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NUMERICAL SIMULATION OF THE FLOW INSIDE A HORIZONTAL CLOSED REFRIGERATED DISPLAY CABINET

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ABSTRACT

A refrigerated display cabinet is a device often used to preserve the products contained inside while enabling the costumer to have a view to the products stored. The main objective of this work was to investigate, using the ANSYS Fluent software, the airflow in a horizontal closed refrigerated display cabinet to better understand the fluid flow behavior in its interior. The turbulent airflow and non-isothermal heat transfer process were computed in a 2D transient state mathematical model where the basic equations governing the transport phenomena inside of the refrigerated display cabinet were solved. Regarding the turbulence model, this was modeled with the three-equation model since it can address the boundary-layer transition regions within the cabinet. After a complete understanding of the fluid flow behavior inside the cabinet, the influence of the door opening was analyzed.

Results of the CFD simulations allowed to achieve a detailed mapping of the cooling process inside the equipment. Generally, stabilizing the interior temperature for an empty cabinet is rapidly achieved with minimal heat losses. The inclusion of products that are at a higher temperature than the cooling air creates a zone of high thermal inertia and makes the temperature stabilization a longer process. Even though specific equipment is used, the results provide standard information on the phenomena occurring inside the cabinet and contribute to the industry and academic society to understand and improve industrial products and obtain more information that is very reduced in the literature.

Keywords: CFD simulation; Display Cabinet; Refrigeration.

NOMENCLATURE

c_p	specific heat, J/kg.K
E	energy, J
F	external force, N
g	gravity acceleration, m/s^2
h	enthalpy, J/kg
J	diffusion flux, kg/m^2.s
k	thermal conductivity or turbulent kinetic energy, W/m.K or m^2/s^2
k_{eff}	effective conductivity, W/(K.m)
p	pressure, Pa
RH	Relative humidity, -
S	user-defined source terms
t	time, s
u	velocity, m/s

Greek symbols

ε	emissivity, -
ρ	density, kg/m^3
τ	stress tensor, Pa

1. INTRODUCTION

A very effective way of preserving food is to keep it at low temperatures, avoiding the formation of microorganisms and, consequently, preventing its degradation. For instance, the regulation imposed by the United States Agency for Food and Drug Administration requires that all refrigerated food should be stored at the maximum temperature of 5 ºC [1].

Over the years, several refrigeration systems have been created and refined for this purpose, the first of which consisted of simple cabinets with ice cubes. Nowadays, this conservation is already effective since its efficiency was improved, reducing the energy consumption without compromising its primary objective. In this way, closed refrigeration equipment becomes more popular because its consumption is much lower than the open ones. This fact has been highlighted by Alfano et al. [2] since around 45% of the energy demand of supermarkets is correspondent to refrigerated equipment, and 30% of the energy can be saved with closed refrigerated cabinets. The application of closed refrigerated cabinets is an alternative that can provide several advantages and has been proven that it does not affect product sales [3].

Nevertheless, the main benefit, which is why closed display cabinets are increasingly used, is the energy savings up to 70% [3]. There is no consensus on this topic as a study by Evans and Swain [4] presented an opposite trend, where the energy consumption was slightly higher in a closed cabinet. The frequency and duration of the door openings are essential factors that could contribute to this finding. However, as recently stated by Chaomuang [5] and Frias et al. [6], there are limited studies concerning the full understanding of closed refrigerated equipment's operating behavior, which suggests the need for further research.

Computational Fluid Dynamics (CFD) simulation appears as an attractive alternative to experimental activities to analyze the fluid flow behavior in a different phenomenon. Its application has been proved in a wide range of applications, such as, combustion phenomena [7–9], filtration processes [10,11], and thermal comfort assessment [12,13]. In recent years, an increasing effort has been devoted to in-depth review studies and analyses inside ventilated packaging during precooling [14], transport equipment [15], cooling, and conservation in display cabinets [3,16]. These studies were based on laboratory experiments, numerical simulations, or a combination of both tools. The option through numerical simulations, mainly the use of CFD techniques, has become popular due to the rapid advances in computational power in the last decades.

