EFFECT OF DOORS OPENING IN REFRIGERATED CABINETS: PHENOMENOLOGICAL STUDY OF THE THERMODYNAMIC BEHAVIOR AND AIR FLOW DYNAMICS

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Abstract: *During last years, supermarkets have increased the demand for closed refrigerated display cabinets due to new regulations and trends on energy and sustainability. However, the performance of this type of refrigerated display cabinets is not completely known, being of utmost importance how the airflow distributions could affect over the temperature distributions inside the cabinet. Consequently, this work presents a numerical evaluation of the performance of closed display cabinets focusing on the effect of the sliding doors opening process. The set of computational fluid dynamics (CFD) simulations served to validate the use of immersed solid approach in order to accurately analyze and evaluate transient behavior of the turbulent air flow distributions and temperature evolutions inside the cabinet and over the products, and characterizing the air curtain disruptions and the warm air entrainment during the opening process of the cabinet sliding doors (i.e. from closed doors, through doors opening process and to doors totally open).*

Keywords: CFD modelling; refrigerated cabinet; doors opening process; immersed solid; thermo-fluid dynamics

1. INTRODUCTION

During last years, supermarkets have increased the demand for closed refrigerated display cabinets due to their potential on energy savings compared to the open refrigerated display cabinets, reducing the infiltration of external warm/humid air. Additionally, non-impact on sales volume has been found by the doors presence in the USA [1]. The described benefits has positioned the closed cabinets as a priority in the new stores of several major retailers in Europe [2]. However, the required door opening and closing cycles for storing or removing food products from the refrigerated cabinets imply the infiltration of hot and humid air, which can have direct consequences on product preservation, increasing the thermal load and producing temperature fluctuations inside the cabinet [3], [4]. Therefore, its studies and analyses are the utmost importance.

Several experimental and computational studies has been developed analysing the performance of open display cabinets and ambient air infiltrations [4], showing the complex performance of the flow distribution in the cabinet, which is affected by many factors such as the location of the air supply and return, the initial velocity and length of the air curtain, the temperature distributions, the turbulent intensity, the shelves distribution, etc. Additionally, parametric studies has also shown the importance of the dimensions of the cabinet cavity and the air supply and return, the discharge angle of the air curtain, and the position of the inside shelves [5], [6], and the effect of the flow distributed through the back panel on the open display cabinet performance has been also analysed [7], [8]. For closed refrigerated display cabinets, few studies has been done, focusing in specific applications [4]. The physical mechanism of the thermo-fluid phenomena of fogging and defogging taking place during the door opening [9], and the influence of the doors frequency opening on the energy consumption [10] have been both numerically studied. Experimental studies of heat transfer and operating conditions effect have been also conducted for closed display cabinets [11], [12]. Recently, the performance of a closed refrigerated cabinets have been extensively experimental and numerically characterized [13], showing the potential of computational fluid dynamics (CFD) models to examine the influence of design parameters and operating conditions. Nevertheless, these time consuming numerical and experimental studies show the performance of a determined cabinet in a particular case without a general application. Little attention has been paid to the performance of the closed refrigerated cabinets focusing on the effect of the doors opening process over the products preservation, being of utmost importance to perform analyses to characterize how the ambient air infiltrations could affect over the flow and temperature distributions.

Accordingly to the stated above, this work presents a numerical evaluation of the performance of closed display cabinets during the doors opening process, reproducing this effect by means of immersed solid approach. Specifically, a refrigerated cabinet with sliding doors under the typical operational conditions was evaluated in order to perform the detailed spatial and temporal study of the air infiltration and its influence on the air temperature and velocity fields inside the cabinet. The set of simulations has served to accurately analyse the transient behaviour of the turbulent air flow distributions and temperature evolutions inside the cabinet and over the product, comparing the cabinet performance when the sliding doors are totally closed, during the opening process, and when the sliding doors are totally open, thus analysing the cabinet behaviour in the common operating conditions when the customer opens the door and takes the product from the cabinet.

2. COMPUTATIONAL DOMAIN AND ASSUMPTIONS

The description of the geometry and physical phenomena considered in the models to carry out the numerical study is detailed below.

