Numerical simulation of Double Skin Facade used to produce energy in buildings

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ABSTRACT

This article introduces a numerical model to project and construct a Double Skin Facade (DSF) in windows facing south, in order to be used on thermal energy generation in winter conditions. The DSF system is applied to a virtual chamber similar to a real experimental chamber and it is connected to a mixing ventilation system. The thermal energy generated by this DSF system is used to further indoor air quality and thermal comfort for occupants. The numerical simulation is done by a software that simulates the virtual chamber and the DSF thermal response. This software uses energy and mass balance integral equations for the opaque surfaces, transparent surfaces and internal air. It also considers the solar radiation simulator, the glass radiative properties and the assessment of radiative and convective coefficients. The results show that the proposed DSF system, using solar radiation, contributes to having acceptable conditions of thermal comfort, during most of the occupation cycle, and indoor air quality.

INTRODUCTION

Double Skin Facade (DSF) is one of the most promising technical solutions applied to building facades that allows control of the building's inside environment from the outside environment (Ghadamian et al., 2012). DSF can be defined as “a special type of envelope, where a second skin, usually a transparent glazing, is placed in the front to a regular building facade” (Hazem et al., 2015). The air cavity between these two “skins” (panes) has a width between 20 cm to 2 m (Parra et al., 2015). Devices such as Venetian blinds (Hazem et al., 2015) or photovoltaic cells (Luo et al., 2018) can be settled in this air cavity. The air ventilation in this cavity can be regulated by natural, mechanical or hybrid (applying fans) ventilation techniques (Ghaffarianhoseini et al., 2016). The performance of the DSF depends on the type of facade, the second pane coverage, the air cavity dimensions and the shading devices here installed, the air ventilation strategies, the use and location of the building, among others (Poirazis, 2004). The use of DSF is a good solution for obtain several improvements such as “heat gain control, thermal buffer zone, energy savings and aesthetics” (Ahmed et al., 2019). Buildings sound insulation and thermal performance can be upgraded by using shading devices within the DSF (Hazem et al., 2015; Lee et al., 2015). The air velocity, airflow and air temperature in the cavity are affected by the blinds geometry, materials, properties and orientation, which in turn will influence energy production and thermal behavior in the DSF (Parra et al., 2015; Lee et al., 2015; Lee & Chang, 2015; Li et al., 2019).

Usually, the evaluation of the indoor air quality and ventilation system performance of a building can be done using indoor measurements of carbon dioxide (CO_2) concentrations (Asif et al., 2018; Conceição et al., 2008a; Laverge et al., 2011). The relationship between CO_2 concentration and ventilation rate, under steady-state conditions, is presented in ASHRAE Standard 62.1:2016. This standard also shows that an acceptable indoor air quality can be achieved for a CO_2 concentration below 1800 mg/m^3.

Developed by Fanger (1970), PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indexes are mostly used to evaluate the indoor thermal comfort in occupied spaces. These indexes were introduced in ISO 7730:2005 to define three comfort categories: category A (−0.2 < PMV < +0.2; PPD < 6%), category B (−0.5 < PMV < +0.5; PPD < 10%) and category C (−0.7 < PMV < +0.7; PPD < 15%).

This numerical work uses a software, developed by the authors over the last years, that simulates the building thermal dynamic response. As example, it was applied to vehicles (Conceição et al., 2000), and to buildings with internal greenhouses (Conceição et al., 2008b), with implemented active and passive solutions (Conceição & Lúcio, 2010a) and with the use of solar radiation from windows (Conceição & Lúcio, 2009). This software also calculates PMV and PPD indexes using the indoor air temperature, indoor air velocity, indoor air relative humidity, and occupants’ clothing and activity levels, as was shown, for example, in the studies of Conceição & Lúcio (2016) and Conceição *et al.* (2009, 2010a, 2018). Concerning the indoor air quality evaluation, this software calculates the CO_2 concentration inside the occupied spaces (Conceição et al., 2010b; 2013).

The objective of this work is the development of a numerical model of design and construction of DSF in windows facing south in order to heat interior spaces in winter conditions. In this way, it is possible to achieve thermal comfort conditions and indoor air quality for the occupants using a passive technical solution with consequent energy savings.