Concerning the CFD numerical simulations, there are available in the literature numerous studies regarding the simulation of open refrigerated cabinets. This equipment was the first to arrive in the market, and as two-thirds of the total heat load in the equipment is related to the environment, investigations to minimize the influence of the ambient conditions were addressed [5]. Söylemez et al. [17] performed a numerical and experimental analysis of a hybrid household refrigerator to determine the optimum location for the thermoelectric cooler. The predictions of the numerical model allowed the creation of new refrigerators with more uniform air velocity and temperature distributions inside the compartments. Chaomuang et al. [18] presented an experimental investigation on heat transfer and airflow in a closed refrigerated display cabinet and compared the results with the case without doors. Lower temperature heterogeneity was observed for the case with doors. The ambient temperature was an important factor since a nearly linear influence on the internal air temperature was obtained. Tsamos et al. [19] presented the experimental and 3D numerical results comparing an open vertical refrigerated cabinet and a cold shelf innovation, which integrates both air-guiding strips and air supply at the front of individual shelves to maintain a product temperature between 5 and -1 ºC. The experimental results showed that significant energy savings from 25 to 42 kWh/day could be achieved and partially validated the numerical model for further optimization of the display case. Sun et al. [20] investigated the influence of air-guiding strips on the performance of a vertical refrigerated display cabinet through the use of a CFD model. The numerical results showed that air-guiding strips effectively improve air curtains' efficiency by accelerating the air curtain vertically and inhibiting the infiltration of the ambient air into the cabinet. This improvement is highlighted by the temperature decrease of approximately 5 ºC inside the cabinet and one-third of the cooling capacity. Moureh et al. [21] experimentally and numerically investigated the aerodynamic behavior and the effectiveness of an air curtain confining cavity and subjected to an external lateral stream. The CFD model, which enables understanding the local air flow characteristics better, has made possible the quantification of the influence of several parameters on the air curtain perturbation. Wang et al. [22] presented a 3D CFD simulation of the air flow and temperature variation in a horizontal open-top display unit for frozen drink products during an automated dynamic cycle of switching on and switching off. The output from the CFD model was considered important by the author for cabinet design and to improve the storage quality of products while reducing energy use. Wu et al. [23,24] performed a more comprehensive CFD simulation with a multi-scale approach to investigate the characteristics of fluid flow and heat transfer of vertical open refrigerated display cabinet coupled with heating, ventilation, and air conditioning system in a supermarket. Wu et al. [25] studied the effect of the back panel structure on the performance of fluid flow and heat transfer of vertical open refrigerated display cabinets by experiments and numerical simulation. The location of perforations has a minor influence on the temperature distribution of the products. However, the suitable porosities in the back panel between the shelves are more likely to improve the uniformity of the temperature of the products. Laguerre et al. [26] experimentally studied the heat transfer and air flow in a vertical open refrigerated display cabinet loaded with packages of test product order to analyze unsteady state phenomena. The temporal variation of the air temperature inside the air curtain is due partly to the "on/off" compressor cycle and partly to the introduction of ambient air via vortices. The latter phenomenon contributes to the rapid velocity fluctuations, which are greatest inside the mixing layer of the air curtain. The product position in the cabinet is a determining factor of its temperature. Gaspar et al. [27,28] performed a detailed CFD modeling of air flow and heat transfer in an open refrigerated display cabinet and performed several parametric studies. The parametric studies are devoted to analyzing the thermal behavior influenced by fans' velocity, holes density, and distribution on the perforated back panel, discharge air grille and return air grille angles, and flow deflectors inside the internal duct. These analyses of the numerical predictions allowed the development of an optimized model with a more efficient configuration. Lower product temperatures and lower electrical energy consumption, allowing the improvement of the food conservation and energy rationalization of the equipment were achieved. This author has already implemented the numerical model to investigate the influence of the air velocity orientation [29] and to evaluate the influence of the discharge air velocity on the performance of its recirculated air curtain [30]. Furthermore, experimental tests for different ambient air conditions were successfully detailed and presented [31]. Amin et al. [32] investigated the infiltration rate of open refrigerated display cases and their dependency on secondary variables experimentally. Yu et al. [33] established a modified two-fluid turbulence model to simulate air curtains' flow and heat transfer characteristics in an open vertical display cabinet more accurately than k-epsilon models.

Regarding the closed refrigerated cabinets, there is minimal research involving this type of refrigeration equipment. Chaomuang et al. [5] carried out air velocity measurements inside a closed display cabinet using the Particle Image Velocimetry technique. They developed a 2D-CFD model to show the capability to reproduce the phenomena. Based on the equipment's operating conditions, two different conditions were studied, and the ambient air infiltration through the door was quantified. Frias et al. [6] evaluated experimentally the effects of two frequencies and four durations of the door opening in a retail display case installed in a research supermarket. At ambient conditions (19.6–20.9°C, 63% RH), with a case thermostat setting of 0.6°C and a daily 30-min defrost cycle, the only statistically significant fluctuation in product simulator temperatures was found for the most aggressive opening schedule where the door was opened every 5 min for 60 seconds at each opening. Furthermore, based on the average opening sequence, an energy consumption analysis was performed. Considering this issue, the energy consumption was 66% lower than an open retail display case. Another important aspect is that typical door opening regimes do not impact the uniformity of the temperature of the products.

Considering the limited study regarding the closed refrigerated equipment and the need for further investigation to obtain additional data about operating this type of equipment, the objective of this work is to study the fluid flow behavior inside a horizontal closed cabinet and understand the impact of the door opening frequency using a CFD model. Even though specific equipment is used, the results will provide standard information on the phenomena occurring inside the cabinet.

2. DISPLAY CABINET

The refrigerated closed display cabinet in analysis can provide to conserve different products like packaged goods of meat, pastry, charcuterie hot and cold. The main dimensions of the equipment in the study are 1,300 mm in height, 985 mm wide and the length can be variable depending on the customer needs. Figure 1 presents the equipment under analysis. The equipment is composed of sliding front doors, allowing to save a considerable amount of energy, and the upper part has LED lighting. Furthermore, the equipment has fan-assisted refrigeration with back shelves perforated that ensures uniformity of temperature in its interior.

