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Design of an Integrated Aero-Thermal Building

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ABSTRACT

In this work a design of an integrated aero-thermal auditorium, with complex topology, is made for winter conditions. The three-dimensional geometry of the auditorium is obtained using cylindrical coordinates. Auditorium thermal response is obtained using the Building Thermal Response (BTR), an own research software. The numerical model is based on mass and energy balance equations, considering phenomena such as radiation, convection, conduction, evaporation and diffusion. The BTR, whether in a transient or permanent regime, allows the assessment, among others, of the level of thermal comfort and the indoor air quality (IAQ) in the auditorium. Here, the thermal comfort is assessed by the Predicted Mean Vote index and the IAQ is assessed by the concentration of dioxide carbon. The auditorium has windows on the east and west facades that allow the entry of solar radiation during the early morning and late afternoon, respectively. The maximum occupancy of 420 people was considered. The ventilation system airflow rate was adjusted to obtain the best compromise between the occupants' thermal comfort level and the IAQ level.

Keywords: Building thermal response, Indoor air quality, Solar radiation, Thermal comfort

INTRODUCTION

In this article, the numerical study of the thermal response of an auditorium considering cold winter conditions is carried out. In this sense, the design of this auditorium is developed from its three-dimensional geometry. This study also involves the evaluation of the thermal comfort of the occupants and the indoor air quality (IAQ) provided by the implemented ventilation system, knowing that this auditorium receives some solar radiation through the windows it has on the east and west facades.

Developed by a numerical model, the design generates the three-dimensional geometry based on geometric equations defined in cylindrical (angle, radius and z length) coordinates. This type of methodology was used, for example, in generating the three-dimensional geometry of buildings (Conceição et al., 2010) or the occupant's human body (Conceição et al., 2018). The grid generated in the surfaces is utilized to evaluate the incident, transmitted and absorbed solar radiation, in internal and external spaces, and the heat exchange by radiation in each space (Conceição and Lúcio, 2010). The buildings surfaces are also used to generate the energy and mass balance integral equations system.

The thermal analysis of occupied buildings is done by building thermal response (BTR) software to calculate distributions of temperature and mass in the several spaces and components of the building, among other parameters (Smith et al., 2012; Guo et al., 2022). A numerical model based on energy and mass balance equations is utilized to obtain the thermal response of the auditorium (Conceição et al., 2019). The energy balance equations ponder the conduction, convection, radiation and evaporation phenomena, and the mass balance equations ponder the diffusion and convection phenomena. Solar radiation, glasses radiative proprieties, convection coefficients, airflow rate, among others, are also calculated by sub-models included in the software Building Thermal Response developed by the authors. The Runge-Kutta-Felberg with error control is used in solving the system of equations. The numerical model was validated in steady-state and transient conditions in large and small buildings, experimental chambers and other spaces.

The thermal comfort is evaluated in this work by the Predicted Mean Vote (PMV), an index developed by Fanger (1970). PMV index depends on four indoors parameters (air velocity, air temperature, relative humidity, mean radiant temperature) and two personal parameters (activity and clothing levels). PMV index is widely used to evaluate thermal comfort in buildings (Cheung et al., 2019; Fletcher et al., 2020), being part of standard ISO 7730 (2005). This standard defines three thermal comfort categories in function of the PMV index, namely, A, B and C. In this article, category C ($-0.7 \leq \text{PMV} \leq +0.7$) is used as the main objective to be achieved.

ASHRAE 62.1 (2016) defines the acceptable limit of IAQ in function of the CO_2 concentration (Conceição et al., 1997; Asif et al., 2018) and the appropriate airflow rate for the ventilation system in function of the number of occupants and their activity. This standard recommends a CO_2 concentration of 1800 mg/m^3 (1000 ppm) as the acceptable limit for IAQ.

The objective of this work is to evaluate the thermal comfort and IAQ of an auditorium, with solar radiation entering through east and west facing windows, using the authors' research BTR software. The auditorium design is achieved using a three-dimensional building generation methodology.

