27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0753
NUMERICAL SIMULATION OF EXTERNAL SWEATING IN A STATIC REFRIGERATOR

Vitor Fiorito da Silva
Leandro Oliveira Salviano
Sao Paulo State University "Julio de Mesquita Filho" – Engineering College - Ilha Solteira Campus
Brasil Avenue, 56 – Centro – Ilha Solteira/SP
vitor.fiorito@unesp.br
leandro.salviano@unesp.br

Abstract. *In this paper, a numerical modeling of a commercial refrigerator is developed to examine its external sweating under different environmental conditions. External sweating is a critical malfunction that may occur in these devices, and it is caused by the condensation of wet air at any point below the dew point. For commercial scenario, the liquefied water slips off on the surfaces which may potentially damage the product or even cause other inconveniences to the end user, aside from the restrictions on product exposure at the point of sale. There are numerous experimental and numerical works in the literature that address the physics of this process and focus on the development of hydrophobic surfaces to mitigate the occurrence of this phenomenon. For refrigerators, most studies focus on the assessment of this problem on external surfaces. However, few works were found conducting a full external analysis of the refrigerator. Thus, the present work focused on the appraising of the external temperature profile by the internal flow modeling and the heat transfer through the walls. The main heat transfer mechanism in the refrigerator analyzed is natural convection due to buoyancy differences in the internal flow and conduction through the walls. The phenomena of air movement and stratification are critical for the emergence of this problem. Condensation zones were identified by evaluating the dew point for different ambient conditions (25 °C - 60% / 32 °C - 65%). The results show relevant condensation zones on all the external surfaces of the refrigerator. The internal air distribution was out to be a crucial factor in both the development and size of these sweating zones. Finally, a parametric study was carried out to investigate the main variables involved in this phenomenon which showed a direct correlation between the phenomenon occurrence and the thermal conductivity level of the insulation material, as opposed to density variation, which has not been shown to be effective.*

Keywords: *refrigeration, condensation, sweating, computational fluid dynamics, parametric analysis.*

1. INTRODUCTION

In the modern society, the usage of refrigerators is indispensable. Within residences for preservation of food and drinks ensuring their quality for an extend duration. At commercial establishments such as bakeries and supermarkets, several cooling equipment maintain food and beverages at the best temperature for consumption. In medical sphere, these devices are crucial for the proper storage of medicines and vaccines, in compliance with regulation and health standards. This huge market justifies a survey published by IBGE (2019), pointing the existence of a fridge in 98,1% of Brazilian homes. Globally, as per Statista (2023), the revenue from the refrigerators segment of the home appliances industry is projected to grow progressively from 2023 to 2028, with a total increase of USD 33.3 billion (+25%).

Among the main potential failures in refrigerators, the external moisture is among the most visible, according to Figure 1, obtained by end users' complaints. The water present in vapor phase in the air may condense on certain surfaces, depending on physical variables of the climate and temperature and conditions of these surfaces exposed to that environment. This problem can occur on the sides and front of the equipment, hindering the exhibition of the internal content in showcase fridges, in addition to eventual damage to the external finish of the product. In a domestic setting, the condensed water in this process can wet the floor of the place, making it difficult to maintain its cleanliness, and even causing accidents. All of these issues directly impact the end customer, and may reduce sales volume (Rauss et al., 2008).

The study of the phenomenology of condensation is significant for a better understanding of the investigated problem, even though, the mathematical modeling of this problem is beyond the purview of this work. Condensation is a thermodynamics process in which vapor is chilled, altering its state to liquid, therefore considered a phase-change phenomenon. In several engineering applications, vapor-liquid phase change processes are commonly explored, due to the high potential heat transferred. Nevertheless, in various applications, the condensation process is highly regulated, whereas in numerous cases, it is undesired. For food packaging application, the primary variable that impact the loss of product weight or the accumulation of moisture inside the package are transpiration and water condensation, contributing to appearance attributes for fresh products (Volpe et al. 2018) and shelf life (Ben-Yehoshua and Rodov 2002). In this context, some studies evaluated the exterior and interior water mass transport in household refrigerators as conducted by Stein et al. (2002) and Laguerre et al. (2010).

Figure 1. Rear and side external condensation on a domestic refrigerator.

Prior studies on condensation focus on examining of phenomenon itself, delving into the theories of sweat formation, which involves heat and mass transferring throughout the process. Some others center on the minimization of this problem inside the refrigerator, or even on isolated parts, mainly on the glass door, at fixed ambient conditions. On the other hand, no studies were found performing a complete analysis of the external condensation in a refrigerator, considering the impact of its internal flow characteristics, thermal insulation and geometric attributions, and also the effect of critical heat transfer variables, such as external convective coefficient, temperature and relative humidity.

This work aimed to establish a scientific methodology for the computational modeling of the dynamics of the flow inside a static refrigerator. Additionally, an objective of determination of the dew point (DP) on the external surfaces was set, under the freezer operational condition at the climatic classes – 25 °C / 60% R.H. and 32 °C / 65% R.H. After characterizing the sweating zones, a parametric study was carried out to evaluate different thermal insulation properties e thicknesses. The computational modeling considered a 3D model of a simplified static refrigerator. Heat conduction on the refrigerator walls, as well as natural convection and radiation inside the cavity was considered. DP of the external surface of the refrigerator was determined from the psychometric analysis of the ambient condition.

1.1 External sudation – review in refrigerators

The open literature does not present many scientific works focusing on the study of condensation in refrigerators. These studies are reportedly thought to have been created by the major household and commercial refrigeration corporations, who restrict the revelation of their innovations for strategic purposes.

The formation of condensate on a vertical surface is mathematically and experimentally evaluated by Zheng et al. (2018), with an emphasis on heat and mass transfer related to the vapor-liquid phase transition process.

