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CFD simulation of heat transfer and airflows in an open refrigerated display cabinet

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Abstract. This paper uses CFD (Computational Fluid Dynamics) method to study the efficiency of the airflow curtain in an empty and full open refrigerated display cabinet. Numerical simulation results show that changing of the angle of the honeycomb can reduce the infiltration of warm ambient air into the refrigerator. It was established that the average intake air temperature in modified design decreased by 0.6 °C compared to the original design. The CFD model presented in the paper can be used to study airflows inside and to design and develop open-type refrigerated cabinets.

Keywords: Open refrigerated display cabinet; CFD; Heat transfer; Airflow; Refrigeration; Temperature; Air velocity

1. Introduction

Most foods sold in supermarkets require cooling. Energy-efficient refrigerated cabinets are needed to keep food fresh. In order to increase the sales, food sellers usually use open-type refrigerators. These refrigerators are less energy efficient compared to closed-type refrigerators, but the market dictates its terms. To improve the performance of open-type refrigerators, single or double airflow curtains are used, which act as the door. The air inside the refrigerator is separated as much as possible from the warm ambient air and human actions. Refrigerated display cabinets must maintain the set temperature in accordance with [1]. For most foods like milk, dairy products, fried meat products and others, 3M2 class refrigerators are required that maintain the temperature of the products in the range from –1 to +7 °C. This temperature range is easily achievable in the most open-type refrigerated cabinets. To keep fresh meat in display cases, 3M0 class refrigerators are required, which maintain the temperature of foodstuffs in the interval from –1 to +4 °C. This temperature interval is rarely achieved in open-type refrigerators due to high ambient air infiltration rates inside the refrigerator. To improve the performance of the refrigerator, it is necessary to study the work of the airflow curtain and improve it. Minor geometric changes can sufficiently improve the efficiency of open-type refrigerated cabinets. However, designing of an energy-efficient open-type refrigerator requires a lot of laboratory testing to measure the infiltration of warm and humid ambient air into the interior of the refrigerator, that can make this task economically difficult for many refrigerator manufacturers.

Computational fluid dynamics (CFD) simulation software can be applied to reduce the cost and amount of laboratory testing of refrigerators. Many studies have shown that CFD simulation is a promising tool to study refrigeration efficiency and temperature mode in the refrigeration zone. Wang *et al.* [2] reported the progress in 3D simulation of a full refrigeration cabinet system under dynamic operation of automated switching on and off. Sun *et al.* [3] investigated the impact of flow guiding strips on the flow of the air curtain, the temperature of the products and (most importantly) on the energy consumption of the cabinet. Chaomuang *et al.* [4] developed a simplified heat transfer model of a closed display cabinet based on the zonal approach. This model enables the identification of the critical zones, i. e., too warm and too cold, which can lead to food quality deterioration and chilling injury, respectively. Rai *et al.* [5] conducted multiple CFD simulations to study the changes in thermal flow pattern inside a refrigerated truck body with and without an air curtain.

This paper presents a steady-state 2D numerical analysis of airflow curtains and temperature changes in an open refrigerated cabinet at different airflow honeycomb inclination angles. The heat transfer and airflows were simulated with commercial CFD software COMSOL Multiphysics 5.5. The aim of this article is to study the influence of the honeycomb angle on the formed air curtain and temperature in refrigerated cabinet. Minor changes in cabinet geometry can reduce the refrigeration temperature, thus improving the refrigeration class.

2. CFD model of refrigeration cabinet

2.1. Research object

The open-type vertical refrigerated display cabinet is schematically shown in figure 1. This cabinet is used for food products that should be stored at temperatures between –1 and +7 °C. It has 5 shelves for food products, their dimensions are shown in figure 1. The air enters into the cabinet through the air grill at the front of the bottom panel. Fans blow air through the evaporator. Then cooled air travels through a tunnel to the top of the refrigerator. The perforated distributor at the top distributes the cooled air. Part of the air is blown through the perforated back panel and the other part passes through the air-off honeycomb at the front top of the cabinet, thus forming 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 back perforated panel into the display area helps to maintain the required food temperature.