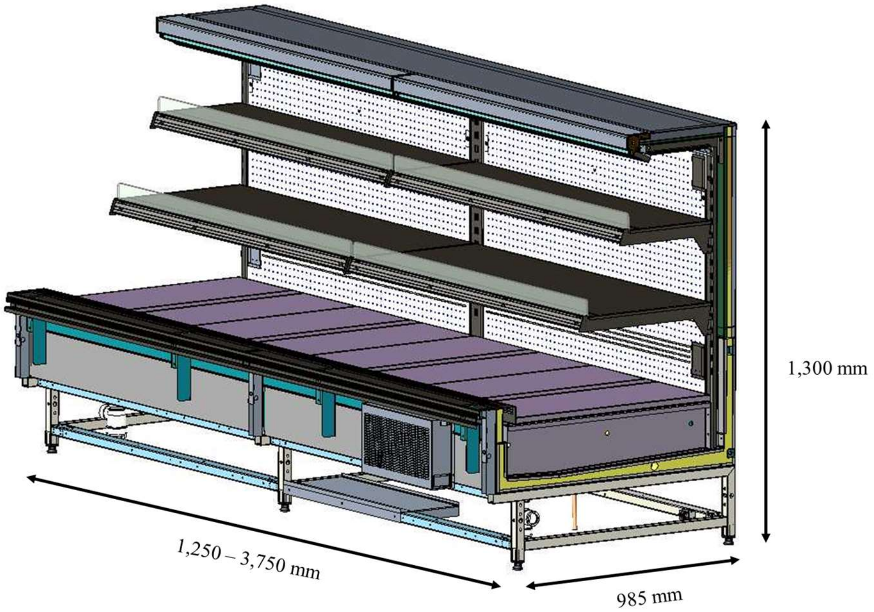


FIGURE 1: THE CLOSED REFRIGERATED EQUIMENT UNDER ANALYSIS.

3. NUMERICAL MODELING

3.1 Geometry

Studying the performance of refrigeration cabinets, this study accounts for two different situations. The first situation consists of an empty cabinet without any products inside. The second simulation uses the same cabinet but with the introduction of products.

The study of both situations was developed using computational simulation through the commercial CFD software ANSYS Fluent®. Since the geometry of the cabinet is symmetric, the model was simplified into two dimensions (2D). While the focus of the study is the interior of the cabinet, the main source of heat comes from the exterior environment, where the air is at a higher temperature. To account for this, the designed domain is divided into two regions, an interior region, and an outer region. Figure 2 a) represents the cabinet domain without products, and Figure 2 b) represents the same cabinet with the product.

3.3 Mesh

Once the simulation domain is defined, it was necessary to proceed with the mesh creation. Here, the authors gave preference to quadrilateral elements with inflation at the walls. Taking into account the importance of the mesh, a study of mesh independence was performed, according to the protocol defined by ASME GUIDE [34]. The mesh study comprised elements with an edge size varying from 10 mm to 0.7 mm with a growth ratio of 1.7. The tested variables were the average temperature, maximum temperature, average velocity, and maximum velocity for both the interior and exterior air. The selected mesh, with an average element size of 2.3 mm was chosen as the estimated error was under 0.2%. After this study, the resulting mesh for case 1 had 197,183 elements with an average orthogonal quality of 0.99 and average skewness of 0.06. For case 2, the mesh had 211,438 elements with an average orthogonal quality of 0.99 and average skewness of 0.05. Figure 3 shows an amplification of the mesh in the inlet region