As this study is focused on the analysis of the opening doors process, the interaction of the doors with the environment should be simulated, defining a large domain which allows to include the geometry cabinet and the environment. See Figure 1 for a schematic representation; a cavity with several shelves was considered in the cabinet calculation domain, reproducing the typical design of a closed refrigerated cabinet, and the calculation domain of the environment was defined to simulate the ambient around the cabinet. In the cabinet calculation domain, the shelves width was equal for all them, and the distance between neighboring shelves was the same. In the display cabinet there were five air entrance from the back panel (V_{inbp}) and one in front that is the air curtain (V_{inlet}), and one return in the bottom (P_{outlet}). The dimensions of the cabinet (L=1.8 m and H=0.85 m), the shelves length (L_s=0.65 m) and the width of the inlets of the air curtain and the back panel (b_{in}=0.04 m), and the outlet of the air curtain (b_{out}=0.08 m) were defined according to current cabinet designs.

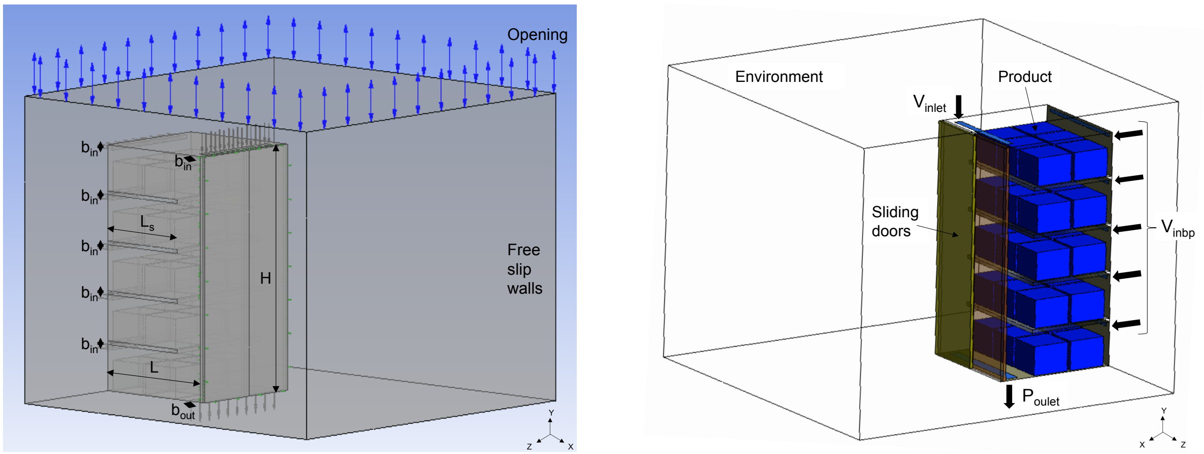

Figure 1. Computational domain views of the analysed case.

To elucidate the phenomena to be considered in the simulations and to better understand the fundamental fluid dynamics in the performance of the case presented herein, the flow was characterized by two dimensionless numbers: the Richardson number (Ri), and the Rayleigh number (Ra) (Equations 1 and 2, respectively).

$$R_i = \frac{g\,\beta\,\Delta T\,L_c}{U^2} \tag{1}$$

$$R_a = \frac{g\,\beta\,\Delta T\,{L_c}^3}{\nu\,\alpha} \tag{2}$$

Where g is the gravitational acceleration, β is the thermal expansion coefficient, ΔT is the temperature increase between the surface temperature and the quiescent temperature (fluid temperature far from the object surface), L_c is the characteristic length, U is the characteristic velocity, ν is the kinematic viscosity, and α is the thermal diffusivity.

The Ri is the ratio of the gravitational forces to the momentum forces to indicate the relative importance of natural and forced convection, and the Ra is associated with buoyancy-driven flow describing the ratio between buoyancy forces and the losses due to viscosity and thermal diffusion. A buoyant flow is a fluid flow for which gravity has an important effect, being able to arise whenever its density varies for any reason. The most common buoyant flow situation is natural (or free) convection, where the fluid density varies with temperature, and may also be present in mixed convection flows, in which both natural and forced (e.g. a fan) convection processes are important.

Ri and Ra were calculated for the conditions of the case presented here, being Ri 1 (i.e. indicating that free and forced convection effects must be considered) and Ra>10^9 (i.e. denoting a higher value over the critical, thus characterizing a turbulent behavior). Therefore, both forced and free convection play an important role on determining the overall temperature distribution in our specific application.

