Assessment of Indoor Thermal Conditions in a Cinema Room Using CFD Simulation: A Case Study

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Abstract. This work aims to characterize the experience lived by a user of a movie theater in the dimension related to the thermal environment. An exhaustive survey of information was made in order to allow the characterization of a set of variables that can affect the user experience in this type of contexts. The collection of information included: a checklist for characterization of space and its use; the experimental measurement of the variables related to the thermal environment and the calculation of thermal comfort indexes and a subjective analysis of the thermal comfort of the users of the space, result of the implementation of two questionnaires to analyze the perception of the users against the conditions of a movie theater. Furthermore, the space was modeled using ANSYS software, which allowed the subsequent simulation of the flow inside the Cinema in order to also study the thermal comfort.

In order to obtain solid bases for a better understanding of the parameters that affect the well-being of the user, the values obtained with the calculation of the thermal comfort indexes and the experimental measurements were compared with those referenced in ISO 7330:2005, the values that resulted from the subjective evaluation and with the results obtained with the CFD simulation. Both results provided a prediction of thermal comfort near thermal neutrality, though with a small difference of 0.6 points in the thermal sensation scale. The simulation provided further insight of the localized thermal environment and about the influence of people's presence.

Keywords: Thermal comfort · Cinema · CFD simulation

1 Introduction

Thermal environment plays a fundamental role in decision making from the point of view of comfort and performance of individuals. It is a complex field that attracts the interest of several researchers, since a long time [1]. The thermal environment is interconnected with a set of thermal variables that influence the heat exchanges between the individual and the environment in which it is inserted [2]. The environmental variables are the average radiant temperature, air temperature, air velocity, and

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air humidity [3, 4]. Additionally, thermal comfort is also influenced by personal variables, namely, metabolic rate and clothing insulation, as well as personal factors such as stress and medication among others [5, 6].

People spend much of their time indoors and many of those spaces are air-conditioned, whose equipment programming must be properly regulated, taking into account the health, comfort, and the productivity of its occupants [7, 8]. When the thermal environment is not the most appropriate, individuals tend to change their behavior and expectations in order to adapt to the environment. This change leads to a lower tolerance regarding the inadequacy of the thermal environment in air-conditioned spaces when compared with naturally ventilated spaces [9]. The physical effects caused by uncomfortable environments, induce agitation, which can reduce attention and concentration, and lead to fatigue and drowsiness. Physiologically, an individual needs to maintain its internal temperature within very narrow limits, at approximately 37 °C, which requires a constant search for thermal equilibrium, namely, homeothermy. Homeothermy is ensured whenever the heat produced by the organism equals the net heat flow to the environment so that the temperature remains constant [10].

Thermal neutrality is attributed to the state of thermal comfort [11], provided there is no local thermal discomfort [12]. ASHRAE Standard-55 (2004) defines thermal comfort as the mental state that expresses a man's satisfaction with the thermal environment that surrounds him, and ISO 7730:2005 defines it as an expression of satisfaction with the environment that surrounds the individual. According to Parsons [5], the environmental variables combined with the indexes of metabolism and clothing (designated by individual parameters), form the basic elements that define thermal comfort. There are several thermal comfort evaluation equations, however, the mostly used method in design guides and standards is the one developed by Fanger [6]. This method is based on the theory of thermo-regulation and thermal equilibrium and defines two complementary indexes, PMV - Predicted Mean Vote and PPD - Predicted Percentage of Dissatisfied People or Predictable Percentage of Dissatisfied.

As of 31 December 2016, there were 549 cinema screens in Portugal, 192 of them in Multiplex venues (8 or more cinemas), with a total of 103,583 seats, of which 35,758 seats in venues with eight or more cinemas. In the year 2016 650,011 cinema sessions were shown, for a total of 14,890,813 spectators[13]. The rooms had an average of 188.67 seats, with an average occupancy rate of approximately 12%. Considering the average duration of TOP 10 of the movies most seen in 2016, 117 min, the sum of hours that the spectators spent inside the Portuguese cinemas will be around 29,037,085 h. The specific case of a cinema experience requires an environment technically prepared for a relaxing and thus comfortable environment. The experience of watching a movie in a movie theater results from a sensory experience, where the inadequacy of the thermal environment or another element such as; the sound, the lighting, and others, may provoke interference and break the established tune between the spectator and the narrative.