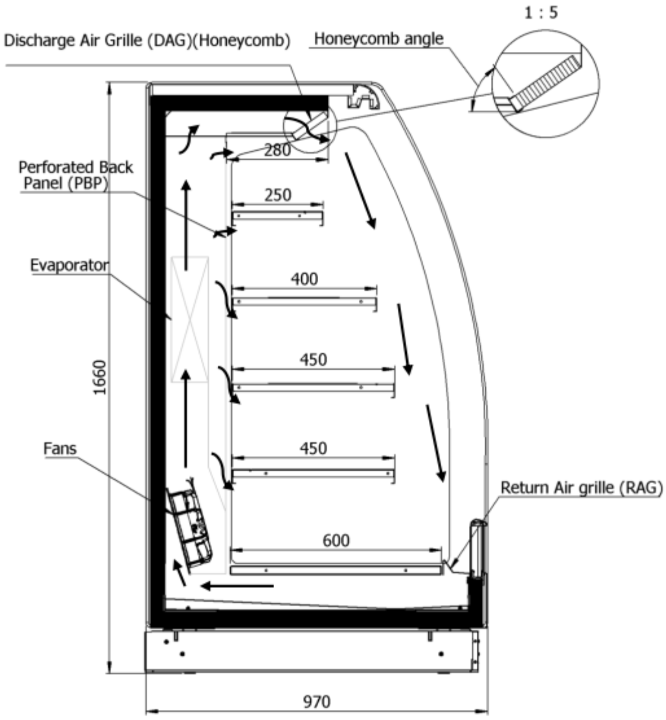

Figure 1. Side view of the refrigerated cabinet.

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The overall dimensions of the cabinet are as follows: 1660 mm in height, 970 mm in depth and 2500 mm in width. Spacing between base and first shelf is 280 mm, between other shelves – 250 mm. The air-off honeycomb dimensions are as follows: 20 mm (height) × 120 mm (width). Its inclination angle (figure 1) with respect to the horizontal plane was varied from 40 to 65°. All model dimensions including back panel, shelves, air ducts, etc. were the same as dimensions of real cabinet.

2.2. Mesh and simulation conditions

"COMSOL Multiphysics" software was used to simulate airflows and heat transfer in the refrigerated cabinet. Figure 2 shows the mesh of 2D model of the cabinet. The total number of 2D finite elements is about 12 000. A higher number of finite elements does not influence the results significantly.

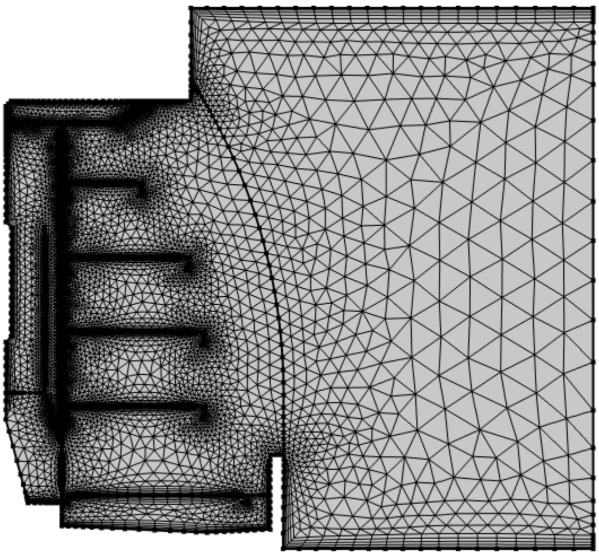

Figure 2. 2D mesh of the air space inside and outside of the refrigerated cabinet.

In the COMSOL Multiphysics model, the fan was simulated with normal outflow velocity, which value was set as 1.2 m/s. The outflow air temperature was considered as constant –1 °C value. This value was measured above the evaporator in the experimental study.

The open-type refrigerated cabinet exhibits strong natural convection between chilled air curtain and warm ambient air. To simulate this natural convection, the gravity was activated in the model and the density of the air was calculated based on the ideal gas formula.

In this study, the thin layer structure was used for honeycomb modelling to provide more accurate flow direction. Hanged shelves, bottom shelf, back perforated panel and other parts of the cabinet are made from a sheet of steel through which heat transfer occurs. Hanged shelves and bottom shelf were modelled as steel walls with a thickness of 1.4 mm. Other inner parts were modelled as steel walls with a thickness of 0.7 mm.

