Design, Thermal Response and Comfort in an Auditorium with Complex Topology

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Abstract. This article presents a numerical study on the design, thermal response and comfort level of an auditorium with a complex topology, taking into account the winter season. The design and thermal response of the auditorium are studied numerically using proprietary research software, called, respectively, Geometric Design Modeling and Buildings Thermal Response Modeling (BTRM). In addition to the thermal response in transient conditions, the BTRM software also assesses the building's interior environmental conditions, particularly the levels of air quality and thermal comfort provided to the occupants. The indoor air quality (IAQ) is determined by the concentration of carbon dioxide (CO_2). The thermal comfort is determined by the Predicted Mean Vote (PMV) index. In this study, it is considered that the auditorium, similar to a real one, has a typical occupancy cycle of a classroom and its maximum capacity of 168 occupants. Connected to the auditorium is a corridor with south-facing windows, so the possibility of this corridor being used as a passive solar greenhouse is also discussed. The results demonstrate that it is possible to guarantee acceptable levels of IAQ as established by the ASHRAE 62.1 standard for the concentration of CO_2, but without being able to reach acceptable values of the PMV index as proposed in the ISO 7730 standard.

Keywords: Geometric and thermal modeling · Indoor air quality · Thermal comfort

1 Introduction

The design and the thermal response of a real auditorium are the main focus of this numerical study. Therefore, it is important to be able to virtually generate the geometry of this auditorium so that its thermal behavior can be analyzed. The auditorium's thermal

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response will make it possible to analyze its thermal comfort conditions. Thermal comfort conditions also depend on the ventilation implemented, as well as indoor air quality (IAQ) conditions.

The design is developed by a numerical model to generate the three-dimensional geometry of the auditorium. Geometric surfaces based on four lines and four points are used to generate this geometry. The calculus of the mesh in the surfaces used geometric equations in cylindrical coordinates characterized by angle, radius and z coordinates. This type of methodology was previously used, e.g., in buildings [1], and in the definition of the geometry of the human body (occupant simulation) [2]. This mesh is used to evaluate incident, transmitted and absorbed solar radiation in interior and exterior spaces, as well as heat transfer by radiation in each space [3]. The meshes on the building surfaces are also used to generate the system of integral equations of energy and mass balance.

The thermal study of occupied buildings uses the Building Thermal Modeling software to calculate the temperature and mass distributions in the different spaces and elements of the building, among other parameters [4, 5]. The thermal response of the auditorium uses a numerical model based on energy and mass balance integral equations [6]. The energy balance equations take into account the phenomena of conduction, convection, radiation and evaporation. The mass balance equations consider the phenomena of diffusion, convection and adsorption/desorption. The research software developed by the authors also included sub-models to calculate solar radiation, radiative properties of glass, energy and mass convection coefficients, airflow rate, among others. The solution of the above mentioned system of equations is obtained through the Runge-Kutta-Fehlberg method with error control. The numerical model was validated, either in a steady-state or in a transient regime, in buildings, experimental chambers and other spaces.

The thermal comfort is evaluated in this study by the Predicted Mean Vote (PMV) index. This index (and also Predicted Percentage of Dissatisfied index) was developed by Fanger [7]. PMV index depends on four indoor environmental parameters and two personal parameters [7]. The indoor environmental parameters are the air temperature, air velocity, relative humidity of the air and mean radiant temperature of the surrounding surfaces (floor, ceiling and walls). The personal parameters are the activity level and insulation clothing level. This is an index commonly used in studies involving the assessment of thermal comfort in buildings [8, 9], having been adopted by international standards such as ISO 7730 [10] to categorize thermal comfort. ISO 7730 establishes three categories of thermal comfort, A, B and C, depending on the PMV index values obtained [10]. For example, the least restricted is category C, being defined by $-0.7 \leq PMV \leq +0.7$.

IAQ usually can be evaluated by the concentration of dioxide carbon (CO_2) released during the occupant's breathing process [11–13]. The international standard ASHRAE 62.1 [14] establishes the acceptable limit of IAQ in function of the CO_2 concentration and the airflow rate of the ventilation system recommend according to the number of occupants and the activities performed by them in the different compartments of the building. The acceptable limit value recommended by this standard is 1800 mg/m^3 (1000 ppm) [14].

The main objective of this work is to evaluate the thermal comfort, in winter conditions, and the IAQ in a real auditorium existing in a university building using research software developed by the authors that simulates the geometry and the thermal response of that auditorium. In addition, the possibility of using a corridor attached to the auditorium as a passive solar greenhouse is studied. This corridor has a large glazed surface facing south, which gives it promising conditions to be used as a solar greenhouse during the winter season in the northern hemisphere, which could be a possible solution to improve thermal comfort conditions [15, 16].