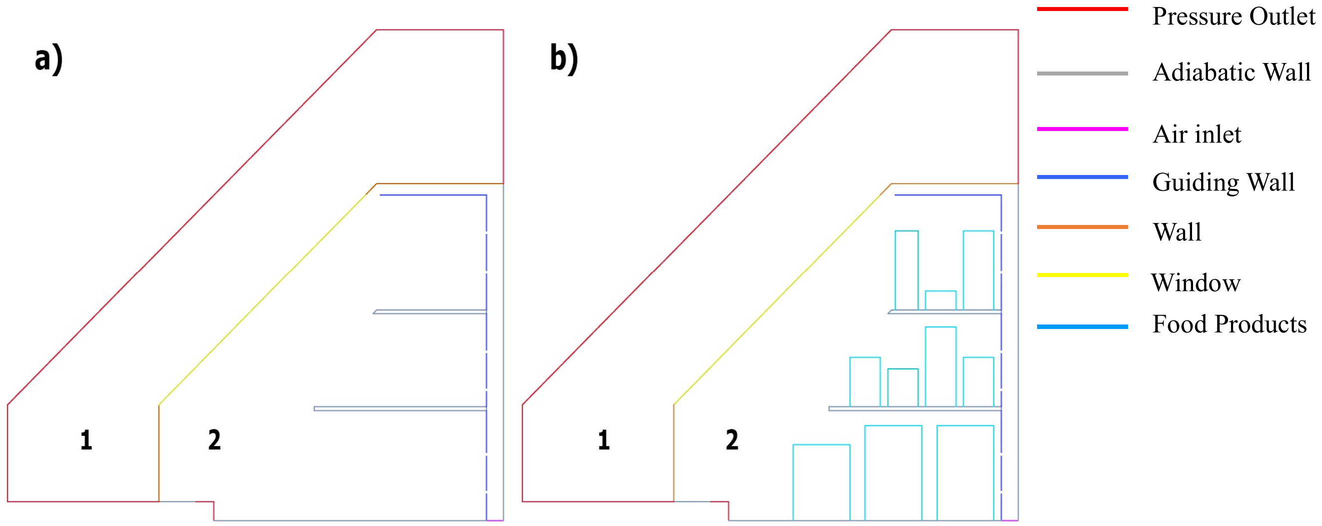


FIGURE 2: REPRESENTATION OF THE TWO DIFFERENT CASES: A) WITHOUT PRODUCTS AND B) WITH PRODUCTS.

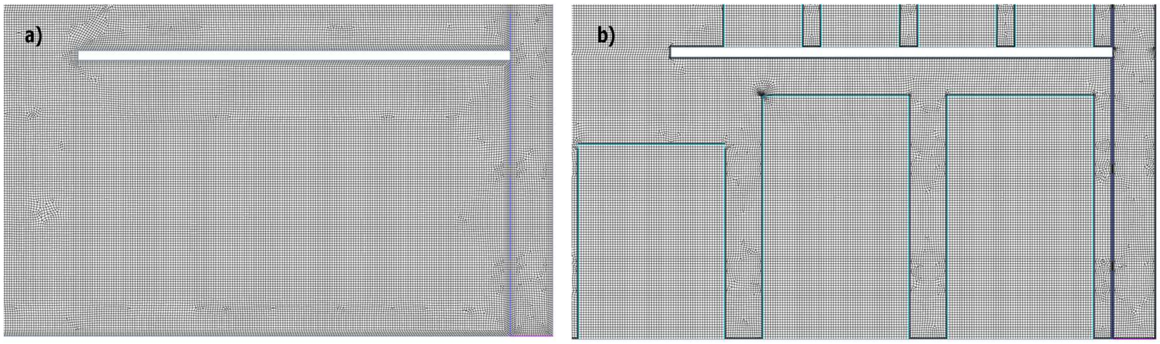


FIGURE 3: DETAILS OF THE MESH: A) NEAR THE SHELVES AND B) NEAR THE PRODUCTS.

3.2 Boundary Conditions

The refrigeration cabinet comprises different materials, each with its own set of properties that define its thermal behavior. In the present case, three distinct solid materials were defined, stainless steel, glass, and alimentary products. While the latter can be composed of different materials, food products have water as the main component ant its properties were approximated to ice. Meanwhile, the fluid material used was air. Table 1 shows the different properties used in the simulation.

Table 1: Material properties.

Material	ρ (kg/m^3)	k (W/m.K)	c_p (J/kgK)	ε (-)
Glass	2,500	0.96	840	0.95
Stainless Stell	7,740	14.4	502.48	0.075
Alimentary Products	916.8	2.22	2040	0.975
Air	1.225	0.0242	1006.43	-

The computational simulation requires the definition of boundary conditions that restrict the domain and allows the convergence to a solution. The domains previously referred to in Figure 2 were defined as represented in Table 2. At first glance, the study of the cooling cabinet appears as a steady state condition. However, during its operation in supermarkets, the cabinets' flow is often disrupted by its door opening. According to ISO 23953, the cabinet door is open for about 15 seconds when the user gets his products [3]. To follow this dynamic behavior, the simulation was defined as transient, and the boundary condition "window" changed, according, with time. For the initial conditions, the "window" was considered as a wall and only allowed heat transfer with the exterior.

Table 2: Boundary conditions.

Variable		Value	Units
Inlet	Pressure	0.5	m/s
	Turbulent Intensity	5	%
	Hydraulic Diameter	0.045	m
	Temperature	0	°C
Outlet	Pressure	0 (relative)	Pa
	Backflow temperature	20	ºC

After 70 seconds, for stabilizing the flow inside the cabinet, the "window" was changed to an interior boundary condition. While this condition was active, the model allowed fluid flow and heat transfer through this boundary condition. After 15 seconds, as defined by ISO 23953, or 85 seconds into the simulation, the boundary condition was changed back into a wall until the simulation ended at 250 seconds. The process of changing boundary conditions was automated using scheme commands in ANSYS Fluent®.