According to the standard [1], a refrigerated display cabinet should be tested in a controlled environment at 25 °C, 60 % RH and 0.1–0.2 m/s airflow velocity conditions for climate class 3. For simulation open boundary condition was applied to the model. Open boundary condition means that air can freely move in and out of the testing environment.

3. Simulation results and discussion

Figure 3 presents profiles of a fully formed airflow curtain at the middle plane of the empty refrigerated cabinet obtained for the different honeycomb angles. In all cases, the airflow curtain fully formed after 60 seconds. It can be seen from figure 3 that as the honeycomb angle increases, the curtain straightens, airflow radius increases. For 55–65° angle interval, the airflow lines almost do not cross the refrigerated cabinet outline presented by black curve in figure 3. The velocity of the airflow out of the honeycomb is 0.6 m/s and it decreases to 0.4 m/s near the intake grill at the bottom of the cabinet. The reason for reduced airflow curtain velocity is cold and warm air mixing in all curtain length.

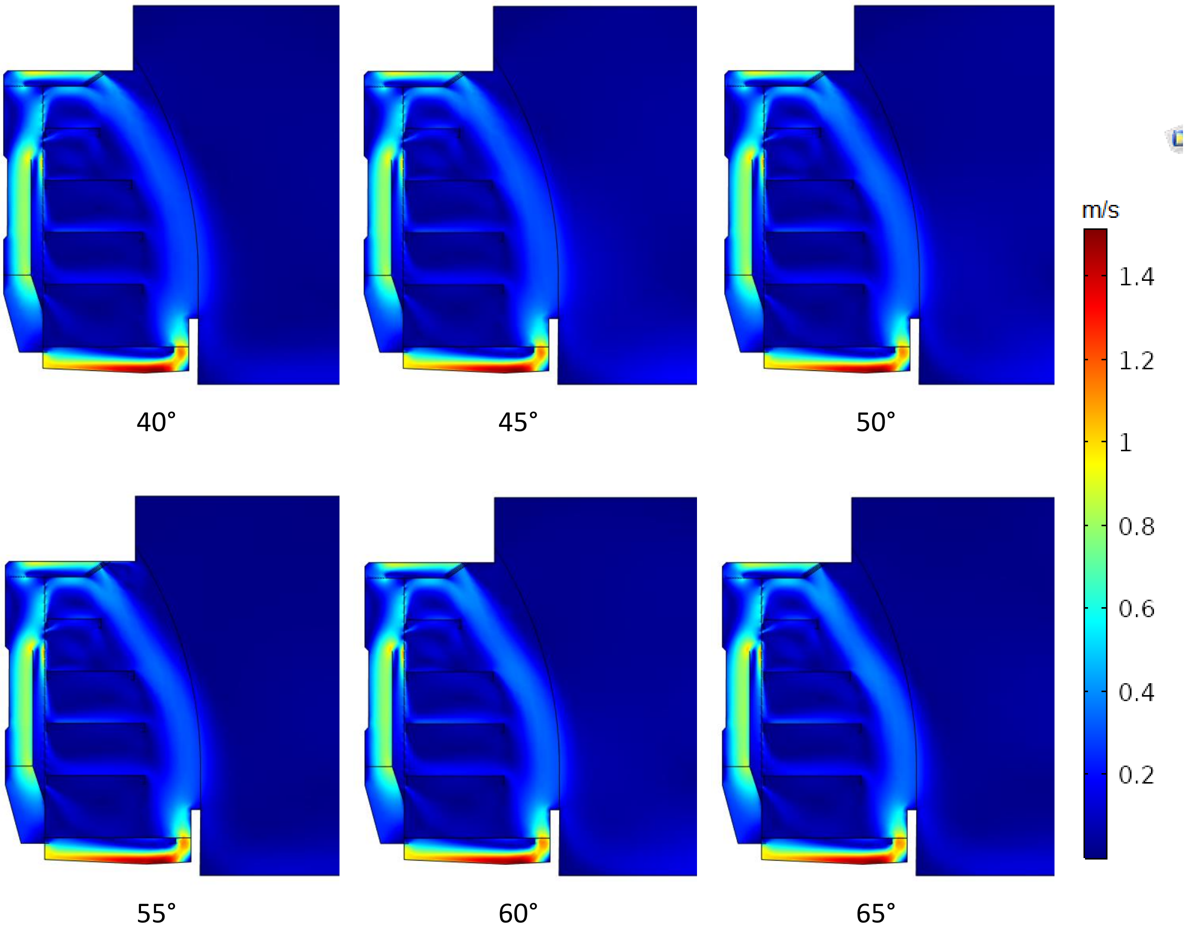

Figure 3. Airflow velocity distribution inside the empty refrigerated cabinet obtained for different honeycomb angles.