Particularly in the matter of the thermal environment, the environmental variables should be adjusted through the air conditioning systems according to the occupancy rate and the outside temperature, considering that individuals they will be at rest, seated and quiet, with the clothing in accordance with the outside temperature.

In recent years, the study of optimum performance and the influence of these set of parameters with numerical models has been an attractive option for researchers [14–20]. Results showed that CFD simulations are an important tool to support experimental campaigns due to their ability to evaluate thermal comfort. Aryal [14] with CFD experiments showed that the thermal comfort level is deteriorated in some specific regions with the installation of partition and can be improved by adjusting air parameters at the supply diffuser and location of extract grilles. Buratti et al. [15] used a CFD tool for thermal comfort evaluation in natural convection and in transient conditions in a room. Results showed that the thermal sensation is uniform in the absence of the direct component of solar radiation. Aste et al. [16] analyzed the performance of an innovative local heating solution in terms of thermal comfort. For this, a 3D CFD model was developed to estimate the effects of set variables on human thermal comfort. It was verified that the air temperature in the room is not significantly influenced by the heating system, but the heat is directly radiated to people, ensuring comfortable conditions and contributing to artworks preservation. Shahzad [17] investigated the application and performance of an advanced personal comfort system, a thermal chair, using CFD. With CFD analysis it was improved by 20% the overall comfort. Alizadeh [18] performed an investigation of the effect of placing ceiling fan on thermal comfort level inside a room using CFD simulation. With this study, it was possible to provide an insightful understanding of the thermal comfort in a room and to perform a parametric study to enhance thermal comfort inside the room. Abdeen et al. [19] developed a CFD model to optimize solar chimney design to maximize indoor air velocity induced by natural convection, with a particular emphasis on thermal comfort. Ahmed et al. [20] carried out a CFD analysis to obtain velocity and temperature profiles inside a room in order to calculate the air diffusion performance index.

The objective of this study is to characterize the thermal environment, trying to obtain solid bases for a better understanding of the parameters that affect the experience lived by the users of these spaces. Afterward, the characterization of PPD-PMV as a method of Thermal Comfort evaluation and the importance of the use of questionnaires as a tool for the subjective evaluation of thermal comfort is made.

2 Methodology

2.1 Cinema Description

The space under study is a room of a cinema complex. The choice of this room is due to the fact that this is the largest room of this cinema complex, with 170 seats and its capacity to be the closest to the average capacity of the National Rooms, 188 seats. The room does not have the means that allow the natural renovation of the air during the sessions of cinema, being the renovation is forced through air conditioning equipment. Air insufflation is done through six points located on the ceiling of the room, and the extraction through holes under the seats of the chairs.

The HVAC system is made up of an MCQUAY Model 75 19 equipment, which is installed next to the facade on the exterior of the building. This equipment does not have a reuse or air recirculation system, so the air in the room is always new air coming

from the outside. The room temperature is set at 22 °C, for an upper capacity of approximately 25%, and the equipment is only activated approximately 10 to 15 min from the beginning of the session. The control that controls the equipment is outside the room, inside the projection booth.

2.2 Field Measurements

Occupancy. In order to select the measurement points, the distribution of occupancy per seat was calculated based on 6,041 tickets sold in the period between December 1, 2016, and January 31, 2017, for the study room. Due to material limitations, for this study only the following measurement points were chosen: B8, place with the highest occupancy rate (2.56%); K14, place with the lowest occupancy rate (0.08%) and G12, a place with the sample median (0.40%). Figure 1 represents the distribution of occupancy in the living room floor plan.

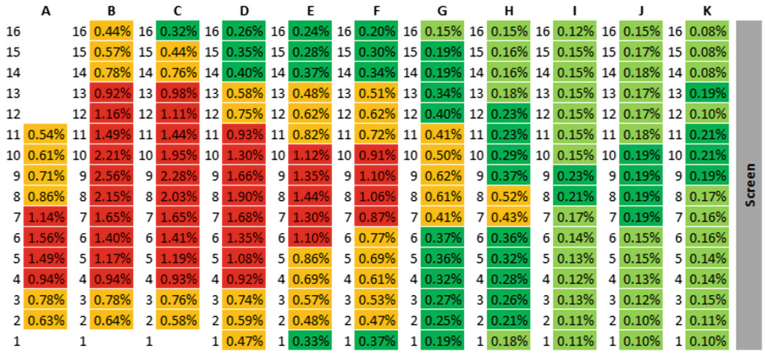


Fig. 1. Occupation and distribution in the cinema room. (Color figure online)

Environmental Characterization. The characterization of the thermal environment of the study space was done by means of experimental measurements in April 2017, at the previously selected points and in randomly chosen sessions. For the measurement of variables in real time, it is necessary to use some instruments simultaneously, and its calibration has much relevance in the accuracy of the data obtained. For this study, the instruments were assigned by the Department of Production and Systems of the University of Minho, and there were no changes in their calibration.