The rest of the content of this paper is organized as follows: Sect. 2 gives a brief description of the numerical models used in the simulation; Sect. 3 presents the geometry of the building as well as the methodology implemented in the numerical simulation; in Sect. 4 the results are shown and discussed regarding the solar radiation obtained in the corridor and the air temperature, PMV index and CO_2 concentration obtained in the auditorium; finally, Sect. 5 presents the most relevant conclusions.

2 Numerical Model

This study uses research software developed by the authors based on two numerical models: Auditorium Geometry Design and Auditorium Thermal Modeling.

The Auditorium Geometry Design is used in the auditorium design and mesh generation. This model takes into account the following:

- Geometric equations in cylindrical coordinates (defined by the angle, radius and z coordinates) are used to develop the geometry of the auditorium and its attached corridor;
- The geometry is used to establish the mesh generation and the system of energy and mass balance integral equations;
- The mesh generation is used to calculate the view factors and the mean radiant temperature;
- The energy and mass balance integral equations are developed for each surface and space; opaque surfaces consist of several layers and transparent and inner ones consist of one layer.

The Auditorium Thermal Modeling uses the previously developed energy and mass balance integral equations to calculate the temperature, contaminants (CO_2 concentration) and water vapor distribution, the thermal comfort and IAQ levels:

- The temperature distribution is calculated in the several layers of the opaque bodies, in the layer of the transparent and inner bodies, and in the air inside the compartment;
- The thermal comfort of the occupants is assessed by the PMV index, so it depends on the air temperature, the air relative humidity and the air velocity inside the compartment, the mean radiant temperature, as well as the activity and clothing insulation levels of the occupants [7, 10];
- The IAQ depends on CO_2 concentration [14].

3 Numerical Methodology

The virtual auditorium (Fig. 1) used in the numerical simulations consists of 759 opaque bodies and 25 transparent bodies (Fig. 2). Each surface is subdivided into at least 100 infinitesimal areas when meshing.

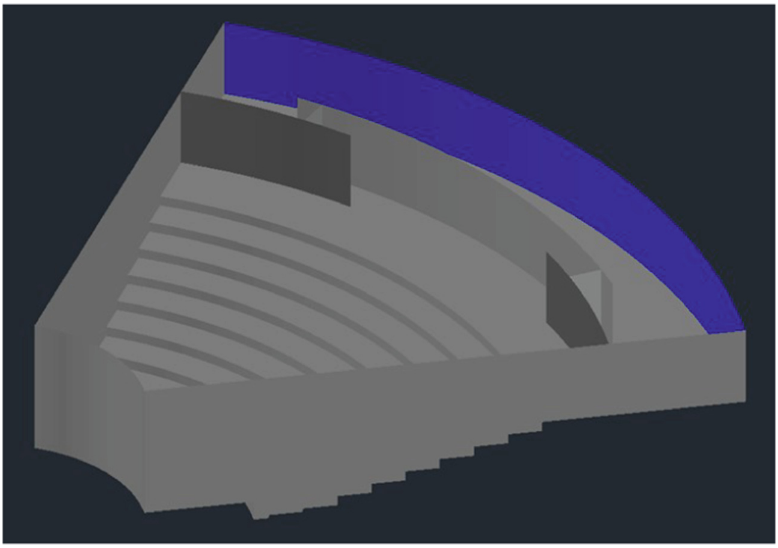

Fig. 1. Virtual auditorium used in the numerical simulation. It consists of the auditorium space for the participants and an attached corridor with a glazed surface facing south (in blue).

The auditorium built from 25 angles and 9 steps (levels) is divided as follows:

- The auditorium for participants with a maximum capacity of 168 people. This space is subject to the heat transfer from the occupants and the airflow renewal from the outside environment;
- The attached corridor with a glazed surface consisting of 25 windows facing south and with infiltrations of airflow from the outside environment;
- A connection between the auditorium and the corridor made by two doors (Fig. 1).

Numerical simulations were carried out considering winter conditions in the region of the building, whose climate is characterized by being of the Mediterranean type. Six consecutive days were simulated although only the results referring to the last day of the simulation are presented. It was considered that the auditorium was occupied by 168 people (maximum occupancy limit) in order to assess the most demanding situation from the point of view of the ventilation system.

