinet (Front and top view), including locations of thermocouples in red.

The K-type thermocouples had an uncertainty narrower than ± 0.5°C, RH sensor (uncertainty ± 1.6%) and air velocity meter with uncertainty ± 3%; data logging system (National Instruments); recording/display system (computer set and monitor).

Fig. 4. Energy consumption metering box.

Fig. shows the metering box that was created to monitor the energy consumption of the cabinet. The cabinet was connected to the box and data were recorded over a period of 48 hours.

2.1. Test conditions

The cabinet was positioned in the test room according to BS EN ISO 23953-2015 (sub-clause 5.3.2.1) [8]. Cross flow direction in the test room was from right to left (referred to the front view of the cabinet). The tests were carried out in a test room conforming to BS EN ISO 23953-2015 standard [8]. The test room walls and ceiling are thermally insulated and are equipped with inner metal skin. The lighting in the test room is provided by fluorescent lights with lighting level in the range between 500 and 650 lux which complies with the standard of 600±100 lux at a height of 1 metre above floor level.

Ambient conditions in the test room can be tightly controlled by a proportional-differential (PD) controller which modulates humidification, heating system and condensing unit of the air conditioning system. The ambient conditions are monitored by temperature and relative humidity (RH) sensors linked to the measurement system.

The mean horizontal air velocity (cross-flow) of the test room was measured in accordance to sub-clause 5.3.1.2 of the standard [8] and was in the range between 0.1 and 0.2 m/s. The tests were carried out at ISO-3 condition as indicated, to evaluate product temperature performance at class 3 (25 °C/ 60% RH). All measurements were recorded every 20 seconds as specified by BS EN ISO 23953-2015 standard. The test was carried out continuously for 48 hours to establish a steady state condition. The temperature performance of the cabinet was established from the 48 hours data for ISO-3.

3. Experimental analysis

3.1. Selected experimental results

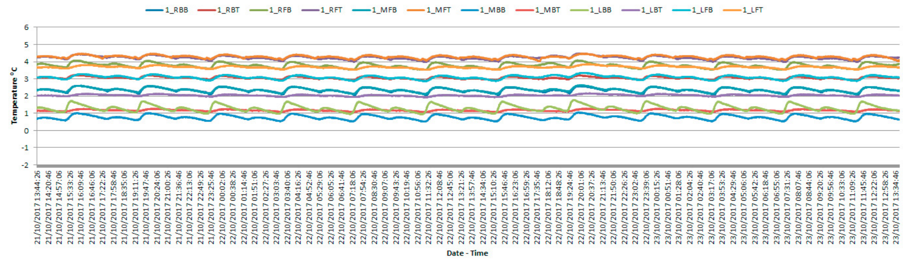

Fig. 5. Product temperature, shelf no.1 (Top).

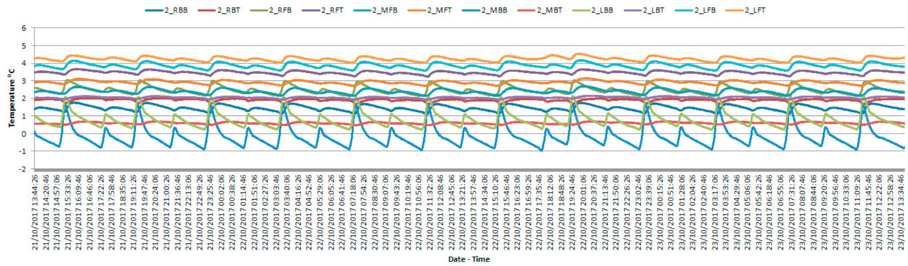

Fig. 6. Product temperature, shelf no.2 (Middle).

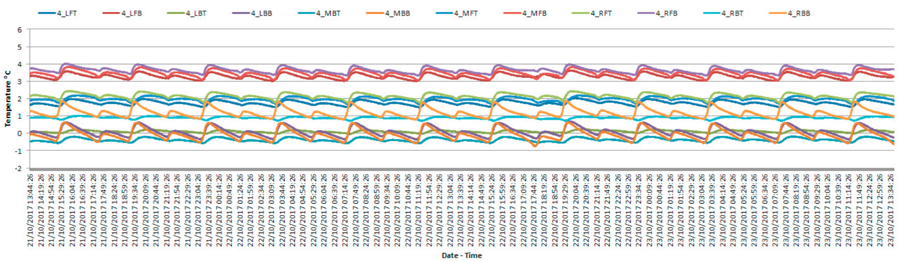

Fig. 7. Product temperature, shelf no. 4 (Bottom).