For the experimental measurements, the following instruments were used:

- A Casella brand globe thermometer model RS2842:1992, to measure individual exposure to radiant heat. This was placed at chest level on a tripod to remain stable, and a stabilization period of about 30 min;
- An anemometer TSI Velocicheck Model 8330 anemometer to measure air velocity, also placed at chest level on a tripod and had a stabilization period of 5 min;

- Three USB Data loggers from Elcar, model EL-USB, to measure the temperature, relative humidity of the air and calculate the dew point. They were also placed on a tripod at chest level.

The temperature and relative humidity of the outdoor air at the time of the different measurements were registered by consulting the website of the Portuguese Institute of the Sea and Atmosphere since these two variables can affect the interior thermal environment and its perception [21].

2.3 Simulation Study

Modelation of the 3D Environment. The first phase of a computational fluid dynamics (CFD) simulation consists in the definition of the study domain. To that purpose, a modelation program, such as DesignModeler® was used. Through the cinema schematics and with local observation, a 3D model of the cinema room was created. Additionally, the full definition of the domain needs the inclusion of boundary conditions. Figure 2 represents the domain with the respective boundary conditions identified.

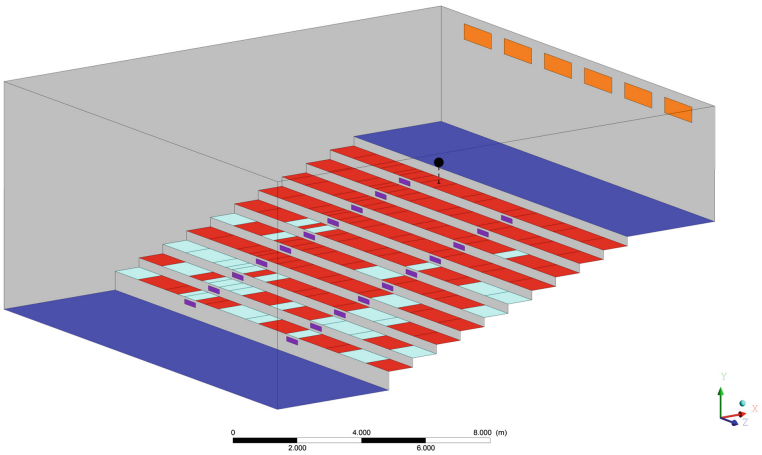


Fig. 2. Representation of the modelated cinema room and its boundary conditions. The black point represents the location of the experimental measurements. (Color figure online)

Each boundary condition is represented by a scheme of colors where: the walls are represented in grey, the air inlets are represented by orange, the dark blue represents the cinema floor, the color purple represents the outlets, the red represents the seats occupied by people and the light blue areas represent the unoccupied seats.

The conditions simulated were based on the conditions verified on April 19, where the cinema had a bigger attendance. As such, the inlets were defined according to the specifications of the HVAC systems and the Portuguese regulations [22], as such, a velocity input of 0.25 m/s was applied. The cinema is within a building and, as such, for simplification, the walls were considered adiabatic. Similarly, the same is true to the cinema floor. The air outlets of the cinema were defined as passive, using pressure outlet boundaries with a relative pressure of 0 Pa.