For the purposes of the simulation, it was considered that each occupant has an average weight of 70 kg, an average height of 1.7 m, an activity level of 1.2 met and a

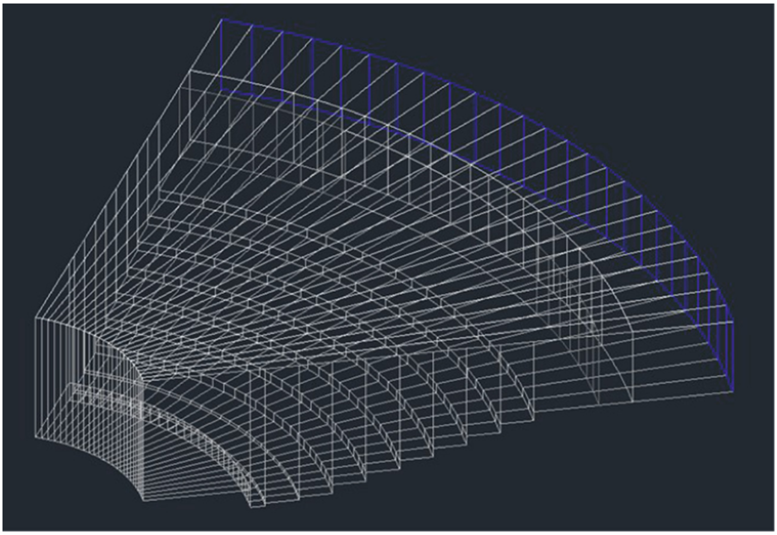

Fig. 2. Auditorium made up of 759 opaque surfaces and 25 transparent surfaces (in blue).

clothing insulation level of 1.0 clo (typical value in the winter season) [6, 10]. The occupation cycle was considered according to the typical timetable of classes in a university auditorium, that is, between 8 am and 12 pm and between 2 pm and 6 pm.

Throughout the day, the ventilation is done as follows: outside air is introduced into the auditorium with a certain airflow rate and then exhausted to the outside. The airflow rate value is a percentage of the airflow rate value recommended by the standards [14] for the people in the occupied space (168 in this study). When the auditorium is with occupation, the percentage is 75%; the rest of the time, the percentage drops to 25%. After several simulations, these values were chosen as the ones that ensure the best compromise between PMV index and CO_2 concentration values throughout the occupancy cycle.

The obtained results considered for analysis are the daily evolutions of solar radiation incident on the windows of the corridor, of the CO_2 concentration inside the auditorium, of the air temperature inside the auditorium and corridor, and of the PMV index.

4 Results and Discussion

In this work, the thermal response, in winter conditions, of a virtual auditorium similar to a real one is analyzed. The thermal response of the corridor (see Fig. 1) attached to the auditorium is also introduced in this analysis in order to assess the possibility that this corridor could later be used as a solar passive greenhouse. Note that the glazed surface of this corridor faces south, which provides positive heat gains in the winter season. So, Fig. 3 shows the daily evolution of solar radiation incident on the glazed surface (consisting of 25 windows) of the corridor. In order to assess the IAQ, it is shown in Fig. 4 the daily evolution of the CO_2 concentration in the auditorium. The thermal response of the auditorium and the attached corridor is shown here in Fig. 6 by the daily evolution of the air temperature obtained in these spaces. Figure 5 also shows the evolution of the outside ambient air temperature in order to serve as a reference. In order to assess the thermal comfort of the occupants, it is shown in Fig. 6 the daily evolution of the PMV index in the auditorium.

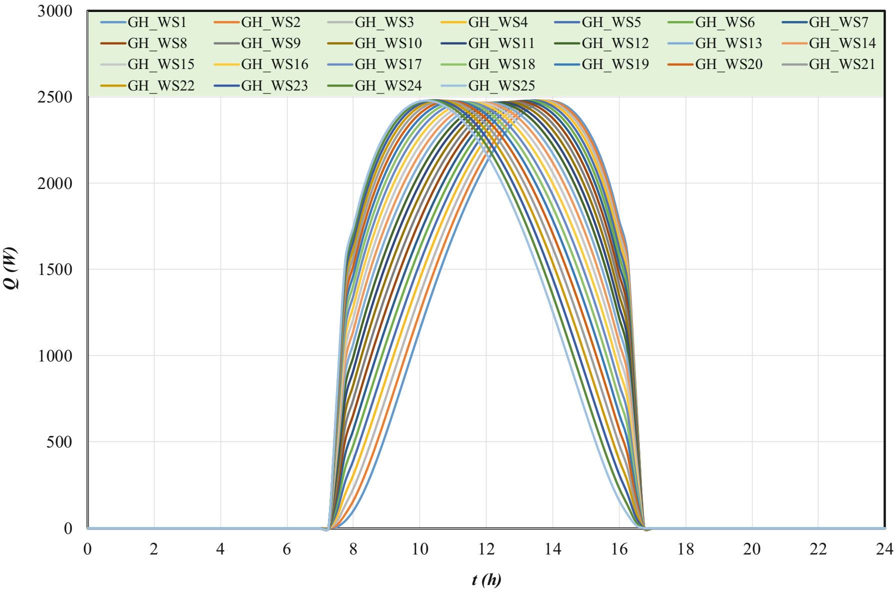

Fig. 3. Daily evolution of solar radiation incident on each of the windows of the corridor.