3.4 Simulation

Regarding the present subject, refrigerated display cabinets, two main fields are solved, namely, the fluid flow and the heat transfer. The former is simulated through the Navier-Stokes equation with the addition of a turbulence and radiation model. The unsteady Reynolds-averaged Navier-Stokes continuity (1), momentum (2) and energy (3) equations, averaged in a time interval together with the transient term, applied in the numerical calculation performed by the CFD software are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0 \tag{1}$$

$$\frac{\partial \left(\rho \vec{u} \right)}{\partial t} + \nabla \cdot \left(\rho \vec{u} \vec{u} \right) = -\nabla p + \nabla \cdot \overline{\tau} + \rho \vec{g} + \vec{F} + S \tag{2}$$

$$\frac{\partial \left(\rho E \right)}{\partial t} + \nabla \cdot \left(\vec{u} \left(\rho E + p \right) \right) = \nabla \cdot \left(k_{eff} \nabla T - h\vec{J} \right) \tag{3}$$

where ρ, u, p and E are the density, velocity, static pressure, and Energy of the fluid, respectively. $\overline{\tau}$ is the stress tensor for the incompressible flow, $\rho \vec{g}$ and $\vec{F}$ are the gravitational and external forces, and the terms k_{eff} and $h\vec{J}$ are the effective conductivity and diffusion energy, respectively.

For the turbulence, the 3-equation *k*l-*k*t-ω model was chosen, being appropriated to address the transition regions within the cabinet. To account the heat transfer in the domain, the energy model and the surface to surface (S2S) radiation model were also activated. The description of these models is presented in detail in the ANSYS Fluent User's guide [35].

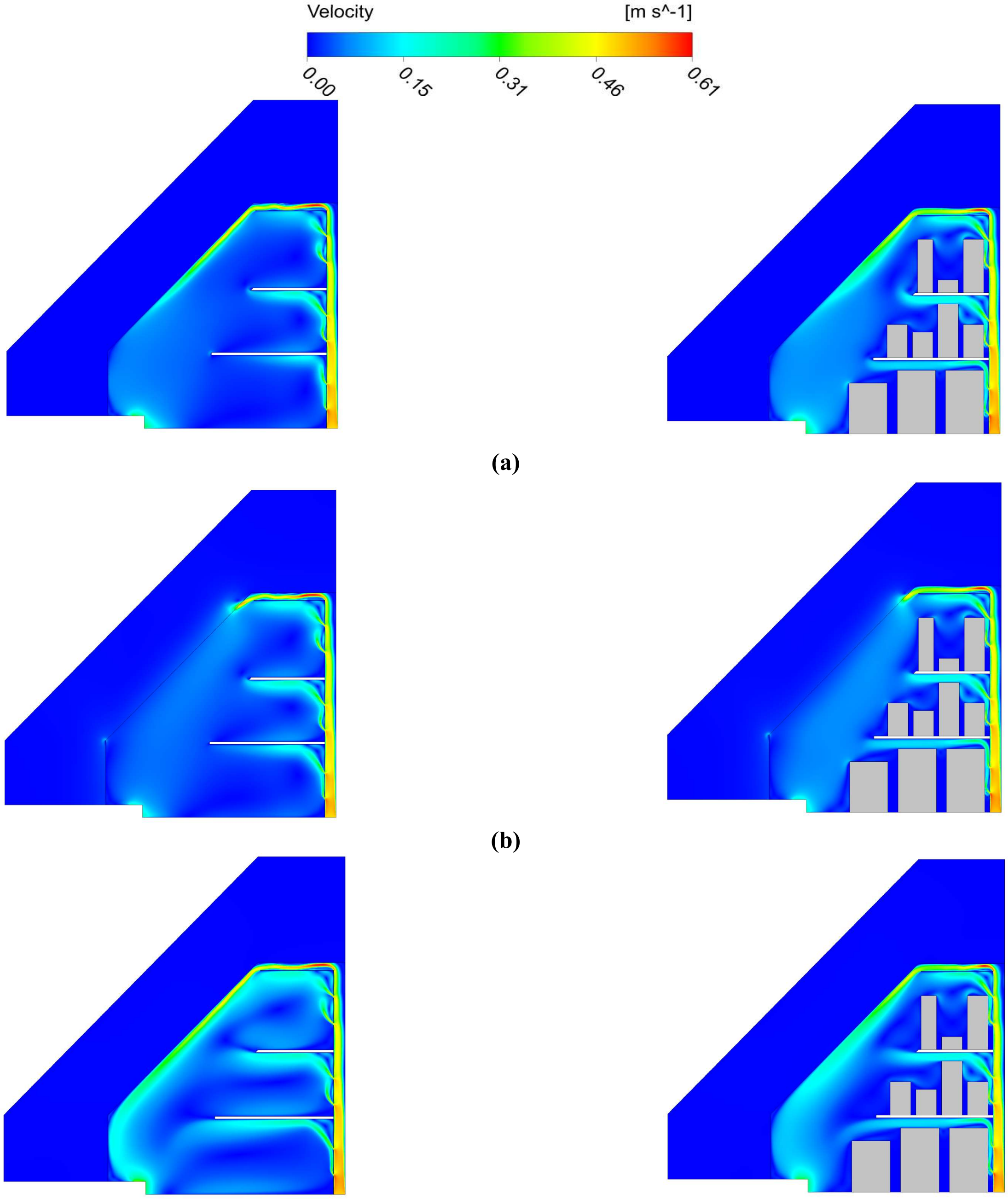
Furthermore, regarding the transient formulation, the computational model was solved using a first-order implicit method, and the convergence criterion was defined as 1E-3 for continuity, momentum, and turbulence equations and 1E-6 for energy equation. The Semi-Implicit Method for Pressure Linked Equations algorithm was used to solve the pressure-velocity coupling since it provides more efficient and robust single-phase flows. The contribution of the gravity acceleration was implemented in a downwards direction.