The simulation of the natural convection fluid flow through the door opening requires the use of a methodology which allows to simulate the doors motion. In this study the immersed solid approach is used, being an emergent method to represent a moving solid without deforming the mesh. This is a very robust methodology, which is valid to analyze the process of opening and closing the doors in a refrigerated cabinet, in which the thermal effects and the resolution of the boundary layer and the wall laws for turbulent flows do not play a critical predominant role in resolving the behavior of the fluid.

In this technique, both the solid and the fluid have their own meshes, and the solid during its movement does not deform the fluid mesh, since generates an overlapping of the fluid mesh on its advance, blocking the volume available to be occupied. The solver locates the fluid nodes that overlap with the solid mesh and the code calculates the volume fraction occupied by the solid and blocks it. This type of approach is based on assigning a rigid solid motion to the solid, for which an equation of motion is assigned that solves for each time step the position of the solid nodes and, thus, at each step solves the overlapping and the effect of the solid motion on the fluid. The fluid velocity at the overlapping nodes is forced to be equal to solid body velocity nodes, capturing the influence of the solid [18]. In this study, a velocity of 15 cm/s has been defined for the immersed solid of the sliding door, setting the opening time in 3 seconds.

Related the considerations assumed in the presented case, in the domain of the cabinet itself, the walls of the cabinet were considered as adiabatic, and the products inside the cabinet were defined as solids. In the environment domain, the top is defined as an opening boundary condition and the rest of wall were considered in free slip condition (see Figure 1).

In closed refrigerated cabinet, the velocity of the jet leaving the honey-comb (i.e. the V_{inlet} in our case) ranges from 0.5 to 1 m/s [9], [13] to form the front air curtain. This velocity must be higher than the air velocity between the shelves (i.e. the V_{inbp} in this case), which cools the load in the shelves and also function as a stabilizer for the air curtain. The choice of low velocities inside the shelves is to protect the load from drying caused by forced convection [14], but higher velocities are required to achieve air curtain stabilization [15]. In this study, in order to have a balance between both conditions, V_{inlet} = 1 m/s and V_{inbp} = 0.5 m/s were defined. Additionally, the turbulent intensity at the inlets was assumed to be 5 percent, and the air return was defined as a pressure outlet (P_{outlet}=-10 Pa) to have stabilized conditions in the cabinet domain.

Finally, as initial conditions, it was assumed that model starts from steady-state over all the domain, with air temperature of T_{incab} = 4°C inside the cabinet computational domain, and T_{inenv} = 25 °C in the envinronment computation domain. The temperature of the cold sources (inlets) was equal to T_{incab} and the temperature in the opening condition of the environment computation domain was equal to T_{inenv}.

3. CFD MODEL

The commercial CFD software ANSYS® Academic Research, Release 2020 R2 and, in particular ANSYS CFX, was used to solve the general conservation equation (Equation 3) for mass, momentum and energy.

$$\frac{\partial}{\partial t}\int \rho\phi\, dV + \oint \rho\phi \boldsymbol{V}\cdot d\boldsymbol{A} = \oint(\Gamma_\phi)\nabla\phi\cdot d\boldsymbol{A} + \int S_\phi\, dV \tag{3}$$

Where V and A are respectively the area and the volume of the cell, ϕ stands for a generalized transport variable, Γ represents the effective diffusivity, and *S* is the source term for the respective transport variable. To describe the turbulent flow, the shear-stress transport (SST) *k-ω* model instead of the standard *k-ε* model, since it can describe better fluid flow in impinging jets within reasonable computational effort [16]. The SST *k-ω* model incorporates a blending function to trigger the standard *k-ω* model in near-wall regions and the *k- ε* model in regions away from the wall. The turbulence kinetic energy, *k*, and the specific dissipation rate, *ω*, are obtained from the transport equations (Equations 4 and 5, respectively) including the convection and viscous terms, together with terms for production and dissipation of *k* and *ω* and cross-diffusion of *ω*.

$$\rho\frac{\partial k}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)k = \nabla\cdot[(\Gamma_k)\nabla k] + G_k - Y_k + S_k \tag{4}$$

$$\rho\frac{\partial \omega}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\omega = \nabla\cdot[(\Gamma_\omega)\nabla\omega] + G_\omega - Y_\omega + D_\omega + S_\omega \tag{5}$$

where Γ_k and Γ_ω represent the effective diffusivity of *k* and *ω*, respectively. G_k represents the production of *k*, and G_ω represents the generation of *ω*. Y_k and Y_ω represent the dissipation of k and ω due to turbulence. D_ω represents the cross-diffusion term. S_k and S_ω are user-defined source terms for k and ω, respectively. More details about this model can be found elsewhere [17].

