

Thermal Simulation of a Supermarket Cold Zone with Integrated Assessment of Human Thermal Comfort

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Abstract. This work seeks to analyze the thermal comfort of the occupants in a large building of Commerce and Services, integrating measures of assessment and energy efficiency promotion. The building is still in the construction phase and at its conclusion, will correspond to a supermarket located in the Central region of Portugal. For the evaluation of thermal comfort, Fanger's methodology was used, where the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) were calculated based on a detailed analysis of the environmental variables. These are essential to obtain, namely, mean air velocity, mean radiant temperature, mean air temperature and relative humidity. The other crucial variables are the metabolic rate and the thermal clothing resistance. The simulations necessary for the thermal comfort assessment were performed in ANSYS Fluent, in order to minimize the energy consumption in the cold thermal zone of the building, the sales area with frozen and chilled food, by means of reducing the inflow of air, without compromising thermal Comfort. The final results showed that the reduction of the amount of air to be inflated did not compromise the thermal comfort of the occupants. The Computational Fluid Dynamics (CFD) methodology allowed the creation of comfort maps, albeit for a single zone due to computational limitations. According to the results, the most comfortable zone was located right below the air insufflation with the summer being a more comfortable season. In winter, the main problem detected was the cold located near the floor.

Keywords: Thermal comfort · Supermarket · Computational Fluid Dynamics

1 Introduction

At the present time, the European Union (EU) faces an increasing energy demand, with volatile prices. The EU is the largest energy importer in the world, corresponding to about 53% of its energy supply and is dependent on a limited number of countries to fulfill their requirements of energy [1]. In this sequence, the European Union is focused on developing a policy that will ensure smart, sustainable and inclusive growth for the

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12254, pp. 214–227, 2020.
https://doi.org/10.1007/978-3-030-58817-5_17

next decades, giving particular attention to the construction sector with significant energy consumption [2].

Allied to this environmental need and knowing that in industrialized countries Humans spend 90% of their time on enclosed spaces [3], the existence of an appropriate thermal environment is one of the determining factors for productivity, prolonged health and well-being [4]. In retail buildings, providing a comfortable environment is essential. When people are comfortable, they tend to spend more time inside the store and are more prone to purchase [5]. In order to provide a comfortable thermal environment, Heat Ventilation and Air Conditioning (HVAC) systems are installed. The managing of these systems is mostly related to the heat balance between the supermarket and the external thermal environment, changing mostly during the extreme seasons, namely, Winter and Summer.

While the indoor environment of Supermarkets is mostly the same, the freezing section presents a challenge while managing the HVAC systems. On one side there is the need to ensure the thermal environment, on the other side, these systems need special configuration to deal with the cold felt due to the freezers. The low temperatures are essential to preserve the food and ensure its quality. However, the cold that they cause must be balanced by the HVAC systems which generally translates in increased use of energy [6]. Finding the balance point where thermal comfort is available to the costumers and at the same time spending the lowest amount of energy is the objective of the HVAC management [7].

Thermal environment can be assessed using the thermal balance principle for which, the heat gained and generated by the human body is lost in the same amount to the environment. In a situation of thermal comfort, it is assumed that the human body is in thermal balance, which means that the heat flux produced and received by the organism is equal to the heat flux given by the organism to the surrounding environment. However this condition of thermal neutrality is not sufficient by itself since localized thermal discomfort phenomena such radiation asymmetry, draught or thermal gradients between head and ankle greater than 3 °C can occur [8]. When thermal comfort is not assured problems may occur to the individual, like poor interpersonal relationships, absenteeism, demotivation and low productivity [9]. In order to translate the thermal balance to an understandable scale, several thermal indices which correlate thermal variables and sensation were created. Among those, Fanger numerical index has been widely applied, by combining different environmental parameters, which can be divided into personal and environmental [4, 10]. The former consist of the metabolic rate and thermal insulation while the latter consist of air velocity, air temperature, relative humidity, and radiant temperature. The numerical index has significance in a scale of 7 points, ranging from −3 to +3, which can be related to the ASHRAE thermal sensation scale [11]. Accurately assessment of thermal comfort is not a simple task and in the case of supermarkets, Lindberg et al. (2017), pointed out that there are no recommendations on the indoor environment for the supermarket costumers [12]. Their study, performed in Sweden, presented measured and perceived comfort information on supermarkets, which can be used to prescribe suitable thermal environments for customers. The study measurements were carried out in functioning supermarkets, at summer and winter in front of twelve display cabinets, containing cold products, with over 1 100 questionnaires. Regarding the assessment of thermal comfort, the authors

