Numerical Design of a DSF System Subjected to Solar Energy and Applied in Building Occupied Spaces

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Abstract

A numerical design of a DSF (Double Skin Facade) system subjected to solar energy and applied to the heating of occupied spaces inside a building, in winter conditions, is presented in this study. The simulation is done using a building dynamic thermal response software to assess, among other parameters, the solar radiation incident on the DSF, the occupant thermal comfort level, indoor air quality level and thermal energy production. The occupant thermal comfort level is assessed by the Predicted Mean Vote index. The indoor air quality is assessed by the carbon dioxide concentration. The space considered in this study is an auditorium occupied by 210 people. The DSF system was installed on the south facade of this auditorium. The DSF system consists of 25 DSF. Each DSF consists of two surfaces, an opaque interior and a transparent exterior, separated by an air channel. This channel is used to heat the air that will be transported, through ducts, to the indoor HVAC (Heating, Ventilating and Air Conditioning) system, which is founded on a mixing ventilation system. The thermal energy produced in this way ensures an acceptable level of thermal comfort during most of the occupancy time and a level of indoor air quality close to acceptable. Therefore, it can be concluded that the HVAC system guarantees a good compromise between the thermal comfort of the occupants and the quality of the indoor air.

Introduction

Double skin facades (DSF) are a kind of architectural element that can provide advantages regarding to thermal comfort and energy savings, among other aspects (Shameri et al., 2011). DSF advantageously uses solar energy for heating indoor spaces in winter conditions (Carlos et al., 2011), on the one hand, and shading devices to limit the entry of solar radiation in summer conditions (Hashemi et al., 2010), on the other hand.

The DSF consists of two surfaces (“skins”), being one usually glazed, divided by a ventilated air channel. Shading devices or photovoltaic cells can be installed in this air channel (Hazem et al., 2015; Lee and Chang, 2015). The characteristics of the DSF depend on the facade typology, surface coverage, air ventilation strategies, incorporation of shading devices, use and location of the building, among others (Poizaris, 2004). The airflow rate within the air channel can be controlled naturally, mechanically or using fans (Ghaffarianhoseini et al., 2016). The thermal process and energy savings provided by the DSF are affected by the air temperature, air velocity and airflow pattern verified in the air channel (Lee et al., 2015; Parra et al., 2015; Li et al., 2019).

The study of Ghaffarianhoseini et al. (2016) demonstrates how some DSF technical features influence energy efficiency and thermal performance of buildings. Building orientation, channel width, surfaces materials, air ventilation strategies, climatic conditions, among others, influence the DSF in terms of thermal and energy behaviour (Ziasistani and Fazelpour, 2019; Fatnassi et al., 2018; Wang et al., 2019; Zhang and Yang, 2019; Kuznik et al., 2011).

The thermal comfort of the occupants of spaces equipped with Heating, Ventilation and Air Conditioning (HVAC) systems is usually evaluated by two indexes, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), both developed by Fanger (1970). These indexes depend on four indoor environmental parameters (air temperature, air relative humidity, air velocity and mean radiant temperature) and two personal parameters (clothing and activity levels). PMV and PPD were included in the ISO (2005) standard to define three indoor thermal comfort categories: A ($-0.2 \leq PMV \leq +0.2$), B ($-0.5 \leq PMV \leq +0.5$) and C ($-0.7 \leq PMV \leq +0.7$). The application of these indices in the assessment of the thermal comfort of occupants of interior spaces of buildings supplied by HVAC systems can be analysed in the numerical studies carried out by Conceição et al. (2009; 2018; 2019).

Carbon dioxide (CO_2) concentration is a useful parameter in assessing indoor air quality (IAQ) as well as ventilation system performance (Asif et al., 2018; Conceição et al., 1997; Laverge et al., 2011). Considering steady-state conditions, ASHRAE (2016) shows the relationship between the airflow rate and expected CO_2 concentration. This standard (ASHRAE,

2016) also refers a CO_2 concentration value below 1800 mg/m^3 as the acceptable level for IAQ.

The numerical work presented here was carried out using an own research software, the Building Dynamic Thermal Response (BDTR). This software has already been applied in previous studies in the analysis of the thermal response of buildings, focusing on some particular characteristics such as orientation, shading (Conceição and Lúcio, 2010), radiant surfaces, air ventilation strategies used, thermal comfort evaluation methods used (Conceição et al., 2010), among others.

In this work, it is applied a DSF system, installed on the south facade of an interior space (auditorium), which is connected by ducts to an HVAC system. The purpose of this numerical study is to evaluate the performance of this ventilation system, both in terms of the thermal comfort of the occupants and in the IAQ of that space, for winter conditions.