Models for individual droplet heat transfer and droplet size distribution, as well as the multimode dropwise condensation, were thoroughly examined by Zhang et al. (2022). The authors also investigate at other droplet distribution models, such droplet jumping as well as how different materials characteristics, as smooth, hydrophobic, or superhydrophobic surfaces, affect these processes.

Despite the numerous problems caused by the presence of this condensate in the external region, a portion of the identified literature is focused on the study of the transport of humid air and its condensation inside the refrigerator, evaluating its impact on the performance and consumption of the refrigerator (Onrawee Laguerre 2010; Stein et al. 2002).

Additional works primarily focus on decreasing condensation on refrigerator doors, analyzing the effectiveness of utilizing resistors as heaters, and estimating the impact on equipment energy consumption (Humar et al. 2022). The authors determined the resistance power required to avoid undesired sweating by estimating the DP temperature. As a result, it was possible to adjust the resistance value in accordance with the environment, avoiding the installation of fixed resistors, reducing energy waste. D'Agaro, Croce, and Suzzi (2021) investigated the use of anti-fog films on glasses to reduce external sweating, which proved to be an advantageous alternative, reducing condensation on the modeled refrigerator doors by up to 50%. Nonetheless, due to the high chance of film detachment from the surface over time, as described by Rauss et al. (2008b), its implementation in large-scale industrial is difficult.

Additional studies examine the interior of the refrigerator, or even isolated pieces, such as the door. Nevertheless, no research was found during this evaluation, examining sweating on the exterior surface of the refrigerator, the characteristics of the flow in the interior chamber, or the materials utilized for thermal insulation. Hence, part of the studies associated to condensation focus on the analysis of the phenomenon itself, deepening into the physical theories of sweating formation, involving the transfer of heat and mass during the process. Other more specific works focus on evaluating the interior of the refrigerator, or even isolated parts, focusing on the door. However, during this review, no studies were found analyzing sweating on the external surface of the refrigerator, and the influence of flow in the internal cavity, as well as the materials used for thermal insulation.

In this perspective, the aim of this study is to contribute to the progress of external sweating analysis under varied operational settings of the refrigerator and in diverse external environment conditions.

2. METHODOLOGY

The methodology for the CFD analysis was implemented in three stages, with details presented in following paragraphs.

2.1 Numerical simulation

In the context of this work, the characterization of the flow dynamics inside the static cooler compartment under various operation circumstances requires the use of computer simulation (CFD). ANSYS R19.0 FLUENT® was considered as simulation tool. The chosen physical model is a commercial static triple-action refrigerator used to conserve ice and different frozen goods in addition to cooling beverages. In Figure 2, a sample market is displayed.

Figure 2. Commercial static triple-action refrigerator

The cabinet of the refrigerator is 553 mm in width and 1375 mm in height. Two 0.43 mm steel sheets and a 100 mm polyurethane wall acting as thermal insulation compose the walls. The inside walls behave as an evaporator, with an operating temperature range between +7 °C and -35 °C, depending on thermostat selection. The condensing unit of the refrigerator is located at the bottom of the appliance, which includes the compressor, condenser, and a fan.

The semicircle refrigerator door is completely foamed with polyurethane (thickness varying from 31 mm to 105 mm). An elastomer polymer gasket is used as insulation between the door and the cabinet to accomplish sealing with the cabinet.

In order to simplify the problem in this work, several assumptions were made. Internal air is a Newtonian and incompressible (Mach number < 0,3). Flow is steady, and inside the cabinet, it occurs due to natural convection. Boussinesq’s hypothesis is considered, i.e., only the gravity term of the momentum equation accounts for density variations; the effects of density variations in other terms are disregarded (Mayeli and Sheard, 2021). Constant thermophysical properties, apart from density. The indoor air is dry, then, there is no presence of water in the vapor phase. Non-slip condition on the refrigerator's internal walls. Constant evaporator temperature over the entire surface. Uniform air temperature and heat transfer coefficient by external convection. Internal energy generation is zero, and viscous dissipation will be disregarded, due to the low internal air velocity in the cooler (Bejan 2004). Since the DP is largely dependent on the external pressure (Gatley 2013), it is assumed that the model is situated in an environment with standard air pressure (101.325 kPa).

Along with conduction and convection, radiation is another mode of heat transfer taken into account in this analysis due to internal surfaces radiate heat into the medium, which in this case is air, and influences rate of energy transferred between the thermal insulation and the environment (Bayer et al., 2013; C. Zhang and Lian, 2014). The Discrete Ordinates

(DO) method developed by Chui and Raithby (1993) was used in computational modeling to simulate the coupling of radiation with convection.

The governing equations were reduced in relation to the aforementioned assumptions. These equations are the conservation of mass, momentum (decomposed in Cartesian coordinates) and energy, respectively (Kundu, Cohen, and Dowling 2016).

$$\nabla.(\rho \overrightarrow{V}) = 0 \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + g\beta(T - T_0) \tag{3}$$

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5}$$

where ρ ,$\vec{V}$, u, v, w, P, ν, g, β, T, T_0 and α are the density, velocity vector, x component of velocity, y component of velocity, z component of velocity, pressure, gravity acceleration, volumetric thermal expansion coefficient, temperature, reference temperature and thermal diffusivity, in this sequence.

The 3D drawing was modelled via ANSYS DesignModeler®. The geometry of the gasket is complex, thus, the gasket was modelled as a parallelepiped with internal air for simplicity, according to the study of Boughton et al. (1996). The model was considered as symmetric, in order to reduce the computational cost. As a result, the analyses will be carried out taking into account half of the geometry. Söylemez et al. (2021) also took this simplification into account in their research. Then, the interior air is part of the fluid domain; foam door, gasket, and the polyurethane cabinet insulation are included in the solid domain.