MATERIALS AND METHODS

The numerical model used in this work (implemented in the BTR software) takes into account energy and mass balance linear integral equations, utilized in the evaluation, in transient conditions, of the temperature field of opaque and transparent bodies of the auditorium, of the air temperature inside the space, and of the mass field of the air indoors for the water and CO_2 concentration. Using dimensionless coefficients, the heat transfer by convection phenomena are calculated by natural, forced and mixed convection. The heat exchanges by radiation, incident solar radiation, solar radiation

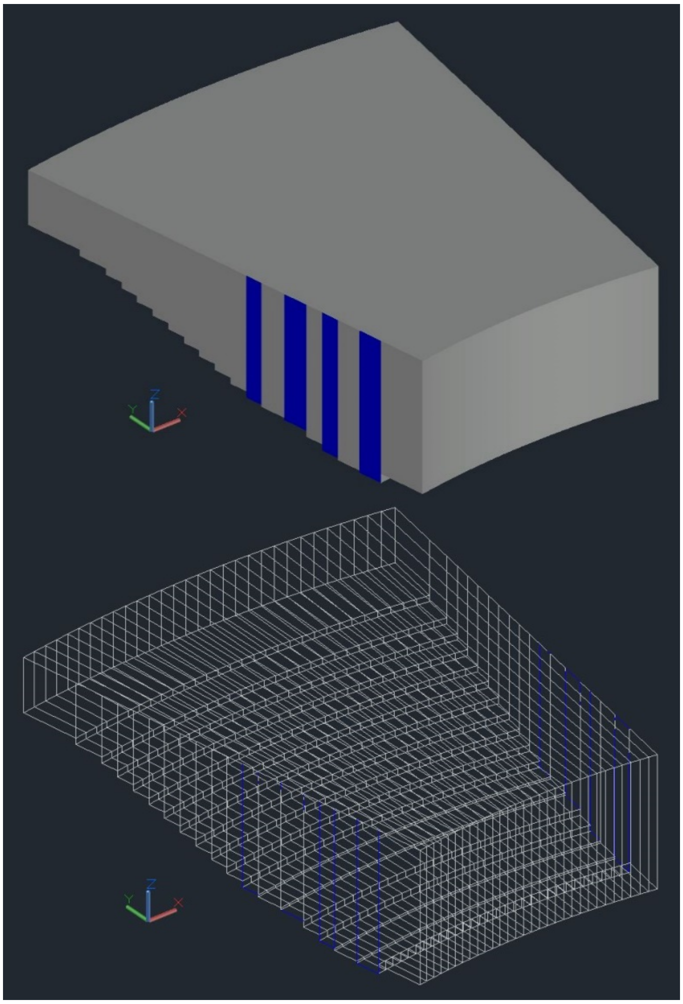

Figure 1: Virtual auditorium. Windows are shown in blue. The grid generation is shown in the bottom image.

absorbed by glasses and solar radiation transmitted through the glass are considered. This numerical model also calculates the PMV index, among other parameters.

The virtual auditorium used in the simulations is shown in Figure 1. The auditorium is occupied by 420 people (maximum occupancy). 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 clothing level of 1.0 clo (ISO 7730, 2005). The occupancy cycle is as follows: from 8 am to 12 pm; from 2 pm to 6 pm. Forced air ventilation with an airflow rate according to the values presented in Table 1 is used in the indoor air renewal process. These values are presented as a percentage of the airflow rate value recommended by ASHRAE 62.1 (2016) for the 420 occupants of this auditorium.

Numerical simulations were done for cold winter conditions in the region of the auditorium, characterized by a Mediterranean-type climate. Six

Table 1. Indoor air renewal process used. The airflow rate is in percentage of the recommended value by ASHRAE 62.1 (2016) for 420 occupants.