concluded that the Predicted Mean Vote (PMV) index can be used to prescribe a suitable thermal environment for customers. Additionally, it was observed that the environmental temperature surrounding a person has more influence on the thermal comfort than the vertical gradient of temperatures.

Alfano et al. (2019) studied the thermal comfort in supermarket refrigerated areas in central Italy [13]. The authors used the PMV index along with the Insulation Required (IREQ) and surveys to assess the thermal comfort of this section. In this study, the gradient temperatures showed a greater effect in the thermal environment, with women feeling generally more uncomfortable. Authors pointed out the difference in using clothing with less insulating, like open lady shoes. The difference in the obtained results is mainly due that the stratification in the cold areas, which are the focus of the study. Regarding the costumers PMV value, both in summer and winter was below −2 (Cold). The IREQ index pointed out the risk of cold exposure for the costumers in two zones, for exposition duration of about 40 min in summer and above 1 h in autumn. Since the costumers do not stay very long in the refrigerated areas, their safety is not at risk.

Accurately mapping the indoor environment is an exhaustive task. The area of study can be wide and have thermal contributions from different sources, such as the freezers. These types of equipment operate by removing heat from their chambers and moving it to the environment through an Inverted Carnot cycle. In this way, they work as a source of heat in the compressor and localized cold in the products' chamber. The latter cannot have good insulation since the products have to be in the costumers' field of view to ease the access and stimulate purchase. This leads to the mixture of cold air with the environment, reducing its temperature. Knowing the thermal environment for this situation is especially useful to achieve a balance between an attractive display of products and a thermal efficient refrigeration system.

Mukhopadhyay and Haberl (2014), studied the energy consumption in grocery stores located in hot humid climate by implementing Energy Efficiency Measures (EEM) [14]. The authors focused on four categories, which include the building envelope; lighting and daylighting; HVAC; Service Hot Water (SHW) systems; and refrigeration systems, performing a whole-building energy simulation. Regarding the HVAC category, the savings for site energy were between 0.2% to 12.1%, making it the second point with biggest savings, surpassed only by the savings in the refrigeration systems with for site energy savings between 0.1% to 16.9%. The results show that these two categories have great potential to promote energy savings. The overall site energy savings were of 57.9% when implementing different EEM.

Ideally, the thermal environment assessment should be performed prior to the construction phase, which allows applying constructive measures, avoiding several costs. On the other side, without a physical medium, the assessment of the thermal environment is inadequate. A recent review study performed by Lindberg (2020), showed the complexity of the thermal assessment in supermarkets, pointing out that multiple studies are necessary as a single study cannot provide a complete set of data [15].

In this regard, predictive methods, such as computer simulation are a crucial tool because it allows a rigorous analysis of the place to be studied, with the possibility of correcting risk factors and thermal discomfort. These methods have proven to be a great

tool for studying in detail the thermal environment [16–18]. In this perspective, computational energy simulation of buildings is an important tool nowadays. Regarding the supermarkets case, Raimondo et al. (2015) used the Energy Plus, a simulation Software, to create a model of a retail floor ventilation system and microclimate. The authors used simulation to delineate improvements for the building control systems, monitoring the results, which showed good agreement. The average energy saving that this methodology offered for the year of 2013 was of 24% [19].

Parpas et al. (2017) conducted a study of the air temperature distribution for chilled food processing areas using numerical simulation [20]. The authors verified a difference of only 5.3% between the experimental and the numerical data for the hourly energy consumption. A numerical simulation was also used in the assessment of the thermal environment for the chilled food manufacturing unit by Parpas, Amaris, and Tassou (2017) [21]. Al-Saadi and Zhai (2018) used CFD to evaluate the impact of three air distribution scenarios for supermarket display cases. The authors aimed to assess the energy efficiency of the different cases, considering the effects on costumers' thermal comfort. The computational simulations allowed the determination of the air flow pattern and temperatures. It was verified that the displacement ventilation, located on the supermarkets' aisle side, offered enhanced thermal comfort for the occupants, with improved energy performance for the vertical displays [22].