ANSYS Meshing® was used to mesh the geometric model. An unstructured grid of tetrahedral elements was built for the indoor air and rest of the geometry, except the gasket, being was structured meshed with hexahedral elements, which is shown in Fig. 3. For the analysis accurate predictions, the quality of the mesh was also checked considering the element metrics of orthogonal quality and skewness. If the average values for the orthogonal quality is 0,95 and skewness, 0,25, they are considered excellent (ANSYS, 2020). According to the values reached, the mesh quality is considered to be at the desired level.

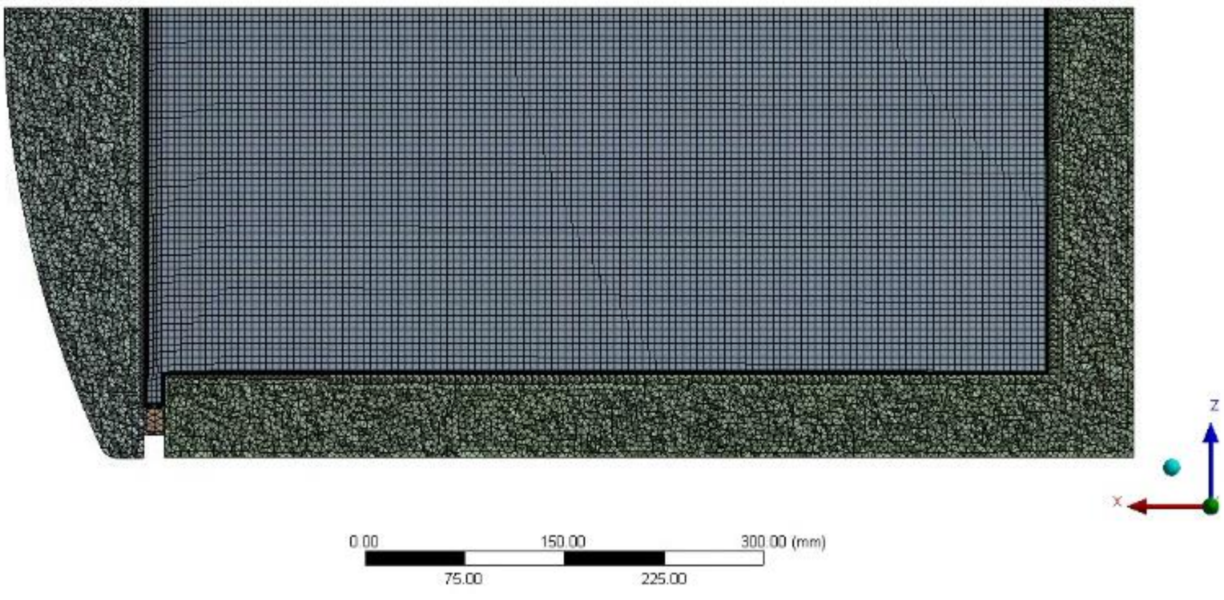


Fig 3. Computational mesh.

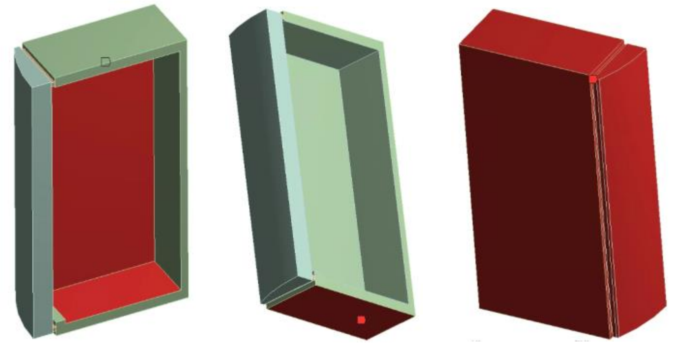
In order to close the Navier-Stokes equations, the computer modeling in this study considered the k-SST model – same used during the numerical validation. The k-ω SST (shear-stress transport) model, proposed by Menter (1994), merges a robust formulation of the Standard k-ω model in the region close to the wall, with the consistent expressions of the Standard k-ε model in the far region from the wall.

The locations of boundaries conditions are demonstrated in Fig. 4, and are presented in the next paragraphs. Materials properties are presented in the Table 1.

A prescribed temperature condition of -35 °C (data provided by the manufacturer) was defined on the side, roof and bottom of the tank (Fig. 4a), being the evaporator average temperature during the ON and OFF cycle of the compressor.

For the purpose of simplification, the condensing unit was not modeled. Then, at the lower outer bottom of the geometry, a boundary condition of convective heat transfer fixed a temperature of 50 °C (Fig. 4b), provided by the manufacturer, with an average convective heat transfer coefficient equal to 2.3 W/m².K (Gowreesunker et al.,2014b).

Only the heat transfer by natural convection between the refrigerator's exterior and the surrounding air was taken into account. This same strategy was adopted by Ding et al. (2004). According to Gowreesunker et al. (2014), the convective boundary condition defined in the model, considered an average convective heat transfer coefficient equal to 1.1 W/m².K for the external door and 1,4 W/m².K for the side walls and ceiling (Fig. 4c).



(a) (b) (c)

Figure 4. Model boundary conditions.

Table 1. Materials properties.

Materials	***ρ* [kg.m^{-3}]**	***C_p* *[J.kg^{-1}.K^{-1}]***	***K* *[W.m^{-1}.K^{-1}]***	***β***	***Absorption Coefficient [m^{-1}]***	***Refractive Index***	***References***
Air	1,478	1006,2	0,0213	0,0042	0,0	1,0	(Moran et al. 2003)
Polyurethane	34,5	1460,0	0,0212	-	0,9	1,67	(Baillis and Sacadura 2002; Merillas et al. 2022)
Elastomer	1200,0	1600,0	0,15	-	0,9	1,0	(Gao 2015)
Steel	7850,0	477,0	50,0	-	0,9	1,0	(Raznjevic 1976)

The external sweating areas were identified in each ambient condition (25°C / 60% R.H. and 32°C / 65% R.H.). For this purpose, the DP was calculated according to the methodology defined by Lawrence (2005).