Models and Materials

The BDTR software is used in this work. The BDTR numerical model is founded in a building thermal response methodology. BDTR functions in transient conditions and considers energy and mass balance integral equations.

The energy balance integral equations are used in the calculation of the temperature field of:

- All DSF surfaces and the air within the DSF channel;
- Opaque bodies (walls and ceiling), indoor bodies and internal air of the auditorium.

The mass balance integral equations are used in the calculation of the mass field of:

- The concentration of water vapor and CO_2 inside the DSF;
- The concentration of water vapor and CO_2 inside the auditorium.

The linear equations system, of first order integral equations, is solved using the Runge-Kutta-Felberg method with error control.

The energy balance linear integral equations considers the convection, conduction and radiation phenomena:

- Dimensionless coefficients are used to calculate the heat transfer by natural, forced and mixed convection. These coefficients are applied in the surfaces of the glasses and the opaque bodies;
- The heat transfer by conduction is calculated in the opaque surfaces, between the different layers;
- The radiative heat exchanges are calculated considering the incident solar radiation, the absorbed solar radiation (by glasses and opaque bodies) and the transmitted solar radiation (through the glass).

All convective coefficients are calculated during the numerical simulation using adimensional coefficients for forced, mixed and natural convection. In this calculus, among other variables, the air temperature, the surface temperature and the air velocity are considered.

The glass radiative coefficients, as the absorption, reflection and the transmission, are calculated, during the simulation, using the incident solar radiation intensity, the incident solar radiation angle and the glass thickness. The opaque radiative coefficients, namely the absorption and reflection, are calculated using the incident solar radiation intensity and the surface color.

The mass balance linear integral equations consider the convection and diffusion phenomena.

As the compartment of a building to be analysed in this work, an auditorium, similar to an existing real one, was find. The geometry of this auditorium (see Figures 1 and 2) was generated by a Computer Aided Design software using cylindrical coordinates. On the south facade of this auditorium, it was installed a set of 25 DSF (marked in blue in Figures 1 and 2) with identical dimensions. Each DSF has an opaque inner surface (consisting of the compartment facade itself) and an outer glass surface. These two surfaces are separated by an air channel with a width of 40 cm.

The auditory geometry is used, in the numerical software, to generate the grid and calculate the opaque, interior and transparent areas. The grid generation is used to calculate the incident solar radiation, in each surface, during all day. The area, with the identification of the opaque, transparent and interior bodies, are used to identify all dimensions and materials.

The auditorium geometry is based on geometric equations, based in cylindrical coordinates, to generate the geometry of the building. The geometry of the auditorium considers the side walls, stage walls, back walls, ceiling, floor, steps, DSF and glasses surfaces. The output data of the auditorium geometry numerical model is then transferred to Computer Aided Design (CAD) software and Building Dynamic Thermal Modelling numerical model.