Numerical simulation is a tool that allows the numerical reproduction of a real case and to evaluate its thermal behavior. With this tool it is possible to consider several parameters such as environmental factors, occupancy rate, characteristics of the materials used in the building construction, air conditioning systems, etc. Also provides a way to change several thermal parameters and assess their influence on thermal comfort, without the costs of physical experimentation. Additionally, numerical simulation also allows the detailed mapping of the environmental variables. The combination of these advantages makes the simulation a great tool to assess the supermarket refrigerated area, giving insight into the thermal conditions, allowing a better understanding and management of the thermal environment.

2 Case Study

The study objective was to evaluate the thermal environment in the cold zone of a supermarket, by applying a numerical simulation methodology. With the simulation, the authors intended to assess the thermal comfort of the users and to reduce the energy consumption in this area. The chosen method, due to its ease of implementation, was to reduce the input of air flow. The developed model was accomplished using ANSYS Fluent with a CFD simulation.

2.1 Building Description

The building in the study is located in the district of Aveiro, Portugal. At the time of the study, it is still under construction and it will be a supermarket. The building comprises of three floors (Fig. 1). The Floor −1, below ground level, will have a technical space and a parking area. The second floor, identified as Floor 0, consists of the spaces

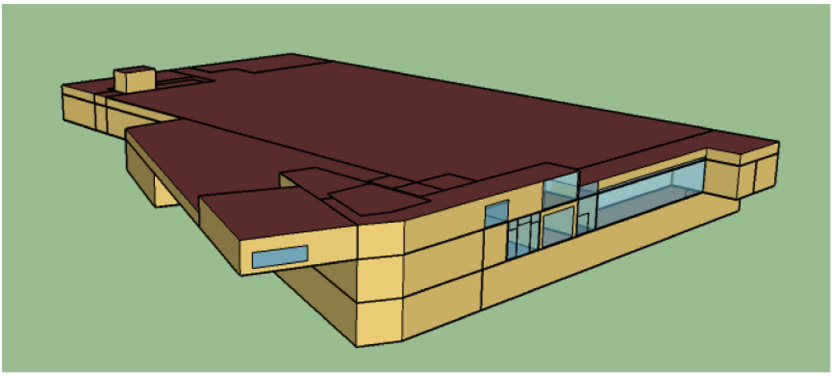


Fig. 1. Exterior view of the 3D modeling of the building.

affected by the commercial/sales area, where customers access the services authorized by the Supermarket policies. Also, this floor will have technical spaces, warehouses, toilets, a coordination room and a garage. The third floor, defined as Floor 1, will consist of a training room, a break room, changing rooms, toilets and technical spaces.

2.2 Simulation Study

The assessment of the thermal environment in the supermarket was performed with ANSYS Fluent. However, due to hardware resources limitations, some simplifications were necessary, such as in the geometry details and zone size. Since the cold section presented the most complex environment, the study was focused on that specific sector. Due to its size and symmetry, the simulation was performed on a fraction of the area, allowing to greatly decrease the computational time. The created geometry is a simplification of the real cold zone. The two parallelepipedal geometries represent two refrigerated murals and the external faces are symmetries, defining a fictional wall that separates a portion of the cold zone. Fig. 2 (a) shows the 3D modelling of this zone, including a diffuser to blow air at the top and an exhaust grid at the corner. For the volume discretization, the domain was divided into smaller and simpler geometries that allowed the creation of a hexahedral mesh. Once performed the mesh independency test, the obtained discretization is represented in Fig. 2 (b) with a total of 2 217 324 elements. The mesh aspect ratio was 1.0755 with the value of 1 being ideal, and a skewness near 0, which is ideal.

Setup. The mass continuity equation and the Navier-Stokes equations for the fluid flow were solved by the Realizable k-ε turbulence model. Additionally, since the focus was the simulation of thermal comfort, the energy equation and the surface to surface (S2S) radiation models were added. The former equation included the simulation of temperature while the S2S model was used to simulate the heat transfer through radiation. The final environmental parameter, the relative humidity, was simulated through the use of the species transport for multiphase flow where the air was defined as a mixture of nitrogen, oxygen and water vapor.