Regarding the temperatures within the cinema, people are the main heat source of the domain, which makes their presence in the simulation important. On April 19, the attendance in the cinema was of 76% of its full capacity. However, people do not spread evenly over the cinema seats, there is a preference for certain seats (Fig. 1). This preference creates a concentration of people and heat that may influence the temperature distribution and affect the localized thermal comfort. Considering this, the seats in the cinema were selected through a distribution that accounted for the probability of a seat to be occupied. The selection mechanism was accomplished through a Python® script. The basic concept consisted of three main steps: The first step was to export the table contained the relative frequencies occupation for each seat in a CSV file that was later imported into a NumPy data structure. The second step consisted in transforming the relative frequencies in integer values to create a list of frequencies. As such, each frequency was multiplied by 100 and rounded to an integer value. This step allowed keeping the relative probability of the seats and the information of the low-frequency values. For example, in the seats where the occupation was only 0.08%, this information would be lost if rounded directly. The third step consisted in the creation of a list of frequencies. The list contained a unique identifier and a reference to a seat, repeated the number of times that matched its frequency. Once the list was created, a random number comprised between the size of the list was generated, giving an index of a seat. After a seat is taken, all its references are removed from the list. This last step is repeated until all people are placed. For the occupied places, the wall temperature was defined as 33 °C as this is the average skin temperature for people in comfort [23].

The resolution of the differential equations that define a CFD problem implies the use of discrete volume methodology in order to discretize the domain. This method consists in dividing the global volume into smaller elements until it is considered that the fluid properties within the small volumes are not significant. The mesh generation was focused on reducing the element deformation, thus keeping a good quality to reduce the computation time and facilitate the numeric convergence. For this purpose, the domain was divided into smaller regular geometries to better accommodate the mesh blocks. In total, the domain was divided into 3604 bodies. To guarantee a good definition of the boundary layer, it is important to obtain a good representation of the near wall phenomena such as heat transfer, each wall had a mesh refinement with elements of reduced size near it, followed by a growing gradient. In total, the final mesh as represented in Fig. 3 had a total of 1,254,690 elements.

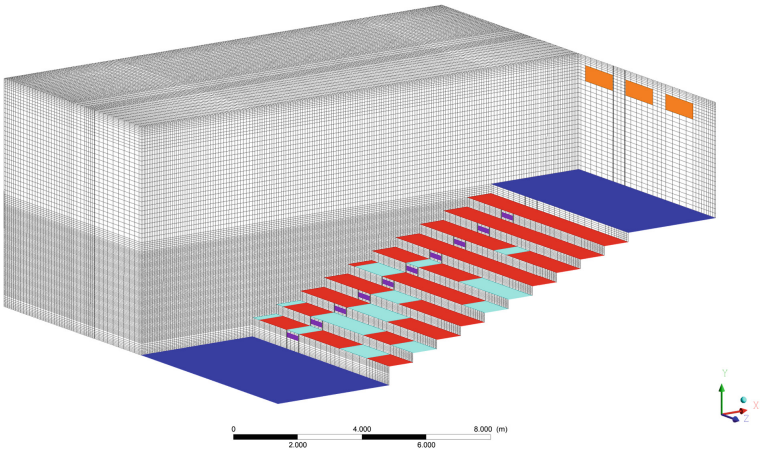


Fig. 3. Representation of the mesh used in the simulation of the cinema room. (Color figure online)

Since a good mesh positively affects the numerical solution and the simulation speed, it is important to determine its quality through different quality indices, such as the "Element Quality", "Orthogonal Quality" and "Skewness". The former two indices vary between the values of 0 and 1, where 0 is an element of bad quality and 1 presents a good quality. The average value for the Element quality and Orthogonal Quality are 0.48 and 1 respectively. As for the latter index, 0 represents a good element which is not distorted and, at the limit, the value 1 represents a completely distorted element. The average value for this index is 0.

Once the domain is discretized, follows the definition of the variables to study. To include the temperature and heat transfer, the energy equation was activated. Additionally, to correctly model the transfer and its mechanisms, the radiation model "Surface to Surface" was included, allowing accounting the thermal radiant fluxes. To account for the turbulence in the flow, the model k-ω was selected since it accounts for flows with low Reynolds numbers [24, 25].

3 Results and Discussion

3.1 Experimental Results

Experimental measurements were performed at a measurement point inside the room at the B8 site, starting at 15:00 and ending at 20:30 on April 19, 2017. During this period there were two sessions of cinema, the first one began at 15:30 and the end at 18:00, with an occupancy rate of 76.4% and the second one starting at 18:50 and ending at 21:00, occupancy rate of 34.7%.

Table 1 summarizes the results of the calculated indexes, identifying the maximum, minimum, mean values and standard deviations of the obtained values for the first session.