ANSYS CFX is a finite-volume solver, using body-fitted grids, and a co-located (non-staggered) grid layout and all variables are evaluated at the cell centres. The pressure–velocity coupling is obtained using a version of the SIMPLE algorithm. The code uses a high order advection scheme, with a numerical advection correction term. Taking as initial conditions the converged solution from the steady-state simulation, transient simulations ran with a maximum time step set to 10^{-3} s for obtaining stable solutions, and fulfilling the condition of the Courant number. The convergence criterion is specified to absolute residuals $\leq 10^{-5}$.

A single-phase 3D model was used to characterize the refrigerated cabinet performance, following the general assumption previously discussed. In this problem mixed convection was considered, including a buoyancy driven-flow, thus the gravity should be activated. The air was defined using the ideal gas law approach. For buoyancy calculations the variable density is evaluated directly as $\rho-\rho_{ref}$, specifying the reference density as an approximate average value of the expected domain density.

An hybrid mesh structured-unstructured was defined in the computational domain. During the meshing process, the guidelines detailed in CFX Best Practices Guide for Numerical Accuracy [18] were took into account, testing mesh dependence and discretization schemes. Then, a sensitivity analysis of the mesh confirmed the null impact of the mesh size element on the simulation results. In addition, mesh quality parameters (orthogonal quality and skewness) had been checked.

4. RESULTS AND DISCUSSION

Present simulations serve to qualitatively asses the closed refrigerated cabinets performance during slinding door opening process. The 3D CFD model defined in this work is based on immersed solid approach to considered the sliding door motion, allowing to perform a transient simulation to analyse temperature and flow distributions during the opening process. As stated in previous works, it is important to consider in the simulation relevant factors such as back panel discharge and buoyancy effects to accurately predict the air flow and temperature distributions in the air curtain and inside the cabinet [15].

In the case presented herein, as can be seen in Figure 2, when the sliding door started to open by second 1, the hot air from the environment (25ºC) began to penetre inside the cabinet, starting to have an effect over the products placed in the first row infront of the of the door that is being opened; after 2 seconds, the hot air started to affect to the products placed in the second raw. So, in general, the product with higher temperatures due to process of openning doors is the one placed in front and in the top of the cabinet, which is in agreement with the experimental results presented in [11]. In the horizontal planes (Planes 1 and 2), it is shown that more hot air enters throught the upper than in the lower part of the cabinet. This effect produced by the bouyancy can be analyzed in more detail in Figure 3, where is depited the air curtain performance during the sliding door opening process. As can be seen, the air curtain is totally disturbed during the opening process, which causes that the hot air to enter inside the cabinet mainly in the top, rapidly propagating to rest of zones, and also entering by the air return. This performance is in qualitatevely agreement with the results presented by Orlandi et al. (2013) [10]. The hot air that have gone inside the cabinet remains there for a few seconds. As can be seen in Figure 4, the air curtain is stabilized after 9 seconds, being the door totally open for 6 seconds. At that time, the horizontal air flow from the back panel has already stabilized the air curtain, returning outside of the cabinet part of the hot air that has entered inside the cabinet during the open process. With the sliding door completely open, the main entrace of hot air is produced in the top of the cabinet. After 20 seconds (having pass 17 seconds with the door completely open), still there is remaining air at approximately 10 ºC inside the cabinet;

this means that the flow from the back panel seems not to be enough to drag all the air that has been entered, but still this air is flowing inside the cabinet for finally being removed. Regarding the product preservation at that time, the product stored infront of the opened door and in the top part of the cabinet is the one most affected by the air infiltrations (see Figure 5); even so, their temperature starts to recover after the air curtain stabilization. The rest of the product inside the cabinet is practically not perturbed.