Figure 4 presents an intake air temperature versus honeycomb angle graph obtained for case of empty refrigerated cabinet. It can be seen from figure 4 that the honeycomb angle influences the temperature of the intake air. In case of 55° angle the temperature is lowest that means that this airflow angle is optimal for case of empty cabinet.

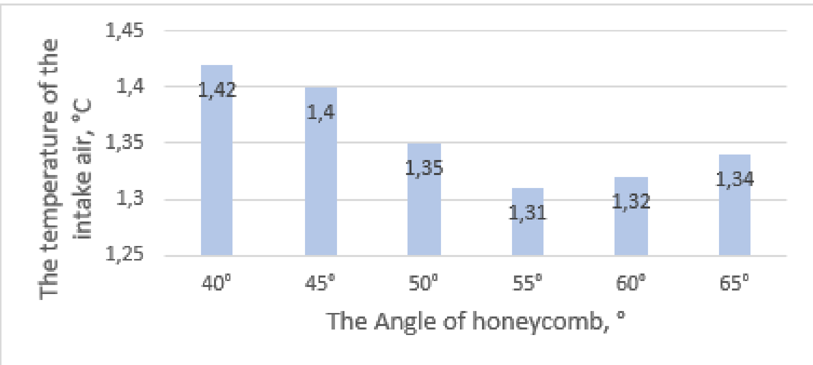

Figure 4. Air temperature at the intake grill versus honeycomb angle (empty cabinet).

Figure 5 presents profiles of a fully formed airflow curtain at the middle plane of the full refrigerated cabinet obtained for the different honeycomb angles. In the case of full (with food products) cabinet, the airflow curtain fully formed after 120 s. However, the airflow curtain changes its shape compared with empty cabinet case (figure 3) and its lines cross the refrigerated cabinet outline over the entire range of honeycomb angles. For 40–45° angle interval, the airflow is formed outside the cabinet outline. In case of 55–65° angle interval, the airflow curtain is formed at the outline and environmental factors do not influence its shape sufficiently. Velocities of the airflow out of the honeycomb and near the grill are the same as obtained for case of empty cabinet (figure 3).