Table 1. Experimental measurements results

	Max.	Min.	Avg.	Std.
Temperature (°C)	24.5	20.0	22.2	0.9
Dew point (°C)	15.5	8.9	14	1.2
Relative humidity (%)	65	37	59.9	4.2

For the calculation of PPD and PMV indexes, the average metabolic value of a 70 kg man with a skin surface of 1.8 m^2 was used as a reference, sitting in a comfortable environment, met = 1, and thermal insulation, which represents a typical indoor clothing combination during the winter. The values of the environmental parameters used to calculate the indexes were those recorded during the periods of the cinema sessions, with an interval of 15 min.

Table 2 summarizes the results of the calculated indexes, identifying the maximum, minimum, mean values and standard deviations of the obtained values.

Table 2. PMV and PPD values

	PMV	PPD (%)
Avg.	−0.30	6.89
Max.	0.05	5.05
Min.	−0.80	18.59
Std.	0.25	6.31

3.2 Numerical Results

Temperature, Velocity and PMV Fields. The results for the computed velocity fields are represented in Fig. 4, which is composed of four orthogonal planes – one parallel to the YZ plane, one to the XY plane and two planes parallel to the ZX plane at different heights, to capture the details of the velocity near the inlets and near the zone occupied by the people. The results allow us to understand how the air moves throughout the cinema, with the greatest air velocities located at the height of the air inlets. This behavior is expected as the boundary conditions in the inlets was defined as 0.25 m/s providing the air with its highest kinetic energy. Besides, this promotes the renovation of the hot air that tends to accumulate near the ceiling due to stratification. Additionally, the results show that there are few regions where the air is stagnant (with zero velocity), adding to the effectiveness and quality of the ventilation. The zones near the cinema seats presented an average velocity near 0.05 m/s, a value which makes the air movement imperceptible.

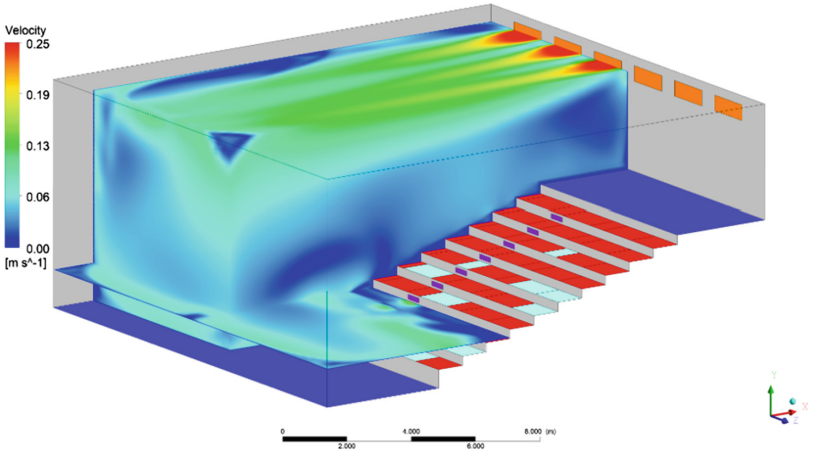


Fig. 4. Simulated velocity fields in the cinema room. (Color figure online)

In order to get a better comparison between different results, the same representation was applied to the temperature field in the cinema, represented by Fig. 5. The air provided by the ventilation system was defined as having 22 °C. In the present case, the ventilation has a lower temperature than the average room temperature, providing a cooling effect. This is visible by the darker blue color near the air inlets representing the lowest temperature. As previously referred, people are the main source of heat in the cinema and their contribution is enough to change the thermal environment. In Fig. 5 is possible to verify this behavior with greater temperatures near the seats and the consequent gradient along the cinema height. Overall, the volume averaged simulated temperature was near 24 °C.