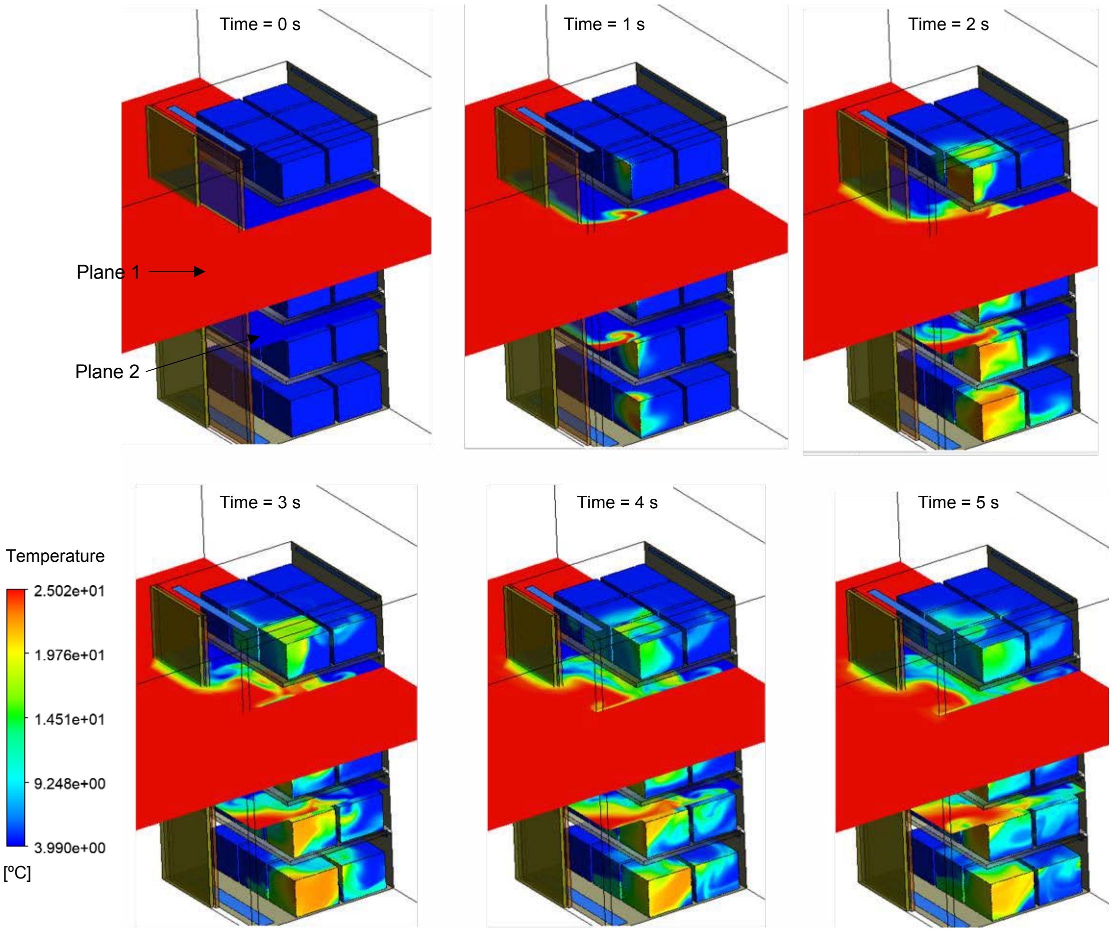

Figure 2. Temperature distributions inside the cabinet and over the products from instants 0 to 5 seconds.

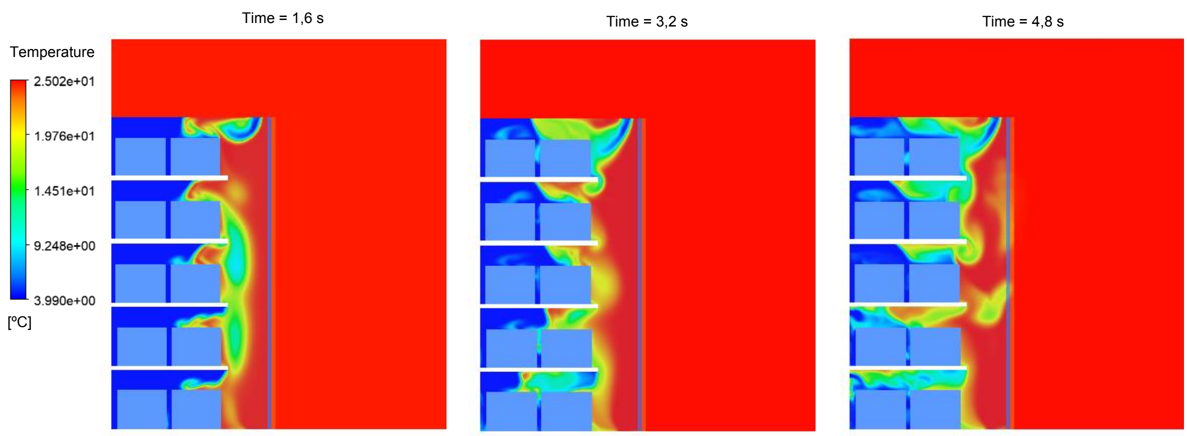

Figure 3. Temperature distributions along the air curtain and inside the cabinet from instants 0 to 5 seconds.