2.2 Numerical validation

The main objective of the second stage was the verification of the setup defined for the numerical simulation, based on the numerical and experimental results obtained by Ben Amara et al. (2008), who explored the fluid dynamic behavior of a residential static refrigerator. PIV (particle image velocimetry) technology was employed to measure and assess the interior flow by the authors. In order to compare the outcomes, a numerical simulation of the appliance was also carried out. Between measured and estimated airflow profiles, there was a comparatively high degree of agreement.

A similar model was run, and the primary output that was studied at this stage was the y component of the velocity profile in the geometrical center of the model, as well as the minimum exterior temperature, a crucial variable to the overall goal of this effort. When there was a good match between the velocity data from each simulation and those acquired by the authors, the simulation was concluded. After a computational grid has been created, the GCI (Grid Convergence Index) technique (Roache, 1994) was utilized to confirm numerical discretization. The maximum and minimum internal velocity, in the middle of the axis of the plane of symmetry, and lowest exterior temperature were both obtained by the GCI at 0,3%, 1,8% and 0,01%, respectively. With a refining factor of 1.8, both are less than 2,2%, which is the methodology's maximum allowable level.

The simulations conducted in the preceding item were built up using the final geometry of the refrigerator and the setup which was defined and validated. The same velocity and temperature characteristics were determined once more between a fine, medium, and coarse mesh. A GCI of 0,2% and 0,02%, achieved correspondingly, showed a low level of uncertainty between the meshes built, allowing it viable to run it with an intermediary mesh, lowering computing costs.

2.3 Parametric study

The parametric research took into account modifications to both the refrigerator's operating circumstances and the properties of the thermal insulation materials.

The main elements investigated were the density and heat conductivity of the refrigerator's thermal insulation. First, the heat conductivity was reduced by 10% and 15% while keeping the density level unchanged. With no alterations in thermal conductivity, the second phase involved changing the polyurethane density by the same proportion. The operational state and the range of variation of the constructive parameters are comparable with standard operating methods employed by major refrigerator manufacturers.

The change in the dynamics of the flow inside the cavity was also examined in order to, for example, characterize the homogeneity of temperature in food refrigeration, in addition to the impact of these constructive parameters and operating circumstances on sweating.

3. RESULTS AND DISCUSSION

Ensight® was used to post-process the results. The condensed external zones in each environmental state as well as the internal velocity profile were the key outcomes studied. Following the results of each case's parametric studies, the initial output was also assessed. The regions below the DP (289,85 K for 25 °C / 60% R.H. and 297,75 K for 32 °C / 65% R.H.) are correspondingly depicted in Figs. 5 and 6. In these illustrations, an isometric, inferior and back view are presented. The temperature profile along these zones was also plotted to determine the coldest areas. Initially, it was anticipated that sweating zones would be more common at 32 °C / 65% R.H. than they would be at 25 °C / 60%. On the one hand, while the DP rises in the worst-case scenario, on the other hand, the material attributes in this initial comparison remained constant. As a result, areas that were highlighted as sweating in the worst instance were those that could have been regarded warm in the first instance.

These results show that, in both scenarios, the exterior region exhibits extensive regions of condensation. Since the convective heat transfer coefficient in those areas tends to climb with increasing velocity, the top, front, and rear of the cabinet all showed higher velocity gradients, compared to the bottom, which increased the heat transfer owing to convection in those areas. Velocity profiles in both conditions are presented in the Fig. 7.

The gasket was the region most impacted in percentage terms, with 92% of its total area below the DP at 25 °C and 96% for 32%. The primary reasons of condensation in this zone are its high thermal conductivity relative to other materials and substantial convective heat transfer coefficient.

At 25 °C, the door showed 70%, and the cabinet 78% of their areas below the DP; at 32 °C, this percentage rose to 79% and 84%. The door insulation thickness varies along the perimeter due to its semi-circular shape (the closer the door is to the edge, the thinner the thickness). The dew band zone that forms and grows from the center to the edges is justified by this. The insulating length at the back and sides, however, is flat and continuous.

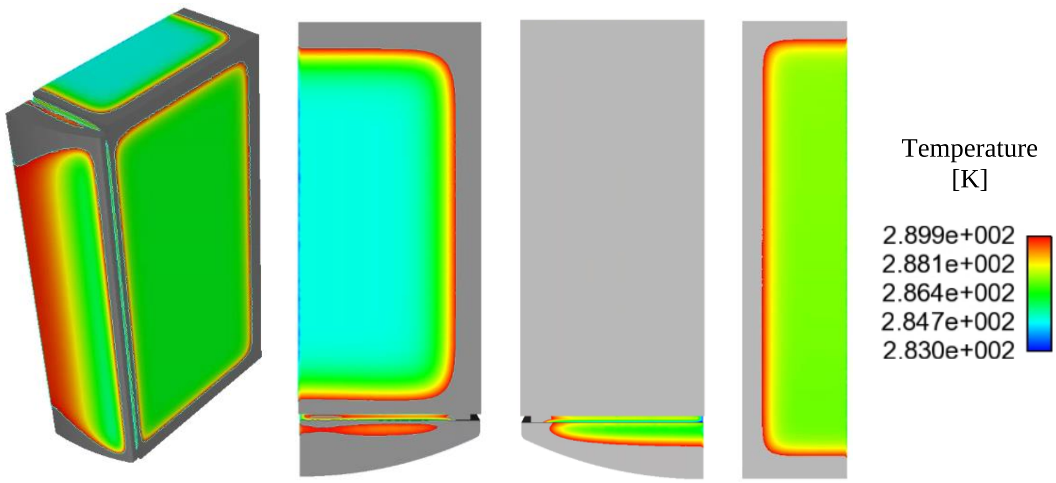


Figure 5. Sweated areas at 25 °C / 60% R.H.