From	To	Daily cycle airflow rate (%)				
		0:00-8:00	8:00-12:00	12:00-14:00	14:00-18:00	18:00-24:00
Outdoors	Indoors	5	50	12.5	50	5
Indoors	Outdoors	5	50	12.5	50	5

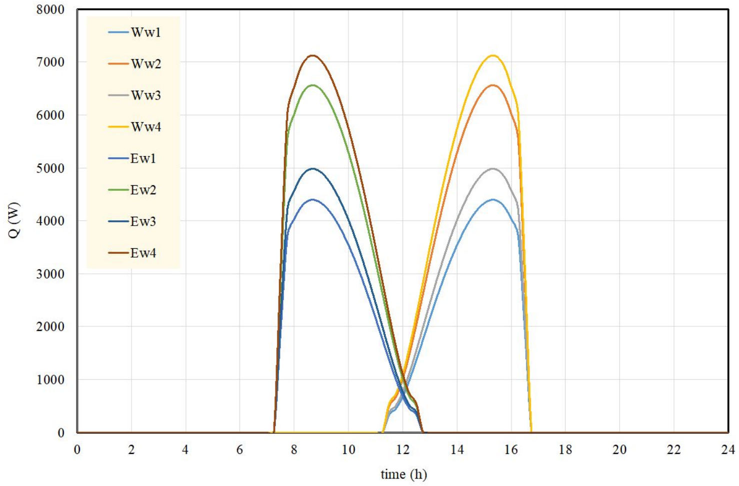

Figure 2: Evolution of the radiation solar in the windows installed on the east (E) and west (W) facades. The lowercase ‘w’ followed by a number refers to each of the windows.

consecutive days were simulated, but only the results of the last day will be shown.

RESULTS AND DISCUSSION

Figure 2 shows the evolution of solar radiation in the windows installed on the east and west facades. As can typically be seen in buildings located in the northern hemisphere, the windows installed on the east facade receive solar radiation during the morning, with the highest amplitudes verified in the beginning of the morning, and the windows installed on the west facade receive solar radiation during the afternoon, with the highest amplitudes verified in the late afternoon. The differences in amplitudes are due to the slight slope of the facades (see Figure 1).

The evolution of CO_2 concentration inside the auditorium is shown in Figure 3. As can be seen, the values are slightly above the acceptable limit for IAQ suggested by ASHRAE 62.1 (2016). However, they meet the acceptable limit of 2250 mg/m^3 suggested by the Portuguese standard (Portaria n.° 353-A, 2013).

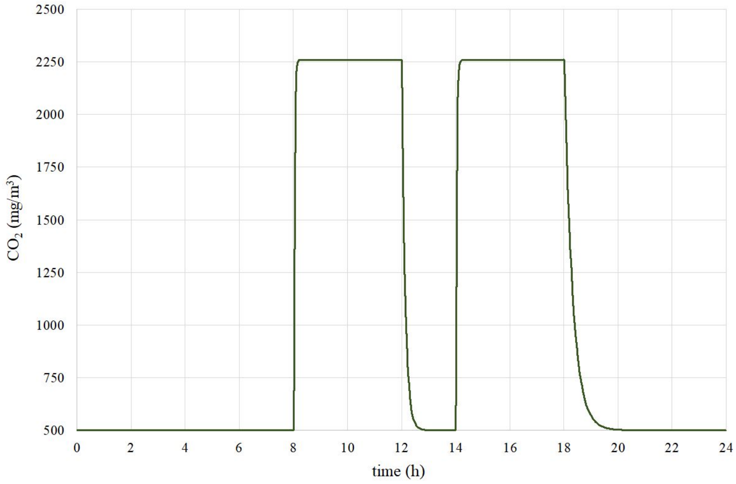

Figure 3: Evolution of the CO_2 concentration inside the auditorium.