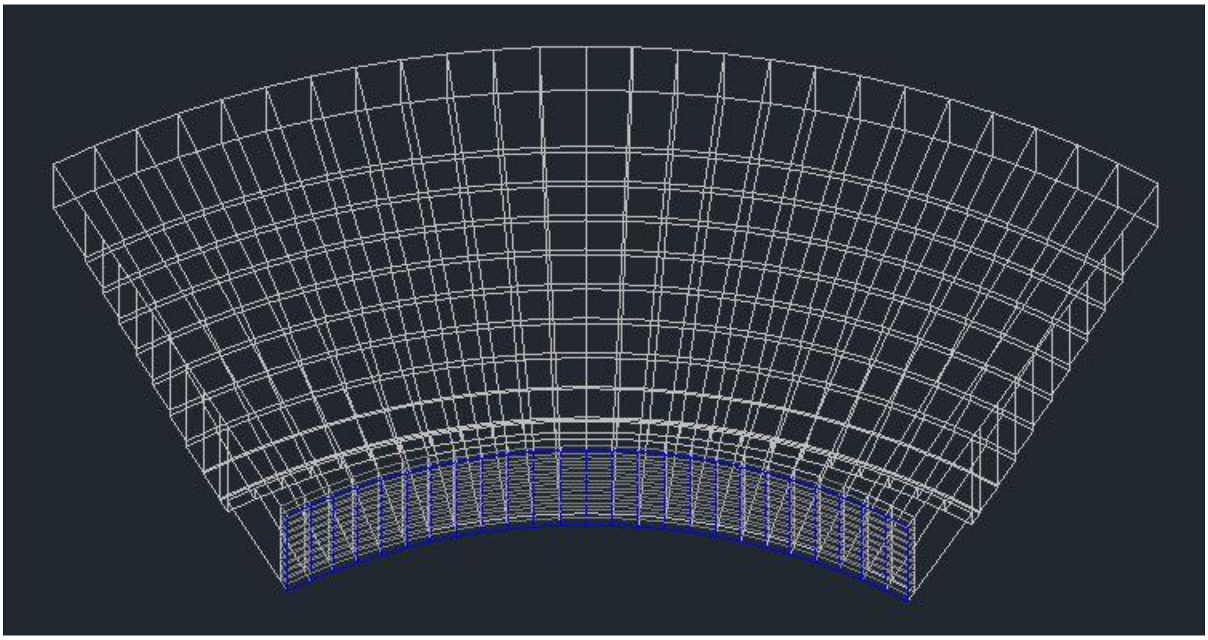

Figure 1: Mesh generation of the auditorium (white lines) and the DSF system (blue lines) – view from the south side.

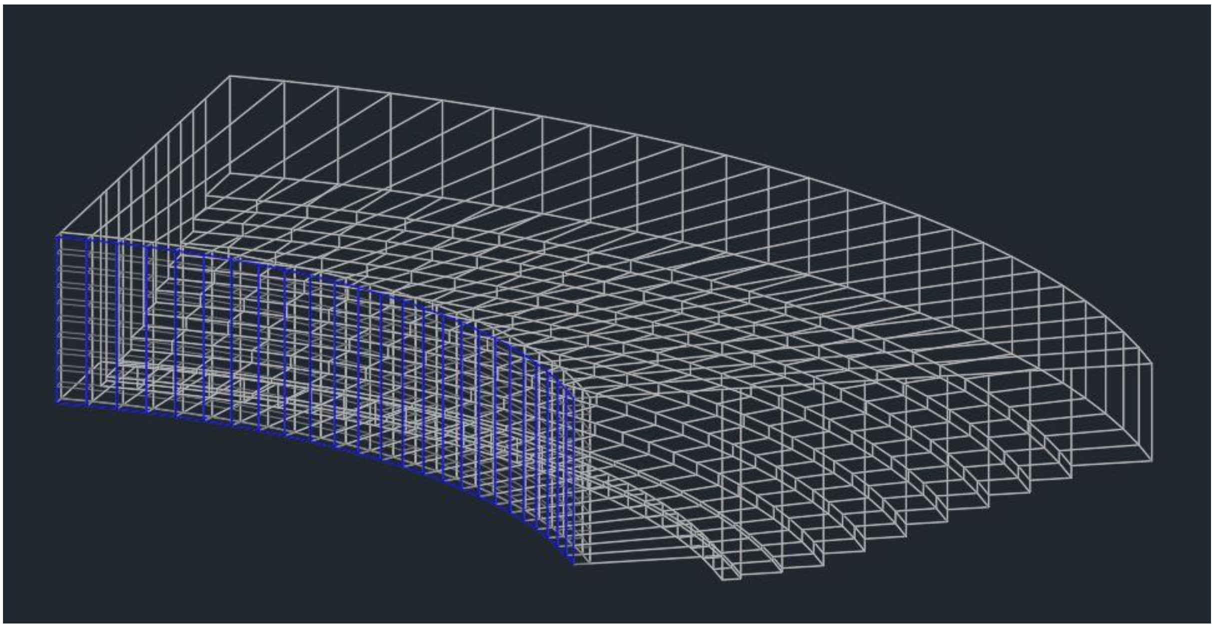

Figure 2: Mesh generation of the auditorium (white lines) and the DSF system (blue lines) – view from the south-east side.

The numerical simulation was carried out for a cold winter day in the region where the auditorium is located, which has a typically Mediterranean climate (south of Portugal). The results presented correspond to the sixth day of the simulation in order to allow them to stabilize.

Considering a day with clear sky, this winter day (22 th December) is characterized by an outdoor air temperature fluctuating between 0.0°C and 7.0°C, an outdoor air relative humidity fluctuating between 37.2% and 65%, and a wind speed fluctuating between 0.01 m/s and 6.25 m/s. The outdoor CO^2 concentration is 500 mg/m^3.

The auditorium is occupied by 210 people during an occupation cycle (variation of occupation during the day) that takes place between 8 am and 12 pm, in the morning, and between 2 pm and 6 pm, in the afternoon. People have a typical clothing level of 1.0 Clo and a seated activity level of 1.2 met (ISO, 2005). The airflow rate used is 1.05 m^3/s, which corresponds to the suggested value for an occupancy of 105 people (ASHRAE, 2016).