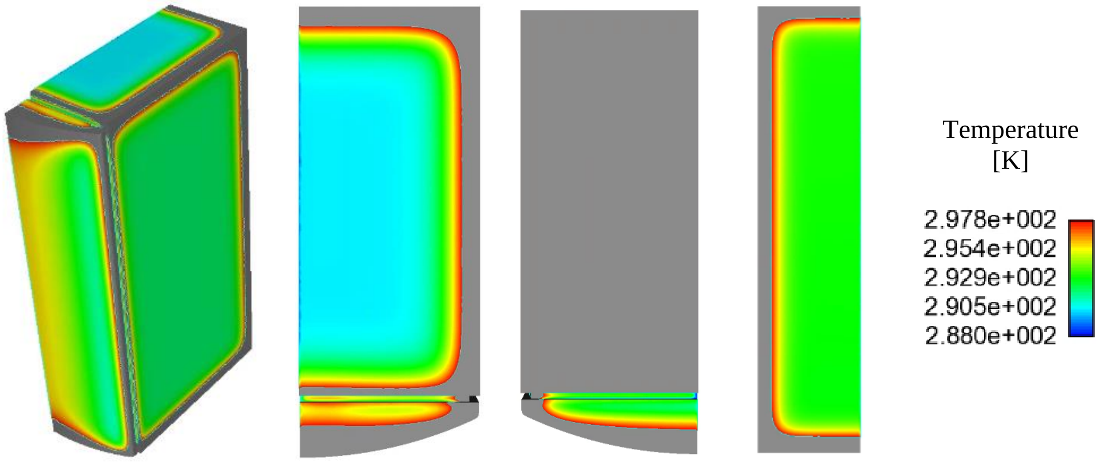


Figure 6. Sweated areas at 32 °C / 65% R.H.

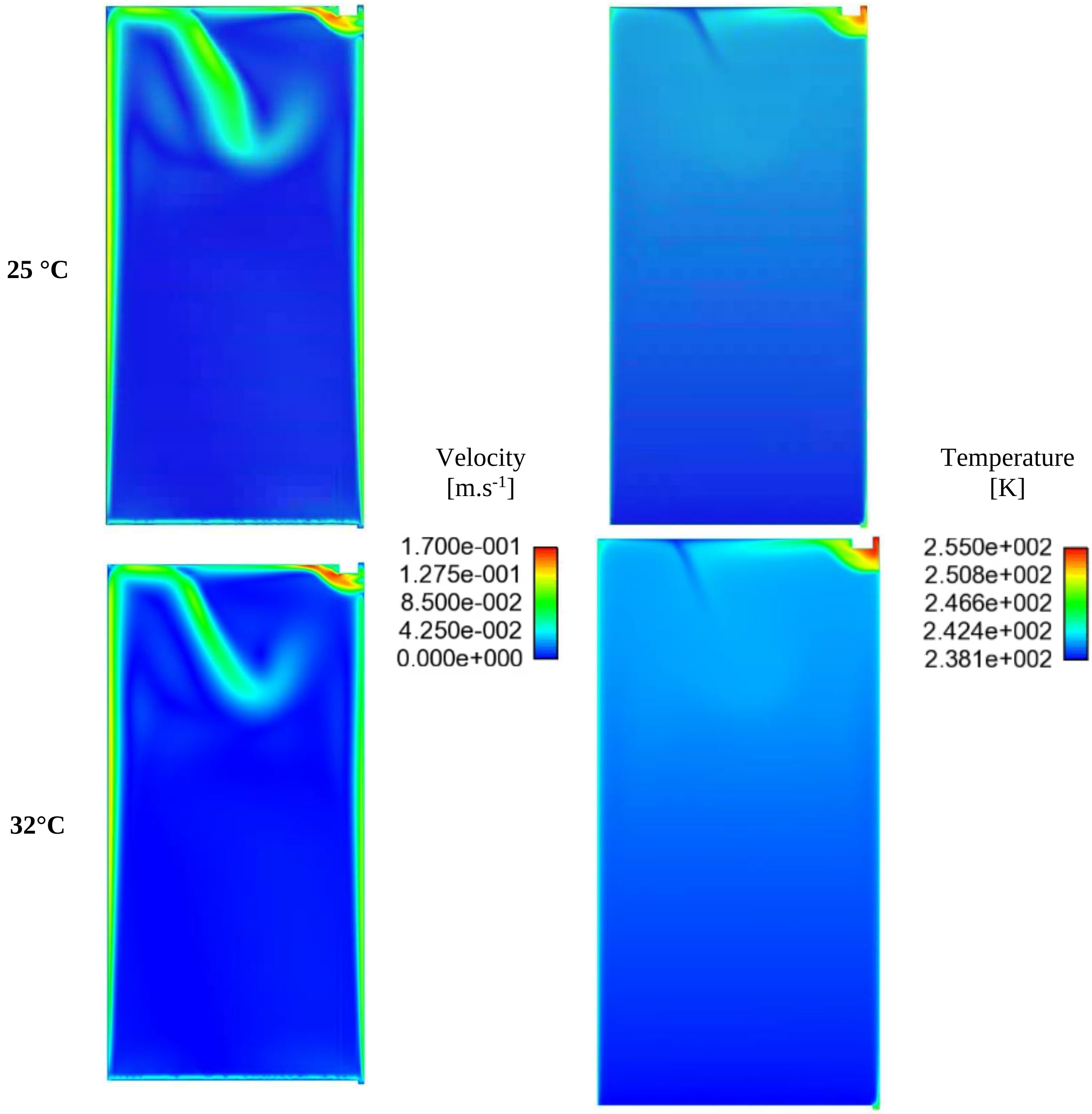


Figure 7. Air velocity and temperature distribution inside the refrigerator.