The initialization is necessary to fill the mesh cells with an initial value that is updated along the iterative simulation process. In the present case, the velocity field was initiated with 0 m/s. Regarding the temperature, two fields were defined. The interior region, including the products, was started at 4 °C, which is a standard cooling temperature and allowed to verify the heat transfer between the products and the input air. The external region was initiated at 20 °C, representing the room temperature at the supermarket. The initialization duality was automated using a user-defined function (UDF).

The simulation was computed in the 20-core (logical) processors, with 128 GB of RAM.

4. RESULTS AND DISCUSSION

The simulations allowed to verify the air flow and heat transfer within the cabinet. Figure 4 shows the velocities profile within the cabinet after 70 seconds, right before the window opening. Regarding the velocities, the openings on the division wall near the inlet allows the cold air to spread into the shelves and provides a better dispersion. At the same time, the wall directs most of the cold air to the top of the cabinet and along the cabinet window. When the cabinet is opened, the direction of the cold air at the top creates a curtain that reduces the entrance of hot air from the exterior. However, at longer openings, the hot air enters the cabinet by natural convection. Within the two cases, with and without products, the velocities profile is very similar. Since the air is directed along the top shelf for each section, the products do not significantly disturb the air flow.



(a)

(b)

(c)

FIGURE 4: NUMERICAL SIMULATION OF THE FLOW FIELD WITH AND WITHOUT PRODUCTS AT DIFFERENT SIMULATION TIMES: A) 70 SECONDS B) 85 SECONDS AND C) 250 SECONDS.

The heat transfer is the focal point in the study of refrigeration cabinets' performance. As referred by Chaomuang et al. [3], the main indicators of the heat transfer are the product's temperature and the temperature of recirculating air.

According to the simulations, while the cabinet is closed, the heat losses to the exterior are minimized with an output temperature of 4.74 °C for case a) and 4.4 °C for case b). When the cabinet is open, the temperature increase in the cabinet is considerable, with an average temperature of 9.72 °C for case a) and 10.53 °C for case b). The cause of this temperature increase is the inflow of hot air from the environment. Figure 5 shows the disturbance in the flow caused by the opening of the cabinet window. Although the contamination with hot air was expected, the geometry of the cabinet with a directional flow creates a cold air curtain that minimizes the loss of cold air to the ambient and consequent influx of hot hair. When the empty cabinet is opened, 28% of the inlet clod air is lost to the environment, directly translating into inefficiency and losses. For the cabinet with products, the flow lost to the environment decreases to 26%.

After stabilization, the output temperature for case a) is 3.74 °C and 3.89 °C for case b). Additionally, when the cabinet has products in its interior, the interior temperature recovers faster (a difference of 16 seconds between the two cases). This occurs because there is a smaller volume of air in this case. The products also transfer heat with the interior air and act as a heat source, causing a higher temperature at the end of the simulation.

After simulating 250 seconds, the temperature of the products maintain the same at 4 °C, indicating the need for a more extended simulation to verify differences in the results.

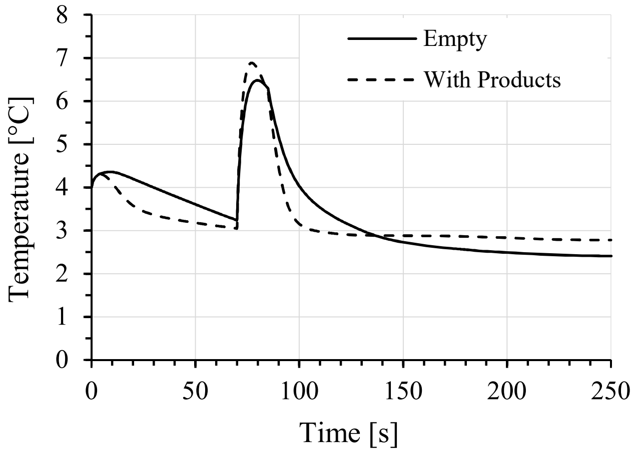


FIGURE 5: AVERAGE AIR TEMPERATURE INSIDE THE DISPLAY CABINET ALONG THE SIMULATION TIME.

5. CONCLUSIONS

In this study, a numerical investigation of the fluid flow behavior inside a closed refrigerated cabinet was performed. The CFD simulations showed to be an essential tool to study the flow with different operating conditions. It allowed the detailed visualization of the mass flow inside the closed refrigerated equipment, how it is distributed, and a close prediction of the real operating condition of this type of equipment simulating the opening of the front door.

The conclusion of the present study showed that simulation is a great tool to achieve the detailed mapping of a cooling cabinet interior. Generally, stabilizing the interior temperature for an empty cabinet is rapidly achieved with small heat losses. The inclusion of products that are at a higher temperature than the cooling air creates a zone of high thermal inertia and makes the temperature stabilization a longer process. To have the correct number for the time necessary to cool the products thoroughly, a new simulation with a higher ending time is essential.