The incident solar radiation is similar in all windows, which have the same dimensions and the same type of glass. However, the evolution of solar radiation presents some delay between them due to the slight inclination of each window in relation to the south-facing plane.

During occupancy, the CO_2 concentration values are below the limit value of 1800 mg/m^3 recommended by the standard [14], so the IAQ provided to the occupants presents an acceptable level. Furthermore, it is also confirmed that the airflow rate is also properly adjusted to the number of occupants as far as the IAQ is concerned.

During occupancy, the auditorium is under the influence of the external airflow and the heat transfer from the occupants. The indoor air temperature in the auditorium is slightly higher than the outdoor air temperature and much lower than the air temperature in the corridor. The air temperature inside the auditorium during the afternoon occupancy is higher than during the morning occupancy, with some heat accumulation, but not enough for the air temperature to reach at least 20ºC. On the other hand, the relatively high temperatures reached in the corridor during the auditorium occupancy allow us to assert that the heat accumulated in this space can be used to improve the thermal conditions inside the auditorium if properly transferred.

During occupancy, the thermal comfort level of the occupants is not acceptable by negative values of the PMV index [10]. The PMV values are far from the values

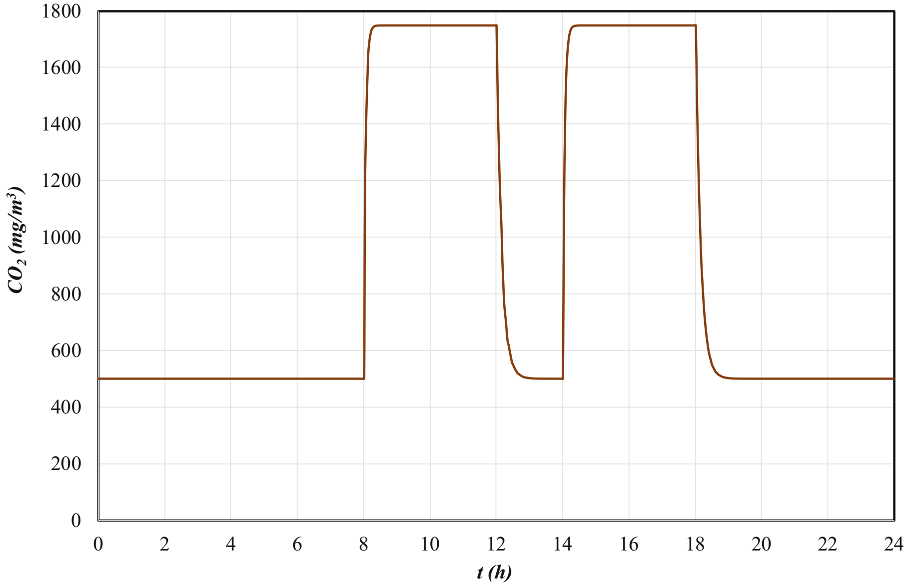

Fig. 4. Daily evolution of CO2 concentration inside the auditorium.