The results of the parametric study performed are presented in the Figs. 8, 9 and 10. The thermal conductivity variation shown which, despite the low reduction in the total external area under the DP, there was an increasing of the average external surface temperature of the refrigerator. At the initial setup, 295,0 K was attained for the cabinet. After the 10% reduction, it achieved 295,8 K, and for a 15% decrease, it achieved 296,3 K. The average temperature of the external door firstly stood at 294,6 K, rising to 295,4 K and 296.0 after 10% and 15% insulation variation, respectively. Notwithstanding, the density variation has not brought any notable advancements. The average surface temperature was maintained at 295,0 K and 294,6 K on the cabinet and door, correspondingly, even with the density variation. As a result, it was established that adjusting density while keeping thermal conductivity constant proved ineffective for reducing dew zones. This result is in accordance with various studies (Jarfelt and Ramnäs, 2006; H. Zhang et al., 2017) in improvement in properties of polyurethane, which focus on its thermal conductivity reduction, despite of the fact that, these researches also shows that the foam density is a key factor to the resultant thermal conductivity.

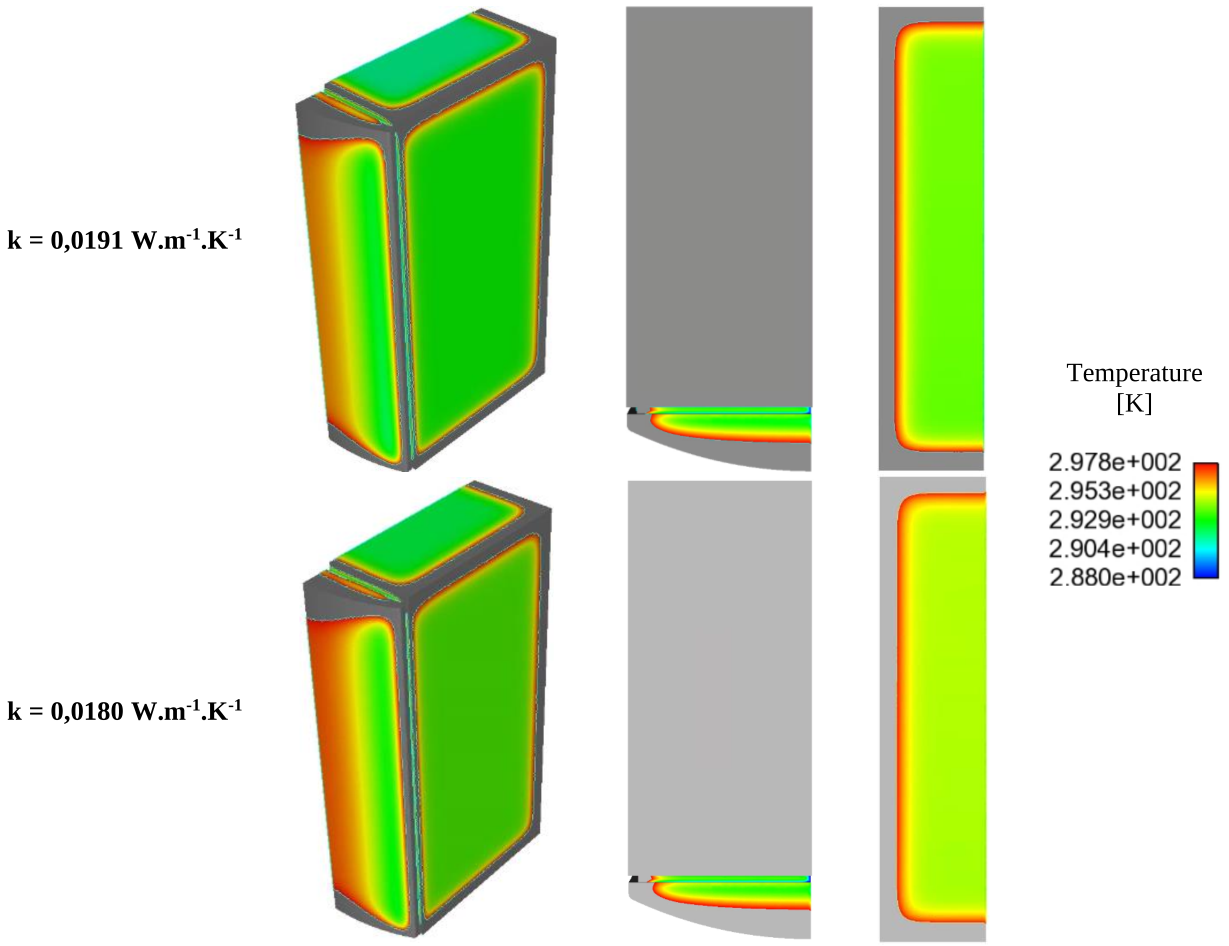


Figure 8. Sweated areas at 32 °C / 65% R.H. after thermal conductivity variation.