The ventilation system, developed in this work, considers the air from the external environment to be heated in the DSF system and to be transported to the auditory interior space. The warm air is diluted in the auditory, around the occupants, and after is transferred to the external environment.

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Results and discussion

This section presents and discusses the results obtained from the one-day evolution of the CO_2 concentration (Figure 3), of the incident solar radiation in the DSF system (Figure 4), of the air temperature (Figure 5) and of the PMV index (Figure 6).

The concentration of CO_2 obtained, when the auditorium is occupied, about 2250 mg/m^3 on average, is slightly above the acceptable value (1800 mg/m^3) proposed by the standard (ASHRAE, 2016). The IAQ level can be considered to be close to acceptable. However, when the auditorium is not occupied, the concentration of CO_2 is lower than the acceptable value.

The evolution of solar radiation incident on the DSF shows that, between about 10 am and 2 pm, the values obtained remain relatively constant and close to their maximum. Analysing DSF by DSF, it appears that the evolution of solar radiation is as expected when the solar incidence varies from east to west. For example, the maximum value of incident solar radiation in DSF1 (facing further east) occurs around 10 am, in DSF13 (facing south) it occurs around noon, and in DSF25 (facing further west) it occurs at around 2 pm. The average value of incident solar radiation obtained was 3392 W. The maximum value of incident solar radiation obtained was 3401 W in DSF4 and DSF23. The minimum value of incident solar radiation obtained was 3381 W in DSF13 and DSF14.

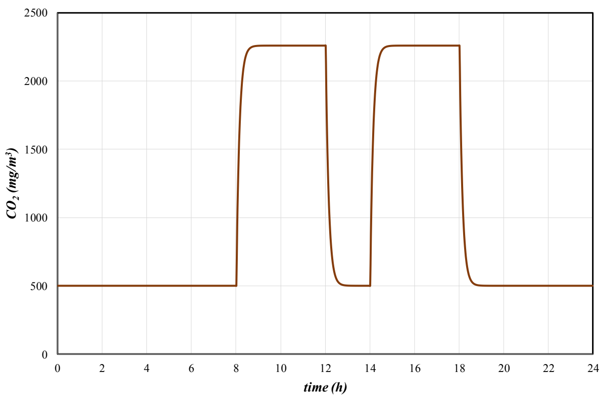


Figure 3: Daily evolution of CO_2 concentration inside the auditorium.

During the occupancy cycle, using the DSF system, there is an increase in the air temperature inside the auditorium with a substantially linear variation between 12.5ºC and 22.4ºC during the morning. During the afternoon, the air temperature inside the auditorium fluctuates slightly between 23.3ºC and 25.2ºC. During this period, it is possible to maintain a relatively constant indoor air temperature within the values recommended by the Portuguese standard.

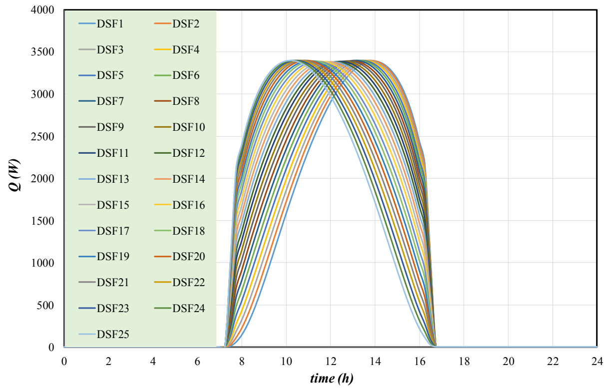
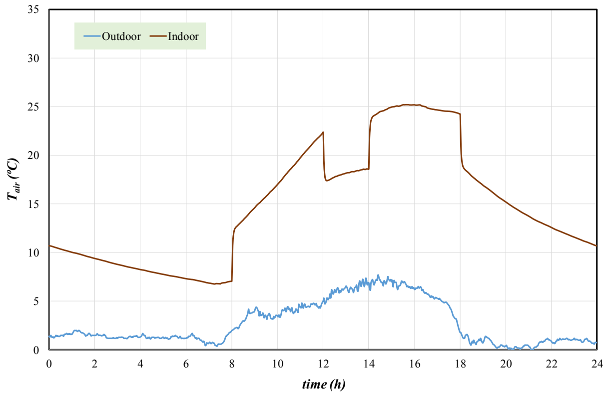
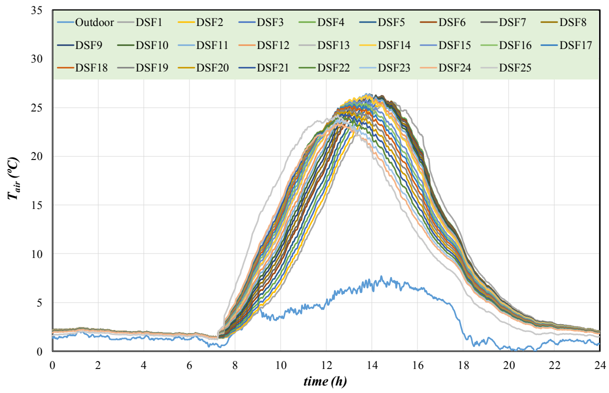