Fig. 5 to Fig. show the temperature distribution of all measured M-packages during the 48 hours test. The overall mean temperature was found to be 2.1°C. During the 48 hour test, all the products were recorded to be between -1°C and +5°C. This indicates that the cabinet can comply with ISO 23953-2015 requirements. The cabinet can also be classified as M1 according to BS EN ISO 23953-2015.

The energy consumption of the tested cabinet was found to be 25.38 kWh/24 hrs in day 1 and 25.31 kWh/24 hrs in day 2, which shows consistency in the energy consumptions by the case.
Compared to the same tested cabinet but without the cold shelf technology, the energy was found to be 42 kWh/24 hrs. Hence, a clear energy savings can be seen when implementing the cold shelf technology along with air guiding strips.

4. CFD Model

A preliminary 3-D CFD model using ANSYS Fluent 14.5 has been created to simulate the air flow behaviour and temperature distribution of the entire tested cabinet. The air inlet and outlet boundary conditions of the model are shown in Fig. . The standard $k - \varepsilon$ turbulence model was chosen for this simulation where the flow is considered to be transient. Due to the complex geometry of the cabinet, ANSYS-ICEM was used to mesh the 3-D model and tetra mesh was chosen with inflated boundary layer cells (Fig.).

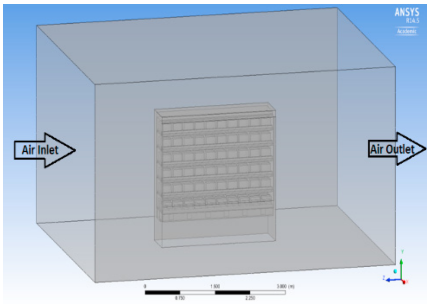

Fig. 8. Geometry drawn in ANSYS Design Modeler.

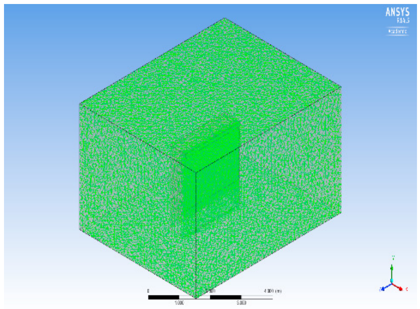

Fig. 9. Mesh elements for the model.

A fan model was implemented within the cabinet to simulate the propeller fan to push the air through the cabinet back tunnel. An energy source model was added after the fan which acts as the evaporator in the cabinet. The energy source model was controlled by a virtual temperature sensor installed in the back tunnel of the model. The temperature sensor controls the on/off status of the compressor defined by a transient controlled program, using a user defined function (UDF) and are included in the following equations, eq. (1):

$$S_{comp} = \begin{cases} on, & T_{sensor} > 5°C \\ off, & T_{sensor} < -3°C \\ off, & t_{d0} < time < t_{d1} \end{cases} \tag{1}$$

where, S_{comp} is the status of the compressor, T_{sensor} is the temperature of the controlling sensor, t_{d_0} and t_{d_1} are the start and finish time of each defrosting period, respectively.

The air heat transfer in the evaporator is calculated based on Fourier's law, eq. (2):

$$q_{evap} = h \times A \times \left(T_{evap} - T_{air}\right) \tag{2}$$

where h, is the heat transfer coefficient in W/m^2K, A is the heat transfer area in m^3, T_{evap} is the evaporator temperature and T_{air} is the air temperature.
In this paper, the heat transfer coefficient h is calculated through an empirical correlation of turbulent flow around the evaporator coils, eq. (3):

$$h = 0.023 \times f \times Re^{0.8} \times Pr^{0.3} \times l / \lambda \tag{3}$$

where f, is the correction factor, λ is the thermal conductivity, l is the selected typical length, Pr is the Prandtl number and Re is the Reynolds number.
Based on equation (2) and (3), the cooling capacity of the evaporator is calculated in eq. (4). When the compressor is on, the energy source is activated, while it is deactivated when the compressor is off, resulting in the following equations:

$$q_{eva} = \begin{cases} hA(T_{eva} - T_{air}), & S_{comp} = on \\ 0, & S_{comp} = on \end{cases} \tag{4}$$

4.1. Selected numerical results

The CFD model was created to be used as tool for further optimisation of the prototype. The preliminary results are not fully validated yet, as more tests need to be carried out.
Fig. shows a comparison made between the experimental and CFD air velocities along the length of the air curtain. The results provide some confidence in the model as both CFD and experimental results are closely following the

same trend at different locations within the cabinet along the air curtain. However, further improvements are required in order to obtain a fully validated model.