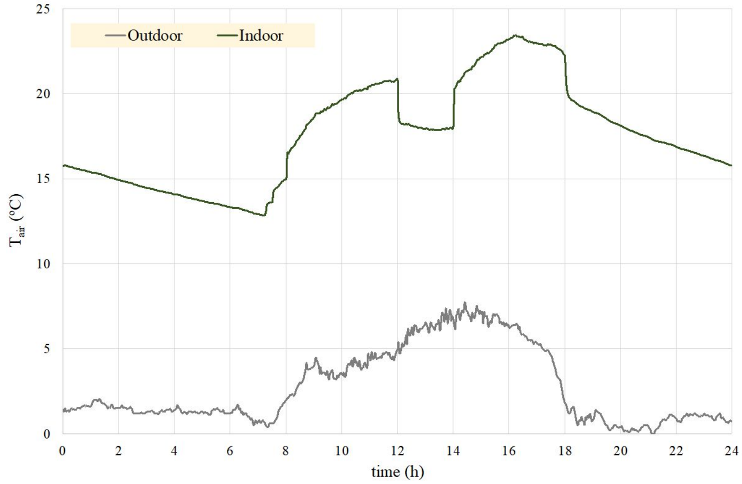

Figure 4: Evolution of the air temperature (T_{air}) inside the auditorium and outdoors.

The evolution of indoor and outdoor air temperature is shown in Figure 4. When the auditorium is occupied, the air temperature is higher in the afternoon than in the morning. The compartment heats up throughout the day due to the accumulation of heat from the solar radiation transmitted through the windows and the heat transferred by its 420 occupants. Note that shortly after 4 pm the compartment stops receiving solar radiation through the windows. During the afternoon occupation period, the indoor air temperature varies between 20.3°C and 23.5°C.

The evolution of PMV index is shown in Figure 5. When the auditorium is occupied, the thermal comfort level is unacceptable due to negative values of the PMV index; however, these values are rapidly approaching the accepted limit. From about 2.45 pm, during the afternoon occupancy period, the thermal comfort level is acceptable by negative values of the PMV index within category C of ISO 7730 (2005).

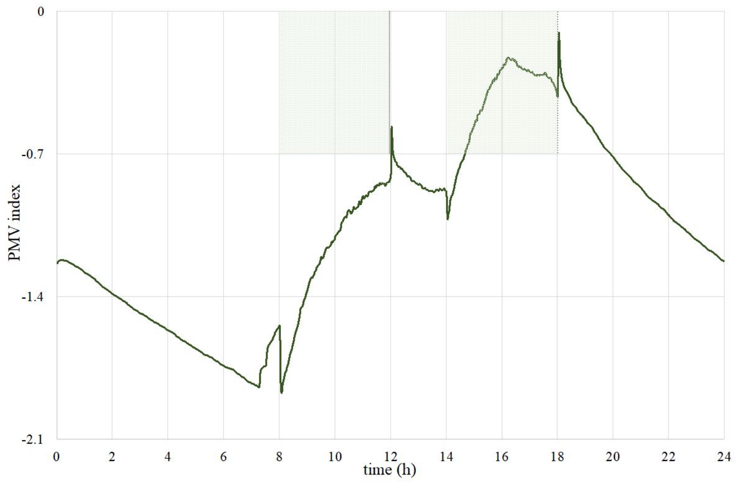

Figure 5: Evolution of PMV index. The shaded area represents Category C of ISO 7730 (2005).

CONCLUSION

In this work, the thermal response of an auditorium occupied by 420 people was analyzed. This auditorium receives solar radiation through windows located on the east and west facades, promoting the heating of the interior space. The air flow rate of the forced ventilation system used was adjusted to provide the best possible levels of IAQ and occupants' thermal comfort. An acceptable level of IAQ was achieved according to Portaria n.° 353-A (2013). An acceptable level of thermal comfort was only achieved during the afternoon, with PMV values within Category C of ISO 7730 (2005). However, during the morning there was a significantly progressive increase in PMV values towards the acceptable level. Thus, in order to take advantage of the incoming solar radiation, it is suggested to install a Dual Skin Facade system on the south facade, using the heat produced in this system to improve the thermal conditions inside the auditorium.

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