Figure 4: Daily evolution of solar radiation incident on each of the twenty-five DSF mounted on the south façade of the auditorium.



a)



b)

Figure 5: Daily evolution of air temperature: a) inside the auditorium and outside; b) inside the air channel of each of the twenty-five DSF.

During the occupancy cycle, the indoor air temperature increases, on average, by 16.0ºC relative to the outdoor temperature. In this natural way, the DSF system contributes positively to the heating of the air to be supplied in the auditorium, thus avoiding additional electrical energy consumption.

The evolution of the air temperature inside the DSF air channel shows its direct dependence on the incidence of solar radiation on its external glazed surface. It can be seen that in the air channel of all DSF the temperature rises well above the outside temperature, up to about 18ºC above. It is also verified that the air temperature in the air channel of the DSF remains significantly above the outside temperature until about 20h, sometime after sunset.

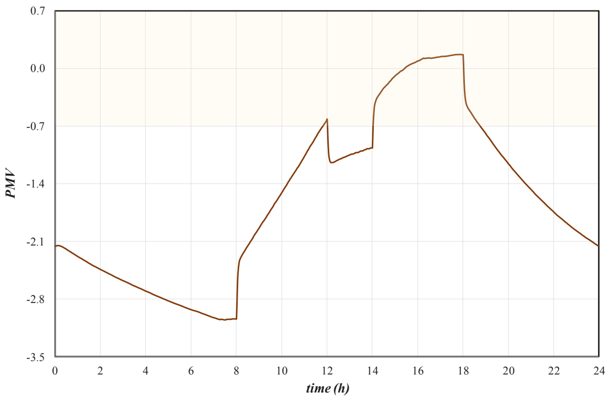


Figure 6: Daily evolution of PMV index inside the auditorium. The shade area represents the limits of Category C of ISO (2005).

During the occupancy cycle, the evolution of the PMV index inside the auditorium shows that its value improves throughout the morning, although within the uncomfortable zone. This evolution follows the evolution obtained for the air temperature. Just before noon, the value of the PMV index reaches the comfortable zone defined by category C (ISO, 2005).

During the occupancy cycle, the evolution of the PMV index inside the auditorium shows that its value, throughout the afternoon, remains within the comfortable zone defined by category C (ISO, 2005).

Therefore, this system somehow manages to guarantee a good compromise between the IAQ and an acceptable level of thermal comfort for the occupants during the afternoon. During the morning, it is possible to obtain a level of thermal comfort for the occupants close to acceptable.

The DSF system improves the thermal comfort level. However, is important analysing the glasses dimensions, the incident solar radiations, the occupation cycle, the ventilation strategies and the airflow rate. In general, in accordance with the obtained results, the internal air temperature and the thermal comfort level increase from the beginning of the morning to the middle afternoon.

The airflow rate promoted by the ventilation system is important to guarantee acceptable thermal comfort level and indoor air quality. The airflow should be used to reduce, in accordance with the obtained results, not only the CO_2 concentration when the space is occupied, but also when the space is not occupied.

Conclusion

This article presented a numerical study on the performance of a DSF system in obtaining thermal comfort levels for the occupants and in the IAQ of an auditorium. The PMV index was used to assess the thermal comfort level of the occupants and the CO_2 concentration was used to assess the IAQ level.

The most relevant conclusions are the following:

- During occupancy, the CO_2 concentration level is slightly above acceptable;
- During occupancy in the morning, the occupants' thermal comfort level is unacceptable due to negative values of the PMV index, although its values improve until reaching the comfortable zone shortly before noon;
- During afternoon occupancy, the occupants' thermal comfort level is acceptable by PMV index values within category C of the standard;
- In general, it can be considered that this system promotes a good compromise between the IAQ and the thermal comfort level of the occupants.

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