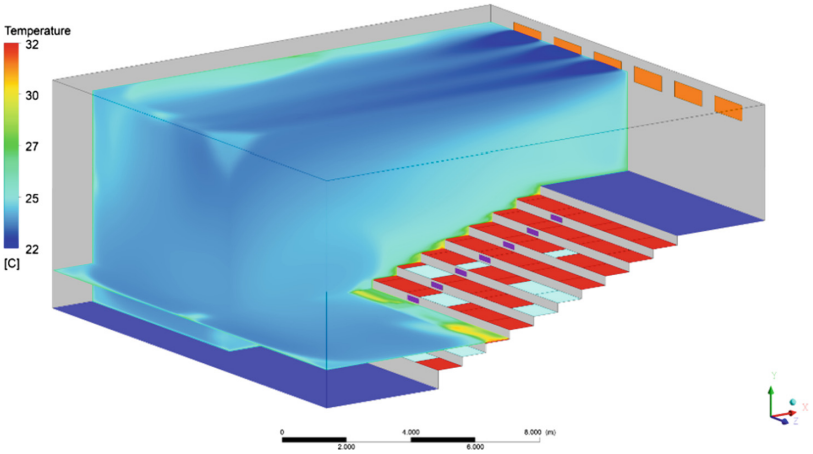


Fig. 5. Simulated temperature fields in the cinema room. (Color figure online)

After taking into account the temperature and velocities variations of an occupied cinema, it was possible to determine a field of local PMV values. For the calculation, there were constant variables, taken from the measurements in the field, namely, the relative humidity with a value of 60%, the metabolic rate of 1 Met and the clothing insulation of 1 clo. The variations occurred in the velocities, air temperature, and radiant temperature. The former variables where the result of the simulation as previously described. As for the latter parameter, since there was not a main source of radiant temperature, in the calculation its value was equal to the air temperature. The local PMV fields were calculated using a Python® script that iterated through the temperature and velocity values of each mesh cell and, together with the other thermal environment parameters calculated the PMV value for that cell. The resulting field is represented in Fig. 6. The simulations performed predicted an average PMV value for the room of 0.3, which is a little above of the ±0.2 limit for the Class A category as described in ISO 7730:2005. The simulation also adds the advantage of being able to verify local discomfort zones. Figure 6 shows that the temperature provided by the people is enough to alter the comfort perception, increasing the PMV value to 1.5.

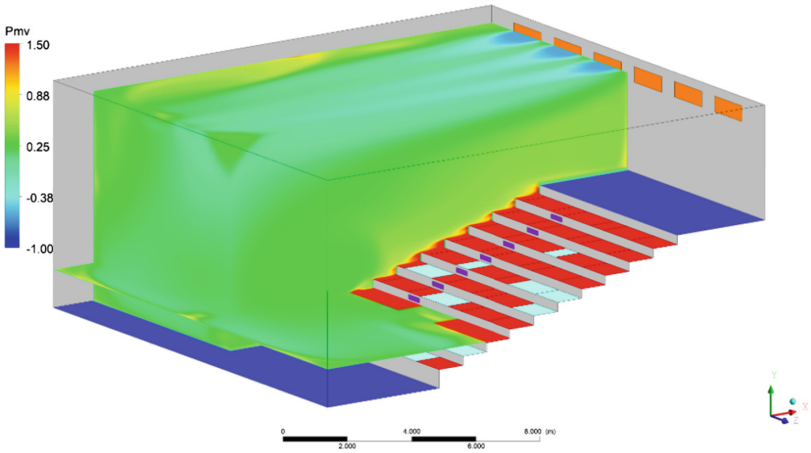


Fig. 6. Simulated PMV fields in the cinema room. (Color figure online)

4 Conclusions

Through field measurements, it was possible to verify that the thermal environment in the cinema room was near thermal neutrality with a predicted mean vote of −0.3. This value predicts that only about 6.89% of the people frequenting the cinema would be dissatisfied regarding the thermal environment.

The simulations were able to provide a better insight into the ventilation system in the cinema, especially regarding localized details. In terms of the ventilation, there were few zones with stagnant air and the temperature was mostly uniform. Comparing with the measured data, there still was a difference of 2 °C from 22 °C measured, to 24 °C calculated.

However, since thermal comfort depends on other parameters, local PMV values were calculated. These fields allowed a better understanding of the predicted thermal sensation throughout the cinema and the verification that the people in the cinema alter the prediction values, thus this energy addition should be included when applying the PMV calculation. In this regard, the difference was of 0.6 from −0.3, local measured, to 0.3 when simulated. This difference changes the direction of comfort prediction towards a hot sensation. Still, both values are near thermal comfort and the Class A region. The CFD methodology also proved to be a valuable tool for the study and improvement of the comfort parameters since they can be easily changed, and the effect known. To better evaluate the simulation performed, further comparison points should be added, as well as a better study of the inlet and outlet conditions.

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