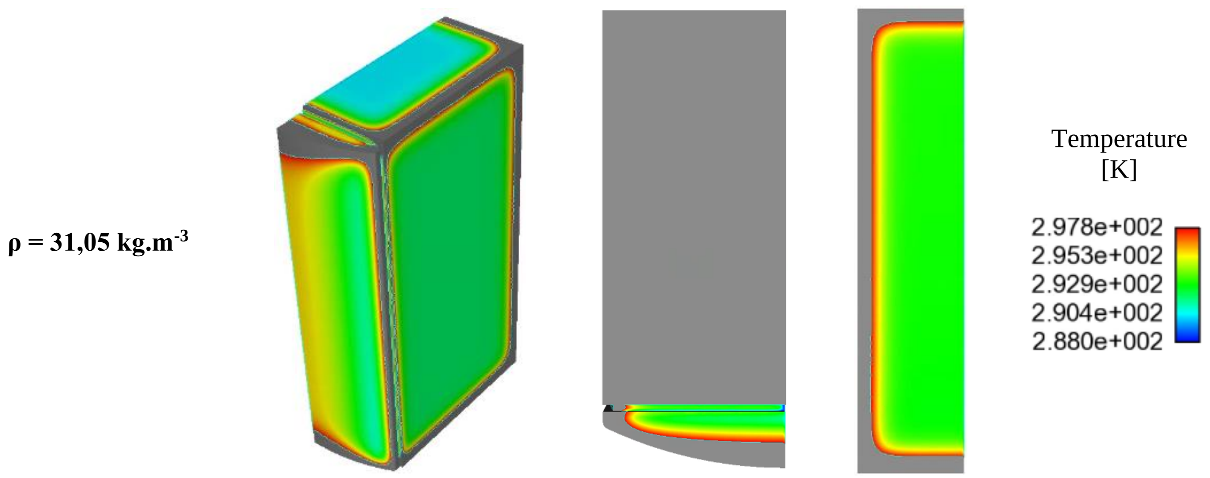


Figure 9. Sweated areas at 32 °C / 65% R.H. after a 10% reduction at polyurethane density.

ρ = 29,33 kg.m^{-3}

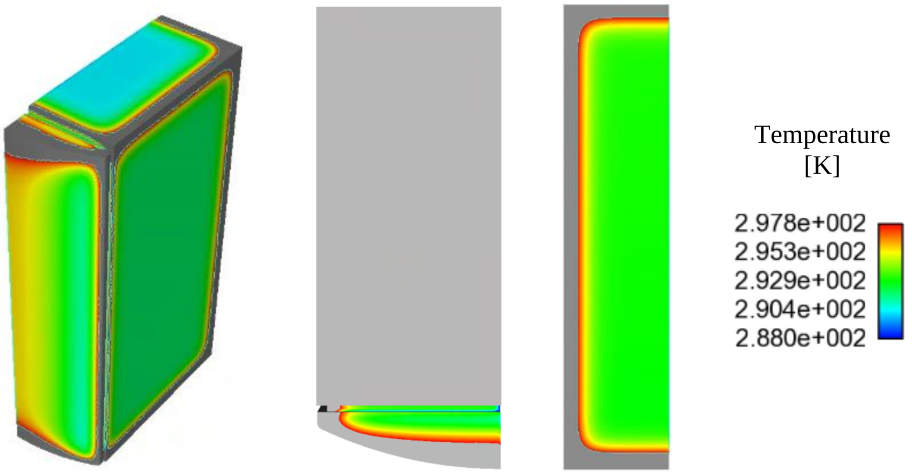


Figure 10. Sweated areas at 32 °C / 65% R.H. after a 15% reduction at polyurethane density.

4. CONCLUSION

In this current work, a simulation study was conducted through CFD analysis to predict the dew zones of a static refrigerator at two different environment conditions. The impact of the insulation's density and heat conductivity in the condensation zones was investigated through a parametric analysis. From the most intense to the least intense, all exterior surfaces in the cabinet, door, and gasket were impacted. The door semi-circular shape and wall insulation thickness are directly related to the outcomes. The exterior surface temperature profile was influenced by changes in the ambient temperature and relative humidity. The results of the parametric study demonstrated that, in order to raise the refrigerator's average exterior temperature, a thermal conductivity decrease is more effective than density optimization. The results of this experiment were derived from a particular refrigerator type and dimension. A noteworthy aspect of this study is the development of a scientific approach and assessment that would allow the academy to get these characteristic values for other cooling appliances, even if the numerical findings obtained from other refrigerators are projected to differ from the current research.

5. ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to the professors at Unesp – Sao Paulo State University "Julio de Mesquita Filho" of Department of Thermal Sciences, for their insightful and helpful suggestions throughout the planning and development of this research work. We are really grateful for their willingness to offer their time in such a great manner. We thank the staff and colleagues at Unesp for offering technical support and other resources throughout the project.

6. REFERENCES

ANSYS, I., 2020. *Ansys R18.1 Fluent*. ANSYS, Inc, Canonsburg.

Ben Amara, S. et al, 2008. "PIV Measurement of the Flow Field in a Domestic Refrigerator Model: Comparison with 3D Simulations." *International Journal of Refrigeration* 31(8): 1328–40.

Baillis, D, and J. F. Sacadura, 2002. "Identification of Polyurethane Foam Radiative Properties — Influence of Transmittance Measurements Number." *Journal of Thermophysics and Heat Transfer* 16(2).

Bayer, Ozgur, Ruknettin Oskay, Akin Paksoy, and Selin Aradag, 2013. "CFD Simulations and Reduced Order Modeling of a Refrigerator Compartment Including Radiation Effects." *Energy Conversion and Management* 69: 68–76.

Bejan, Adrian, 2004. *Convection Heat Transfer*. 3rd edition. New York: Wiley.

Ben-Yehoshua, Shimshon, and Victor Rodov, 2002. "Transpiration and Water Stress." In *Postharvest Physiology and Pathology of Vegetables*, Boca Raton: CRC Press, 111–59.

Boughton, Brian E., Arthur M. Clausing, and Ty A. Newell, 1996. "An Investigation of Household Refrigerator Cabinet Thermal Loads." *HVAC and R Research* 2(2): 135–47.

Chui, E. H., and G. D. Raithby, 1993. "Computational of Radiant Heat Transfer of a Non-Orthogonal Mesh Using the Finite-Volume Method." *Numerical Heat Transfer, Part B: Fundamentals* 23:3: 269–88.

D'Agaro, P., G. Croce, and N. Suzzi, 2021. "CFD Simulation of Anti-Fogging Coatings Performance in Refrigerated Display Cabinets." *Journal of Physics: Conference Series* 1868(1).