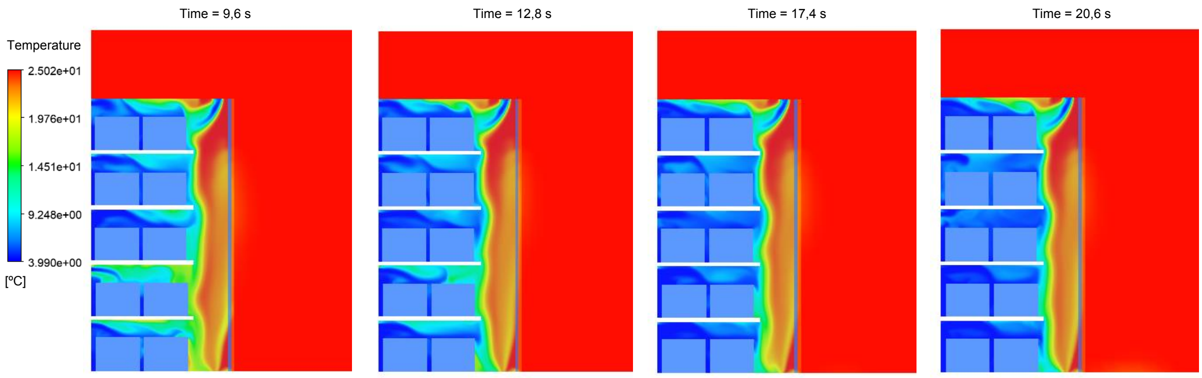

Figure 4. Temperature distributions along the air curtain and inside the cabinet from instants 9.5 to 20.5 seconds.

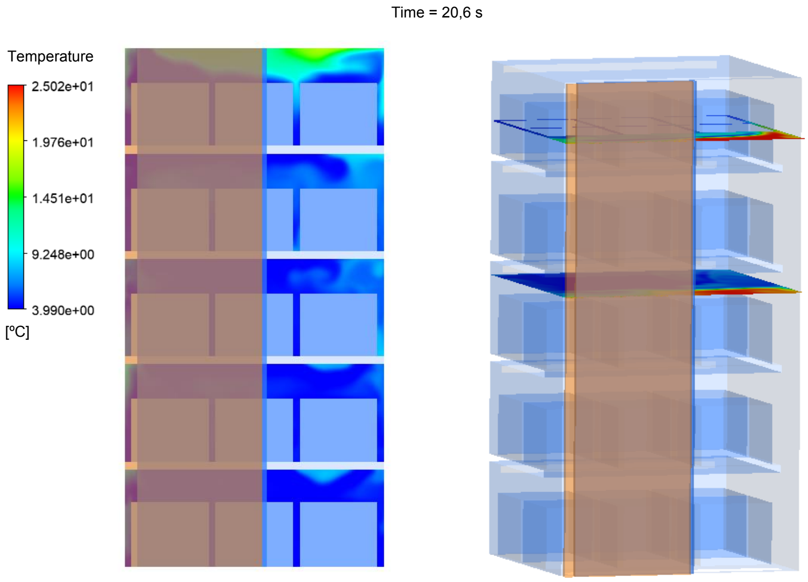

Figure 5. Temperature distributions in differents planes inside the cabinet at instant 20.6 seconds.

5. CONCLUSIONS

The performance of a closed refrigerated cabinet during the sliding doors opening process was numerically analysed. As a novelty, the immersed solid approach has been tested and validated to consider doors motion using a 3D CFD model. The results indicated that buoyance, air curtain and back panel flow have a great effect on the flow and temperatures distribution inside the cabinet in the process of sliding doors opening. Additionally, most unfavourable places for product preservation are detected. With this phenomenological study, technical improvements that can minimize air infiltration can be suggested, and consequently improving thermal performance and energy consumption rationalization.

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