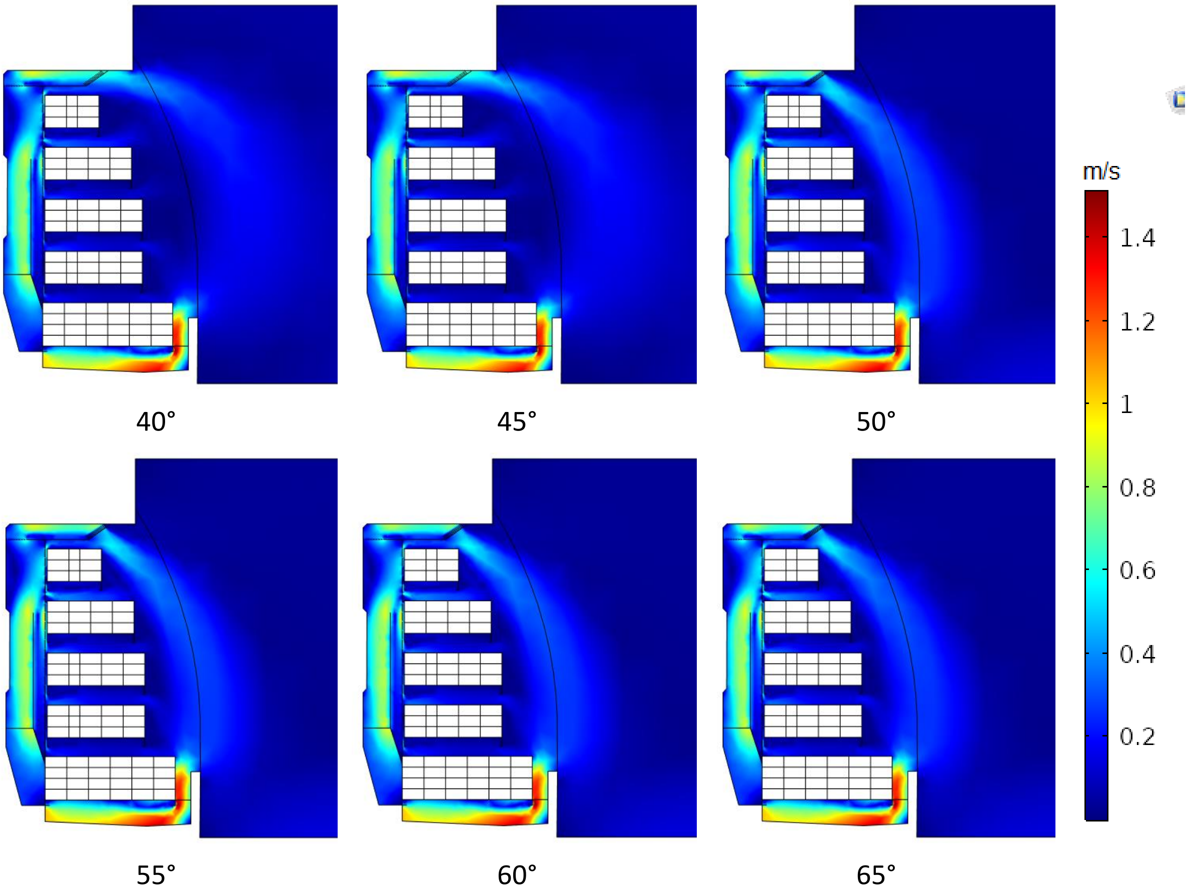

Figure 5. Airflow velocity distribution inside the full refrigerated cabinet obtained for different honeycomb angles.

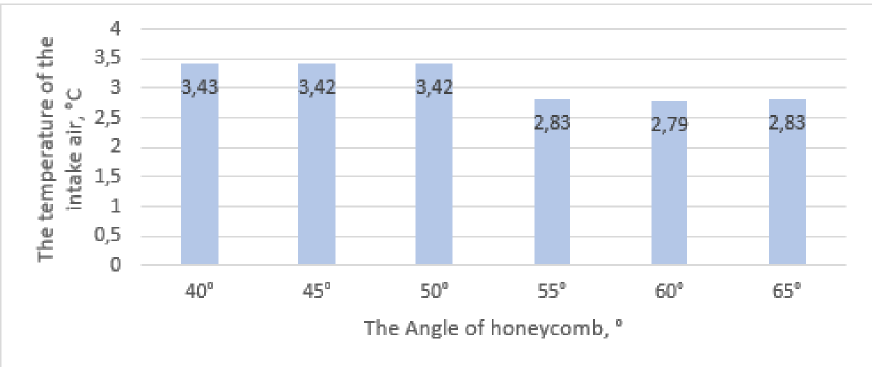

Figure 6. Air temperature at the intake grill versus honeycomb angle (full cabinet).

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Figure 6 presents an intake air temperature versus honeycomb angle graph obtained for case of full refrigerated cabinet. It can be seen from figure 6 that temperature of the intake air decreases with increase of honeycomb angle. The temperature simulation results are different from results obtained for empty refrigerated cabinet (figure 4). The heat exchange between the airflow curtain and the environment takes longer because the airflow rate remains the same, but the path it travels is increased, so the elongated airflow curtain does not completely separate the interior of the refrigerator from the warm ambient air.

4. Conclusions

- A simplified steady-state heat transfer model was developed to analyze airflows and heat transfer in open-type refrigerated cabinet according with ISO 23953-2 standard.
- Numerical simulation results show that intake air temperature decreases with an increase of honeycomb angle in both cases of empty and full refrigerated cabinet.
- Numerical simulation results show that the highest efficiency of the airflow curtain is achieved by increasing of the honeycomb angle to 55° only. Further increase of the angle doesn't lead to significant changes in efficiency.
- The simple heat transfer model developed for this study will be used in further studies investigating the effect of hanging shelf lengths on food temperature. The 2D research methodology will be used to study 3D models.

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