MODELS

In this work, a whole building thermal response software, founded in numerical methods developed by the authors over the years, is applied (Conceição & Lúcio, 2010a; Conceição et al., 2000). The building thermal response numerical model was presented and applied in the study of Conceição & Lúcio (2010a). The solar radiation and glass radiative proprieties numerical models, and the convection heat transfer coefficients were introduced in the study of Conceição et al. (2000). The building thermal response numerical model was validated in winter conditions (Conceição et al., 2004) and in summer conditions (Conceição & Lúcio, 2006).

The numerical model uses energy and mass balance linear of first order integral equations, which are solved by the Runge-Kutta-Felberg method with error control. These equations are used to calculate, in transient conditions, the temperature field of the DSF system and of the virtual chamber opaque and transparent bodies, and the water and contaminants mass field of the air within the DSF system and virtual chamber.

The energy balance linear integral equations take into account the phenomena of convection, conduction and radiation:

- The heat transfers by natural, forced and mixed convection are evaluated using dimensionless coefficients, which are used in the opaque and glazed surfaces;
- The heat transfer by conduction is verified within the opaque surfaces, between the different layers;
- The considered radiative heat exchanges are the incident solar radiation, the absorbed solar radiation by transparent (glasses) and opaque bodies and the transmitted solar radiation through the transparent (glasses) surfaces;
- The radiation phenomenon considers the shading devices within the DSF system. Details about this phenomenon are presented in the study of Conceição & Lúcio (2010b), where a curtain of trees is used to improve the thermal comfort level of the occupants, and in the study of Conceição & Lúcio (2008), where a building structure shading device is applied according to the same objective.

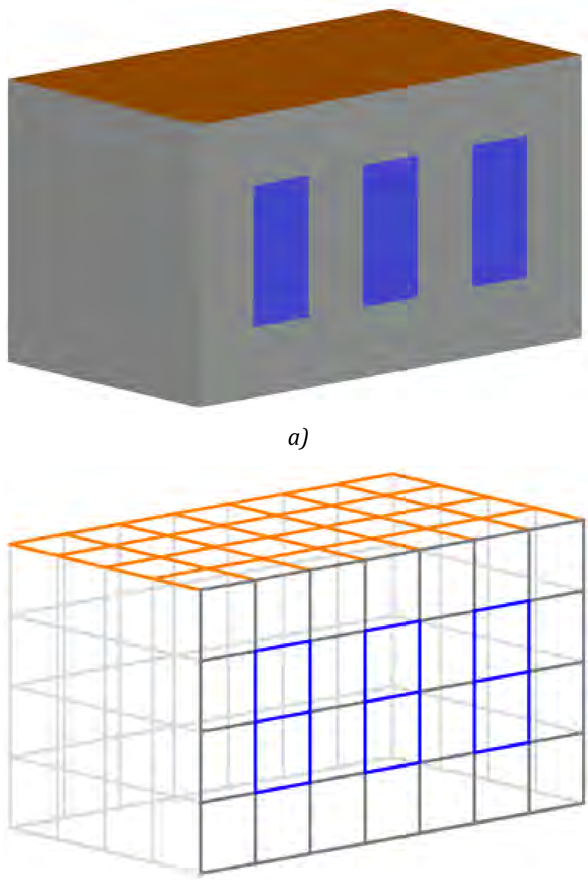
The energy balance linear integral equations are used to evaluate the temperature of the:

- Venetian blind, inner (window) and outer glasses, DSF surrounding structure and air inside the ventilated DSF;
- Opaque bodies (door, walls, floor and ceiling), transparent (glazed) bodies, indoor bodies and internal air of the virtual chamber.

The mass balance linear integral equations, considering the convection phenomenon, are used to evaluate mass concentration of the water vapour and contaminants (for example, CO_2) concentration inside the DSF and inside the virtual chamber.

MATERIALS

The virtual chamber (Figure 1) used in this work is similar to an existing experimental chamber and it has the dimensions presented in Table 1. It consists of wood and is insulated with extruded polystyrene with a thickness of 40 mm. The virtual chamber is built with square-section bars, that support 108 square modules of 60×60 cm^2 distributed as follows: 28 modules in each side wall and ceiling; 16 modules in the rear wall; and 8 modules in the front wall. The virtual chamber has two doors, each one with 0.6 m by 2.5 m dimensions, and three windows, each one with 0.6 m by 1.2 m dimensions.