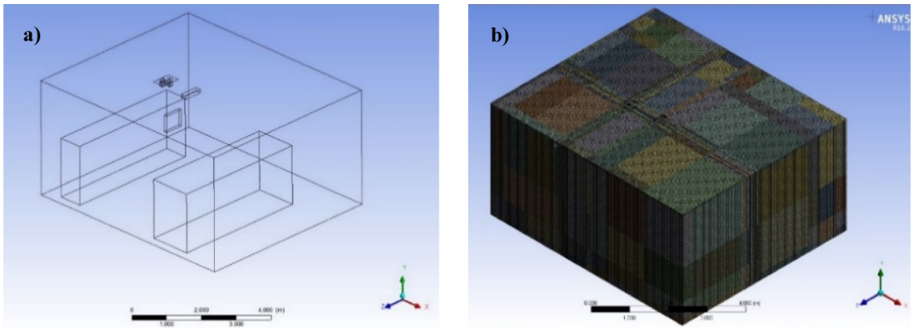


Fig. 2. CAD design of CFD model (a) and mesh of CFD model for simulation (b).

Boundary Conditions. The conditions that define the thermal environment are mostly governed by outside environmental conditions. For this reason, two sets of boundary conditions, one for summer (22nd August), and other for winter (21st January) were defined, differing in the conditions of air insufflation and gains/losses across the boundaries. The objective of CFD was to optimize the insufflation conditions and thus the energy consumption of the sales area, adopting a strategy of evaluating thermal comfort only in an area of interest. In other words, an attempt was made to establish a trade off that would guarantee a reduction in the insufflation flow and thus a reduction in the thermal power of the rooftops, but that would not compromise the thermal comfort in locations with human presence. The area of established interest corresponds to an area limited horizontally by the refrigerated murals and vertically by a horizontal plane that has a height of 1.85 m from the ground, in the area that is affected by human presence. Table 1 and Table 2 represent, respectively, the different types of boundaries used in the model to be simulated, for both winter and summer conditions. In these simulations, the air insufflation was defined as 15% lower than the initial projected and with a minimum insufflation rate of 855 m^3/h. The values presented on in the tables were estimated based on the common characteristics for the materials and data from other supermarkets.

Table 1. Boundary conditions used in the CFD model for January 21.

Location	Boundary condition	Physical property		Material
Lamp	Wall	Heat flow	8.0 W/m^2	Glass
Roof	Wall	Heat flow	−5.3 W/m^2	Sheet metal
Floor	Wall	Heat flow	−5.1 W/m^2	Ceramic
Exterior wall	Wall	Exterior temperature	10.0 °C	Plaster
		Heat transfer coefficient (convection)	25.0 W/m.K	

(*continued*)

Table 1. (*continued*)

Location	Boundary condition	Physical property		Material
Fictitious wall	Symmetry	–	–	–
Mural refrigerated	Wall	Temperature	5.0 °C	Glass
Extraction grid	Outflow	–	–	–
Insufflation diffuser	Inlet Velocity	Velocity magnitude	6.6 m/s	–
		Turbulent intensity	4.33%	
		Temperature	33.0 °C	
		Fin angle	33.0º	
		Relative humidity	30.0%	
		Hydraulic diameter	0.08 m	

Table 2. Boundary conditions used in the CFD model on August 22.

Location	Boundary condition	Physical property		Material
Lamp	Wall	Heat flow	8.0 W/m^2	Glass
Roof	Wall	Heat flow	4.7 W/m^2	Sheet metal
Floor	Wall	Heat flow	4.4 W/m^2	Ceramic
Exterior wall	Wall	Exterior temperature	32.0 °C	Plaster
		Heat transfer coefficient (convection)	25.0 W/m.K	
Fictitious wall	Symmetry	–	–	–
Mural refrigerated	Wall	Temperature	5.0°C	Glass
Extraction grid	Outflow	–	–	–
Insufflation diffuser	Inlet Velocity	Velocity magnitude	6.6 m/s	–
		Turbulence intensity	4.33%	
		Temperature	16.0°C	
		Fin angle	33.0º	
		Relative humidity	50.0%	
		Hydraulic diameter	0.08 m	

Regarding the materials used to define the boundary conditions, their properties are identified in Table 3.