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REFERENCES

[1] FDA, US: Food and Drug Administration - Food Code 2017, United States, 2017.

[2] F.R. d'Ambrosio Alfano, M. Dell'Isola, G. Ficco, B.I. Palella, G. Riccio, A. Frattolillo, Thermal comfort in Supermarket's refrigerated areas: An integrated survey in central Italy, Build. Environ. 166 (2019) 106410. doi:10.1016/j.buildenv.2019.106410.

[3] N. Chaomuang, D. Flick, O. Laguerre, Experimental and numerical investigation of the performance of retail refrigerated display cabinets, Trends Food Sci. Technol. 70 (2017) 95–104. doi:10.1016/j.tifs.2017.10.007.

[4] J.A. Evans, M.V.L. Swain, Performance of retail and commercial refrigeration systems, in: IIR Int. Cold Chain Conf., Cambridge, United Kingdom, 2010.

[5] N. Chaomuang, D. Flick, A. Denis, O. Laguerre, Experimental and numerical characterization of airflow in a closed refrigerated display cabinet using PIV and CFD techniques, Int. J. Refrig. 111 (2020) 168–177. doi:10.1016/j.ijrefrig.2019.12.001.

[6] J.A. de Frias, Y. Luo, B. Zhou, B. Zhang, D.T. Ingram, K. Vorst, J.K. Brecht, J. Stommel, Effect of door opening frequency and duration of an enclosed refrigerated display case on product temperatures and energy consumption, Food Control. 111 (2020) 107044. doi:10.1016/j.foodcont.2019.107044.

[7] J. Silva, J. Teixeira, S. Teixeira, S. Preziati, J. Cassiano, CFD Modeling of Combustion in Biomass Furnace, in: Energy Procedia, Elsevier B.V., 2017: pp. 665–672. doi:10.1016/j.egypro.2017.07.179.

[8] J. Silva, J. Teixeira, S. Teixeira, S. Chapela, J. Porteiro, Application of a biomass combustion model to an industrial boiler, in: ECOS 2018 - Proc. 31st Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst.,

2018. http://www.scopus.com/inward/record.url?eid=2-s2.0-85064182527&partnerID=MN8TOARS.

[9] J. Silva, L. Fraga, M.E. Ferreira, S. Chapela, J. Porteiro, S.F.C.F. Teixeira, J. Teixeira, Combustion Modelling of a 20 kW Pellet Boiler, in: Vol. 6B Energy, ASME, 2018: p. V06BT08A036. doi:10.1115/IMECE2018-88063.

[10] M.I. Vinha, J. Silva, S. Teixeira, A. Gomes, J.C. Teixeira, Numerical Study of the Flow Inside a Modular Bag Filter From a Biomass Power Plant, in: Vol. 10 Fluids Eng., American Society of Mechanical Engineers, 2020. doi:10.1115/IMECE2020-23484.

[11] J. Lopes, J. Silva, S. Teixeira, J. Teixeira, Numerical Modeling and Optimization of an Air Handling Unit, Energies. 14 (2020) 68. doi:10.3390/en14010068.

[12] D. Esteves, J. Silva, N. Rodrigues, L. Martins, J. Teixeira, S. Teixeira, Simulation of PMV and PPD Thermal Comfort Using EnergyPlus, in: ICCSA 2019. Lect. Notes Comput. Sci. Vol 11624. Springer, Cham., 2019: pp. 52–65. doi:10.1007/978-3-030-24311-1_4.

[13] R. Noversa, J. Silva, N. Rodrigues, L. Martins, J. Teixeira, S. Teixeira, Thermal Simulation of a Supermarket Cold Zone with Integrated Assessment of Human Thermal Comfort, in: ICCSA 2020. Lect. Notes Comput. Sci. Vol 12254. Springer, Cham., 2020: pp. 214–227. doi:10.1007/978-3-030-58817-5_17.

[14] C.-J. Zhao, J.-W. Han, X.-T. Yang, J.-P. Qian, B.-L. Fan, A review of computational fluid dynamics for forced-air cooling process, Appl. Energy. 168 (2016) 314–331. doi:10.1016/j.apenergy.2016.01.101.

[15] N.J. Smale, J. Moureh, G. Cortella, A review of numerical models of airflow in refrigerated food applications, Int. J. Refrig. 29 (2006) 911–930. doi:10.1016/j.ijrefrig.2006.03.019.

[16] U. Lindberg, Research for the retail grocery context: A systematic review on display cabinets, Trends Food Sci. Technol. 100 (2020) 19–34. doi:10.1016/j.tifs.2020.03.027.

[17] E. Söylemez, E. Alpman, A. Onat, Y. Yükselentürk, S. Hartomacıoğlu, Numerical (CFD) and experimental analysis of hybrid household refrigerator including thermoelectric and vapour compression cooling systems, Int. J. Refrig. 99 (2019) 300–315. doi:10.1016/j.ijrefrig.2019.01.007.