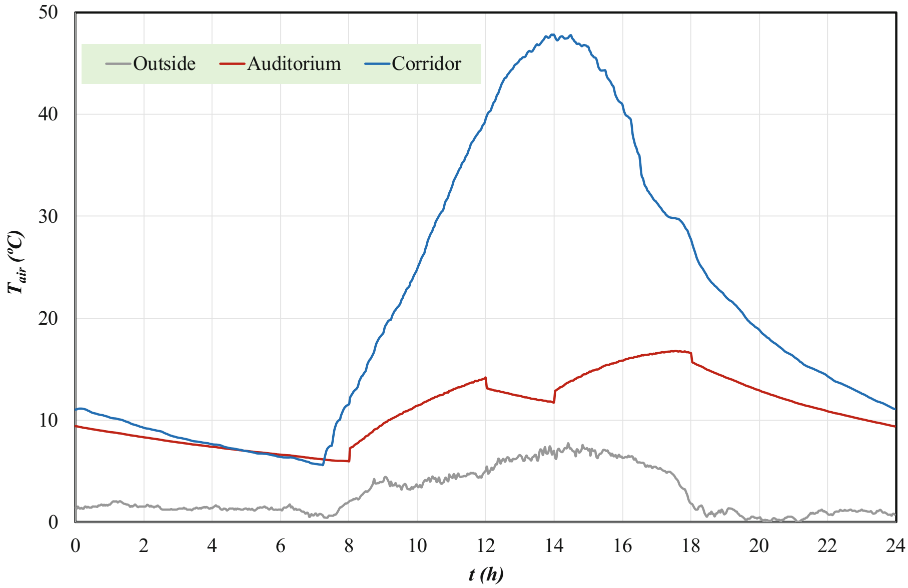

Fig. 5. Daily evolution of air temperature inside the auditorium and corridor as well as outside air temperature.

corresponding to category C of the standard [10], however they increase throughout the day, especially during occupation. This shows that the airflow rate of the ventilation

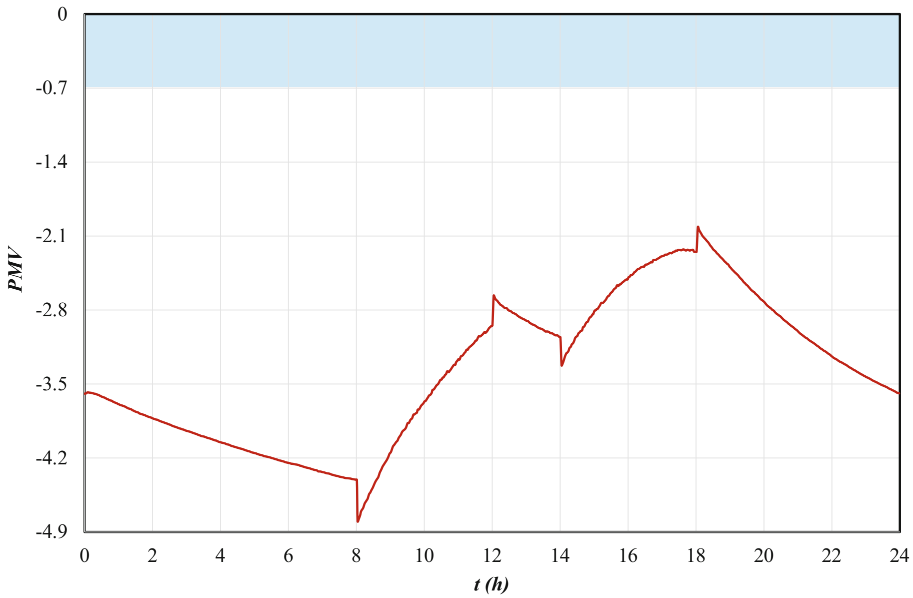

Fig. 6. Daily evolution of PMV index inside the auditorium. The shaded zone defines the thermal comfort zone by negative values of the PMV index according to Category C [10].

system is too high and should therefore be reduced, a solution that will lead to a decrease in the IAQ.

As the results show, an increase in the airflow rate decreases the concentration of CO_2, contributing to the improvement of the IAQ, and decreases the values of the PMV index, thus worsening the thermal comfort level of the occupants. Therefore, as an alternative solution, the corridor attached to the auditorium can be used as a solar passive greenhouse to further the increase in the air temperature inside the auditorium, without jeopardizing the concentration of CO_2 inside the auditorium, as the corridor essentially serves for the movement of people during the break between classes.

5 Conclusions

The design, thermal response and comfort evaluation of an auditorium with complex topology was presented in this article. An own research software, Auditorium Thermal Modeling, was used to numerically evaluate the amount of solar radiation incident on the south-facing glazed surface of the corridor attached to the auditorium, the air temperature inside the corridor and auditorium, the thermal comfort (using PMV index) and the IAQ (using CO2 concentration).

The results obtained show that it can be concluded that the implemented ventilation system provides an acceptable level of IAQ, but cannot guarantee an acceptable level of thermal comfort for the occupants. The CO2 concentration is within the acceptable limit of 1800 mg/m^3 [14]. However, during occupancy, the thermal comfort level is quite far from the C category of the standard [10] due to negative values of the PMV index.

The results of the air temperature obtained inside the corridor show that this space has heating conditions conducive to improving the thermal comfort in the auditorium, which suggest its operation as a solar passive greenhouse. Thus, in the future works the airflow used in the auditorium during the occupancy will come from the corridor (operating as a solar greenhouse).

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