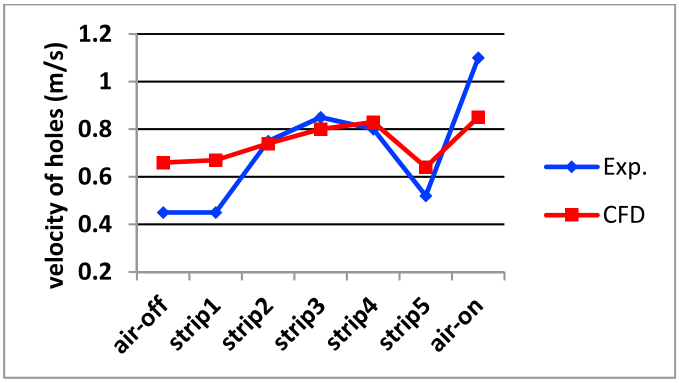

Fig. 10. CFD vs experimental air velocities along the air curtain.

Fig. shows the velocity contours across the cabinet in the middle plane at 1.25 m. The Fig.11 shows the velocity within the shelves where the velocity is seen to decrease in each shelf towards the top of the cabinet. The air exiting the bottom of each shelf is joining with the air curtain by making it stiffer which results in reduction of air filtration from the warm ambient to the cool air inside the cabinet. Along the air curtain, more air infiltration is seen towards the air-ON which is due to flow becoming fully developed, hence more turbulent.

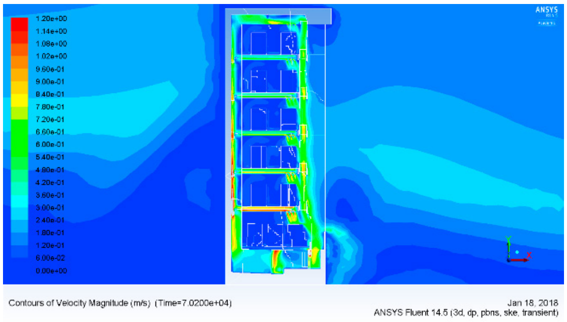

Fig. 11. Velocity contours across the cabinet.

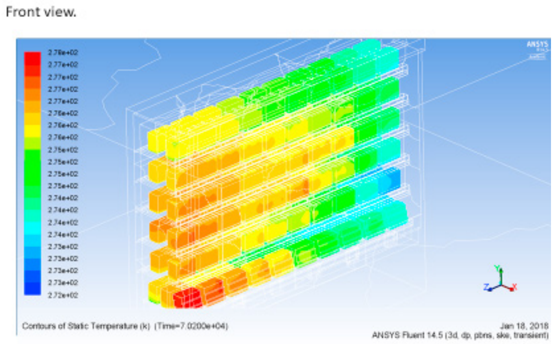

Fig. 12. Food temperature distribution.

Fig. 12 shows the temperature distribution within the food inside the cabinet. As it can be seen, the food temperature decreases along the shelves. This is due to having a strong air curtain at the top of the cabinet preserving the cool temperature of the food within the cabinet. However, the air curtain becomes weaker when the air flow travels further down, due to becoming fully turbulent. Hence, the air infiltration increases which increases the entrained warm air inside the cabinet and increasing the products temperature.

Within the simulation, the cross draft in Fig. is traveling from right to left. This results in a lower food temperature on the right, due to the cross flow being less turbulent at the start of the cabinet, hence less air infiltration with the inside products. However, as the cross draft progresses to the left of the cabinet, it becomes more turbulent and air infiltration is enhanced which increases the air interaction, resulting in a higher food products temperature.

5. Conclusion

To improve the energy consumption of an open front vertical display cabinet, the cold shelf technology was proposed. Previously, the air guiding strips had shown significant improvement in the energy savings [5]. In this project the cold shelf technology where air circulates in each individual shelf was tested. Where, air enters each shelf and the bottom perforated part of the shelf supplies cold air to the products below it while the top side of the shelf transfers the energy by conduction to the products above it.

This technology was integrated with air flow guiding strips and have shown greater energy savings from 42 kWh/24 hrs to 25.3 kWh/24 hrs. Also, the cabinet has shown food temperature to be between -1 and +5 °C which complies with class M1 as stated by ISO 23953-2015 [8].

A preliminary transient CFD model was also created in ANSYS Fluent and was partially validated as more experimental tests are still needed to be conducted for complete validation of the model. The results show the air flow behaviour and temperature distribution across the whole model, including M-packages, room, food zone, back tunnel and inside the shelves. The perforated shelves have shown stronger air curtain to reduce the entrained warm air to affect the food temperature during operation.

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