Table 3. Characteristics of the thermal properties of the materials considered in the definition of the CFD model.

Material	Specific heat capacity (J/kg.K)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Emissivity
Stainless steel	500	15.0	8 000	0.70
Aluminum	871	202.4	2 719	0.15
Ceramic	1 000	1.3	2 300	0.90
Micro perforated sheet metal	1 000	78.0	4 000	0.20
Plaster	1 000	1.3	2 000	0.91
Glass	750	1.1	2 600	0.93

Numerical Solution. The standard algorithm SIMPLE (Semi-Implicit Method for Pressure Linked Equations) was selected to define the pressure and velocity coupling. Additionally, second-order interpolations were used. The transient regime was simulated, defining a fixed timestep of 0.5 s and to achieve convergence conditions, a maximum number of iterations per step of 105 has shown to be appropriated. To guarantee the convergence, maximum residues of 1E−4 were defined for continuity, k, ε and for the species H_2O and O_2.. Regarding the energy equation, the default value of 1E−6 was maintained.

PMV Calculation. To assess the PMV and Predicted Percentage of Dissatisfied (PPD) index, an analysis was initially made of the spatial distribution of environmental variables (air temperature, air speed and relative humidity). Then, as these two indexes are not a direct output from ANSYS, a routine programmed in Phyton language was used. The algorithm is referred in ISO 7730:2005 and in its definition it was necessary to manually enter the average values for the thermal resistance of the clothing and the metabolic rate of the occupants.

3 Numerical Results

Figure 3 records the distribution for the temperature values in the three plans, for the zone of interest, on January 21. It is possible to verify that the inlet airflow follows a jet-like pattern. This behavior, promoted by the inlet grill, is necessary since the insufflation air temperature is higher than the surrounding air. This kind of insufflation gives the inlet flow enough kinetic energy to surpass the temperature stratification tendency and reach the bottom volume for better mixing of the air. The results also show that the higher air temperature provided by the insufflation is mostly located in the center plane, which will influence thermal comfort. In Fig. 4, is observed that the values of PMV show a tendency towards negative values, whose the most negative value is close to −2. In some regions of the middle plane, namely, next to the floor and away from the diffuser, as well as in the middle of the right plane the PMV value is 0. Additionally, the middle plane also registers the highest values of the PMV, given that it is also the region whose temperature is the highest due to the action of the diffuser,

with an average value of −0.5 for the PMV. As we move away from the middle plane and approach the other planes, the PMV value slightly decreases, reaching average values of −0.8. This average value, according with ISO 7730:2005, is slightly over the limit of comfort of −0.7. However, there is also the matter of thermal asymmetries and discomfort by cold floor, which fall within the limits specified for comfort. Nevertheless, the local PMV near the floor has a lower value and should be addressed to improve the overall comfort. In this regard, the easiest parameter to change is the temperature. An increase in temperature near the floor could be achieved either by placing heated tiles or by adding an inlet of hot air near the floor. However, it should be addressed that this source of heat right near the freezers could affect their thermal efficiency.

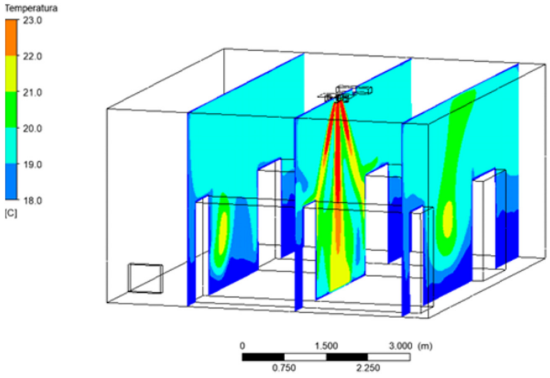


Fig. 3. Analysis of the temperature's distribution in the CFD model, on January 21.