Ding, Guo Liang, Hong Tao Qiao, and Zhi Li Lu, 2004. "Ways to Improve Thermal Uniformity inside a Refrigerator." *Applied Thermal Engineering* 24(13): 1827–40.

Gao, F., 2015. “*Numerical Simulation of Heat Leakage At Gasket Region Of Domestic Refrigerators*". Clemson University.
Gatley, D. P., 2013. *Understanding Psychrometrics*. 3rd edition. Atlanta: ASHRAE.
Gowreesunker, B. L., S. A. Tassou, and A. H. Raeisi, 2014. “Numerical Study of the Thermal Performance of Well Freezer Cabinets.” *Refrigeration Science and Technology* (January): 351–58.
Humar, Iztok, Uroš Hudomalj, Alexander Marinšek, and Mark Umberger, 2022. “Optimizing the Power Usage of Anti-Sweat Heaters in Glass-Door Refrigerators According to the Dew Point.” *Energies* 15(13): 4601.
IBGE, 2019. SIS - Síntese de Indicadores Sociais. IBGE. Rio de Janeiro. https://www.ibge.gov.br/estatisticas/sociais/saude/9221-sintese-de-indicadores-sociais.html?edicao=30983. Accessed in 02 May 2023.
IEA, 2022. Worldwide average household ownership of appliances and number of households in the Net Zero Scenario, 2000-2030. IEA. Paris. https://www.iea.org/data-and-statistics/charts/worldwide-average-household-ownership-of-appliances-and-number-of-households-in-the-net-zero-scenario-2000-2030. Accessed in 06 May 2023.
Jarfelt, Ramnäs, 2006. “Thermal Conductivity of Polyurethane Foam - Best Performance Thermal Conductivity of Polyurethane Foam Best Performance.” 1*0th International Symposium on District Heating and Cooling*.
Kundu, Pijush K., Ira M. Cohen, and David R. Dowling, 2016. *Fluid Mechanics*. 6th edition. London: Elsevier.
Laguerre, O., S. Benamara, and D. Flick, 2010. “Study of Water Evaporation and Condensation in a Domestic Refrigerator Loaded by Wet Product.” *Journal of Food Engineering* 97(1): 118–26.
Laguerre, Onrawee, 2010. “Heat Transfer and Air Flow in a Domestic Refrigerator.” In *Mathematical Modelling of Food Processing*, ed. Mohammed M. Farid. Boca Raton: CRC Press, 453–82.
Lawrence, Mark G, 2005. “The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications.” *Bulletin of the American Meteorological Society* 86(2): 225–33.
Mayeli, Peyman, and Gregory J. Sheard, 2021. “Buoyancy-Driven Flows beyond the Boussinesq Approximation: A Brief Review.” *International Communications in Heat and Mass Transfer* 125(May): 105316.
Menter, F. R., 1994. “Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications.” *AIAA Journal* 32(8): 1598–1605.
Merillas, Beatriz, Judith Martín-De León, Fernando Villafañe, and Miguel Ángel Rodríguez-Pérez, 2022. “Optical Properties of Polyisocyanurate–Polyurethane Aerogels: Study of the Scattering Mechanisms.” *Nanomaterials* 12(9).
Moran, Michael J., Howard N. Shapiro, Bruce R. Munson, and David P. DeWitt, 2003. John Wiley And Sons. *Introduction to Thermal Systems Engineering Thermodynamics, Fluid Mechanics, and Heat Transfer*.
Rauss, Devin, Scott Mitchell, Faramarzi, and Southern California Edison, 2008. “Cool Retrofit Solutions in Refrigerated Display Cases.” In *ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove: ACEEE, 233–44.
Raznjevic, Kuzman, 1976. *Handbook of Thermodynamic Tables and Charts*. ed. McGraw-Hill Interamericana. Washington: Hemisphere Pub. Corp.
Roache, Patrick J., 1994. “Perspective: A Method for Uniform Reporting of Grid Refinement Studies.” *Journal of Fluid Engineering* 116: 405–13.
Söylemez, Engin, Emre Alpman, Ayhan Onat, and Hartomacıoğlu, 2021. “CFD Analysis for Predicting Cooling Time of Domestic Refrigerator with Thermoelectric Cooling System.” *International Journal of Refrigeration* 123: 138–49.
Statista Search Department, 2023. Revenue of the refrigerators industry Worldwide 2018-2028 (in millions). Statista. https://www.statista.com/statistics/1124245/refrigerator-unit-sales-worldwide/. Accessed 12 May 2023.
Stein, Mark A., Cemil Inan, Clark Bullard, and Ty Newell, 2002. “Closed Door Moisture Transport in Refrigerator/Freezers.” *International Journal of Energy Research* 26(9): 793–805.
Volpe, Stefania et al., 2018. “Condensation and Moisture Regulation in Packaged Fresh-Cut Iceberg Lettuce.” *Journal of Food Engineering* 216: 132–37.
Zhang, Chaolei, and Yongsheng Lian, 2014. “Conjugate Heat Transfer Analysis Using a Simplified Household Refrigerator Model.” *Energy Economics* 45(2009): 210–22.
Zhang, Hu, Wen Zhen Fang, Yue Ming Li, and Wen Quan Tao, 2017. “Experimental Study of the Thermal Conductivity of Polyurethane Foams.” *Applied Thermal Engineering* 115: 528–38.
Zhang, Tian Yu, Lin Wei Mou, Min Jie Liu, and Li Wu Fan, 2022. “Advances in Modeling Investigations of Multimode Dropwise Condensation Heat Transfer on Smooth and Textured Surfaces – A Review.” *International Journal of Thermal Sciences* 172.
Zheng, Shaofei et al., 2018. “Modeling of Heat and Mass Transfer for Dropwise Condensation of Moist Air and the Experimental Validation.” *International Journal of Heat and Mass Transfer* 120: 879–94.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.