[18] N. Chaomuang, D. Flick, A. Denis, O. Laguerre, Experimental analysis of heat transfer and airflow in a closed refrigerated display cabinet, J. Food Eng. 244 (2019) 101–114. doi:10.1016/j.jfoodeng.2018.09.009.

[19] K.M. Tsamos, H. Mroue, J. Sun, S.A. Tassou, N. Nicholls, G. Smith, Energy Savings Potential in Using Cold-shelves Innovation for Multi-deck Open Front Refrigerated Cabinets, Energy Procedia. 161 (2019) 292–299. doi:10.1016/j.egypro.2019.02.094.

[20] J. Sun, K.M. Tsamos, S.A. Tassou, CFD comparisons of open-type refrigerated display cabinets with/without air guiding strips, Energy Procedia. 123 (2017) 54–61. doi:10.1016/j.egypro.2017.07.284.

[21] J. Moureh, M. Yataghene, Numerical and experimental study of airflow patterns and global exchanges through an air curtain subjected to external lateral flow, Exp. Therm. Fluid Sci. 74 (2016) 308–323. doi:10.1016/j.expthermflusci.2015.11.028.

[22] L. Wang, L. Zhang, G. Lian, A CFD Simulation of 3D Air Flow and Temperature Variation in Refrigeration Cabinet, Procedia Eng. 102 (2015) 1599–1611. doi:10.1016/j.proeng.2015.01.296.

[23] X. Wu, Z. Chang, X. Zhao, W. Li, Y. Lu, P. Yuan, A multi-scale approach for refrigerated display cabinet coupled with supermarket HVAC system – Part I: Methodology and verification, Int. J. Heat Mass Transf. 87 (2015) 673–684. doi:10.1016/j.ijheatmasstransfer.2015.04.004.

[24] X. Wu, Z. Chang, X. Zhao, W. Li, Y. Lu, P. Yuan, A multi-scale approach for refrigerated display cabinet coupled with supermarket HVAC system-Part II: The performance of VORDC and energy consumption analysis, Int. J. Heat Mass Transf. 87 (2015) 685–692. doi:10.1016/j.ijheatmasstransfer.2015.04.003.

[25] X. Wu, Z. Chang, P. Yuan, Y. Lu, Q. Ma, X. Yin, The optimization and effect of back panel structure on the performance of refrigerated display cabinet, Food Control. 40 (2014) 278–285. doi:10.1016/j.foodcont.2013.12.009.

[26] O. Laguerre, M.H. Hoang, V. Osswald, D. Flick, Experimental study of heat transfer and air flow in a refrigerated display cabinet, J. Food Eng. 113 (2012) 310–321. doi:10.1016/j.jfoodeng.2012.05.027.

[27] P.D. Gaspar, L.C.C. Gonçalves, R.A. Pitarma, Detailed CFD Modelling of Open Refrigerated Display Cabinets, Model. Simul. Eng. 2012 (2012) 1–17. doi:10.1155/2012/973601.

[28] P.D. Gaspar, L.C. Carrilho Gonçalves, R.A. Pitarma, CFD Parametric Studies for Global Performance Improvement of Open Refrigerated Display Cabinets, Model. Simul. Eng. 2012 (2012) 1–15. doi:10.1155/2012/867820.

[29] P.D. Gaspar, L.C.C. Gonc¸alves, X. Ge, Influence of Ambient Air Velocity Orientation in Thermal Behaviour of Open Refrigerated Display Cabinets, in: ASME 2010 10th Bienn. Conf. Eng. Syst. Des. Anal. Vol. 2, ASMEDC, 2010: pp. 453–462. doi:10.1115/ESDA2010-24124.

[30] P.D. Gaspar, L.C.C. Gonc¸alves, A. Vo¨geli, Dependency of Air Curtain Performance on Discharge Air Velocity (Grille and Back Panel) in Open Refrigerated Display Cabinets, in: Vol. 9 Heat Transf. Fluid Flows, Therm. Syst. Parts A, B C, ASMEDC, 2009: pp. 1067–1076. doi:10.1115/IMECE2009-11029.

[31] P.D. Gaspar, L.C. Carrilho Gonçalves, R.A. Pitarma, Experimental analysis of the thermal entrainment factor of air curtains in vertical open display cabinets for different ambient air conditions, Appl. Therm. Eng. 31 (2011) 961–969.

doi:10.1016/j.applthermaleng.2010.11.020.

[32] M. Amin, D. Dabiri, H.K. Navaz, Effects of secondary variables on infiltration rate of open refrigerated vertical display cases with single-band air curtain, Appl. Therm. Eng. 35 (2012) 120–126. doi:10.1016/j.applthermaleng.2011.10.013.

[33] K. Yu, G. Ding, T. Chen, Modified two-fluid model for air curtains in open vertical display cabinets, Int. J. Refrig. 31 (2008) 472–482. doi:10.1016/j.ijrefrig.2007.07.006.

[34] Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications, J. Fluids Eng. 130 (2008) 078001. doi:10.1115/1.2960953.

[35] ANSYS, ANSYS FLUENT Theory Guide, (2013).