The values of the PPD index, shown in Fig. 5, are a direct consequence of the PMV values. In the regions where the PMV values are close to zero, the number of dissatisfied people is smaller, corresponding to 5% of dissatisfied people. As the PMV value deviates from 0, the percentage of people dissatisfied increases. This way, the intermediate plane presents more favorable values in terms of thermal comfort than the other planes, with an overall PMV closer to 0 and an average PPD value of 10%. This is a value considered as comfortable according to ISO 7730:2005. In the plane next to the extraction grid, the average PPD value increases to 19% and in the other plane, at the opposite end, the average PPD is 18%.

Through the observation of Fig. 6, it is possible to verify that in the summer the insufflation tendency is inverted. In this case, the environment temperature is generally higher, and the insufflation air is used to lower the overall temperature. The insufflation air together with the temperatures set for the refrigerated murals can maintain a lower temperature near the floor. Additionally, the temperatures at this location are more uniform with localized colder zones near the murals. One important information is that the simulation allowed to verify the presence of air stratification with hot air near the ceiling, which can lead to inefficiency in cooling the area. If the issue is not addressed, this air will mix with the input air and act as a source of radiant heat. Fig. 7 records the

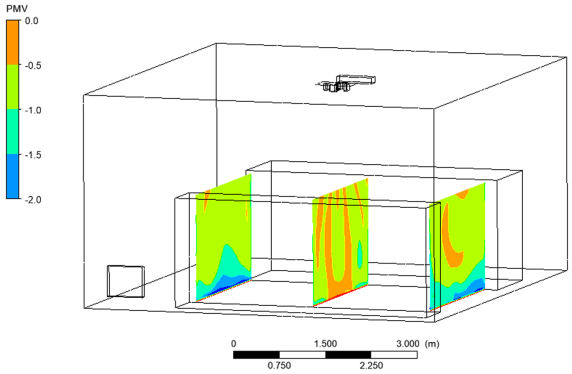


Fig. 4. Analysis of the PMV distribution in the CFD model, on January 21.

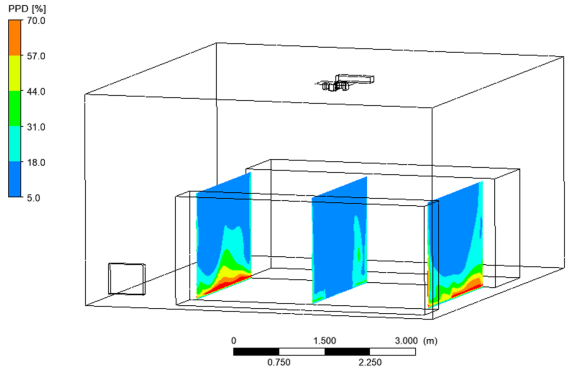


Fig. 5. Analysis of the PPD in the CFD model, on January 21.

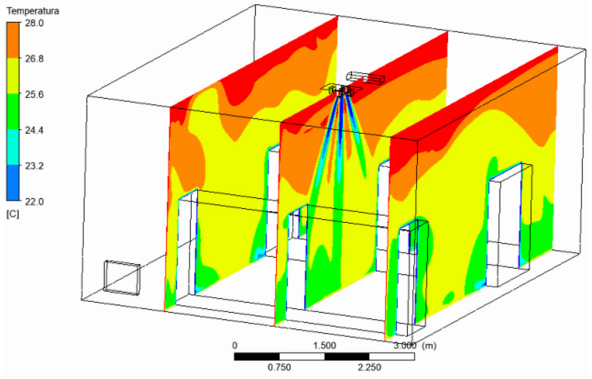


Fig. 6. Analysis of the temperature's distribution in the CFD model, on August 22.

values calculated for the PMV, on August 22. In this simulation, the trend is to obtain values in the range between −0.5 and 0.5. In the intermediate plane, because of the movement of the inflated air at a reduced temperature, there is a region with values close to −1. However, the average value in this plan is −0.1, which translates into an ideal PMV value for obtaining thermal comfort. In the extreme plane, close to the extraction grid, the average value of this index is 0.2, whereas in the opposite extreme plane, the average PMV is 0.1.

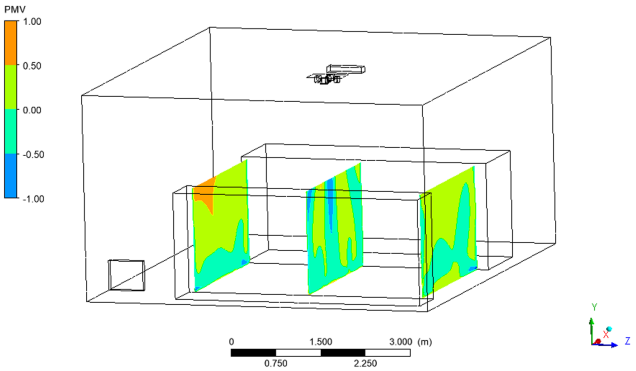


Fig. 7. Analysis of the PMV in the CFD model, on August 22.

As for the PPD index shown in Fig. 8 appears that the PPD values are very close to the minimum value of 5%, allowing occupants to feel thermally comfortable. The intermediate plan and the extreme plan next to the extraction grid present an average value of 6%, of dissatisfied people, whereas the rest plan registers a value of 5%.

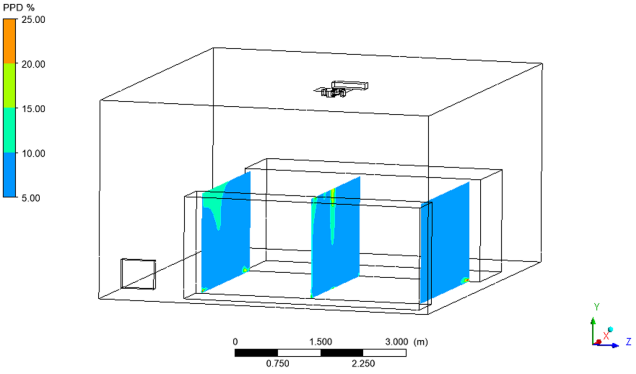


Fig. 8. Analysis of the PPD in the CFD model, on August 22.

Overall, the thermal comfort for the summer was not problematic. However, the simulation showed an accumulation of hot air near the ceiling. Providing a system that extracts this hot air from the ceiling and preventing its accumulation could lead to improvements in the HVAC energetic efficiency.

4 Conclusions

The objective of calculating PMV and PPD, seeking to adopt energy efficiency measures, was successfully met through Ansys Fluent.

In order to promote energy efficiency, but also to ensure thermal comfort in a supermarket, the sales area (the most consuming area in the building) was simulated in ANSYS Fluent. With the definition of a zone of interest and a reduction in flow by 15%, for the 21st of January, the average values are close to the lower limit value (−0.7) that the ISO 7730:2005 stipulates for thermal comfort. In the three planes, the average PMV varies between −0.5 and −0.8, with a PPD between 10 and 19%. However, in this case, there are values of local PMV that are lower than the limit. This issue could be addressed by providing localized heating such as heated tiles or air inlets. As for the August 22 simulation, the values are closer to thermal neutrality, with average values of PMV in the three planes between −0.1 and 0.2 and PPD of 5 to 6%. In short, very acceptable values of thermal comfort were guaranteed with the reduction in flow achieved, allowing to reduce energy consumption without compromising the well-being of individuals. However, the concentration of hot air near the ceiling showed that there is further potential for the energy optimization in the summer.

The CFD methodology, although restrictive in terms of computation power, allowed the assessment of the space and the creation of detailed comfort maps, otherwise hardly obtainable with traditional assessment methods. However, in the created CFD model the process of evaluating the average radiant temperature should be improved in future work, in order to better evaluate this variable contribution in the overall comfort index. In the current study, the model used only accounts for radiant heat exchanged between opaque surfaces. However, since the PMV is being calculated for each cell of the domain, an averaged value for the radiant temperature was used instead. Additionally, the effects of the number of occupants in the studied zone should be added for a more accurate simulation. Although the metabolic input is implemented in the PMV index calculation, if the zone has a great number of people, this may cause a raise in the surrounding temperature.

Acknowledgements. The authors would like to express their gratitude for the support given by FCT within the R&D Units Project Scope UIDB/00319/2020 (ALGORITMI) and R&D Units Project Scope UIDP/04077/2020 (MEtRICs).

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