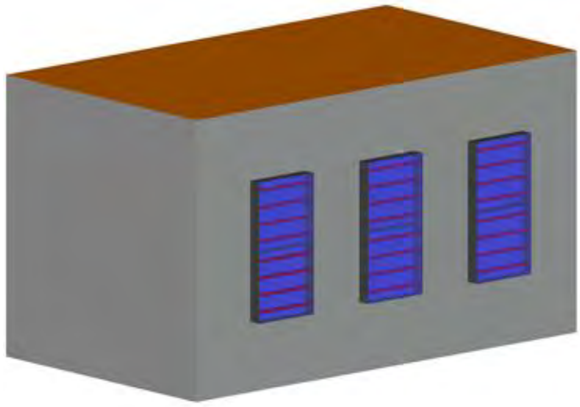


a)

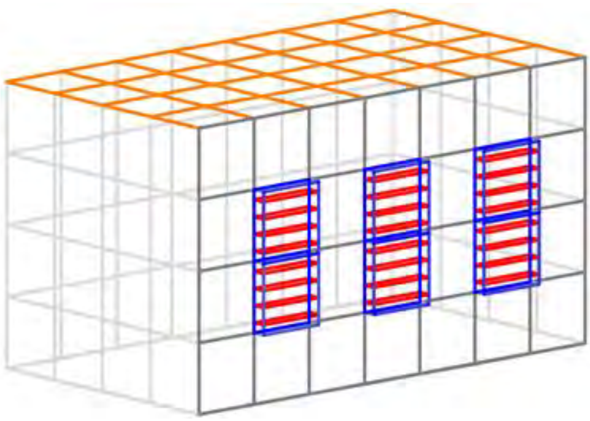
b)

Figure 1. Virtual chamber: a) without and b) with the representation of the square modules. Grey colour represents the opaque walls, orange colour represents the ceiling and blue colour represents the windows

The projected and constructed DSF system by the numerical model is constituted by three DSF (Figure 2) and each one has the dimensions presented in Table 1. The DSF are installed in the south-facing envelope of the virtual chamber and are subject to the effect of incident solar radiation. Each DSF consists of two glazed surfaces, each one with a thickness of 4 mm, and a surrounding structure. It is outfitted with a Venetian-type blind with an adjustable set of eight aluminium lamellae located in the air cavity. The dimensions of each lamella are presented in Table 1. The DSF consists of two transparent surfaces (glasses), each one with a thickness of 4 mm and a surrounding structure. It has an adjustable set of eight aluminium lamellae located between the transparent surfaces. The dimensions of each lamella are presented in Table 1.



a)



b)

Figure 2. Virtual chamber with DSF system: a) without and b) with the representation of the square modules. Grey colour represents the opaque walls, orange colour represents the ceiling, blue colour represents the windows and red colour represents the Venetian blinds

Table 1. Dimensions of the main elements

Element	Virtual Chamber	DSF	Lamella
Length (m)	4.50	0.60	0.60
Width (m)	2.55	0.20	0.12
Height (m)	2.50	1.20	-
Thickness (mm)	-	-	10

The input data of the numerical simulation are the outdoor air temperature, air relative humidity, wind velocity and wind direction, obtained in a winter typical day by a weather station located in the South region of Portugal. The simulation was done for 24 hours supposing clean sky. A typical winter day, as the 21st December, was used to determine the evolution of solar radiation on that day.

The virtual chamber has eight occupants during an occupation cycle between the 8 and 12 hours and between the 14 and 18 hours of the day. In the assessment of the PMV index, a metabolic rate of 1.2 met and a clothing insulation level of 1 clo were used (ISO 7730:2015). During occupation, an airflow rate of 0.0778 m^3/s, suggested by the standards for an occupation of eight persons, was used in the numerical simulation. In the vacancy period, one renewal airflow rate per hour is used.

RESULTS AND DISCUSSION

At this point, the numerical results obtained, for winter conditions, in the virtual chamber and DSF will be presented and discussed, where appropriate, according to the following parameters: CO_2 concentration, Mean Radiant Temperature (MRT), air temperature, PMV index, thermal power and thermal energy.

Indoor air quality

Indoor air quality is assessed by the concentration of CO_2 (ASHRAE 62.1:2016). Figure 3 shows the evolution of the CO_2 concentration inside the virtual chamber.

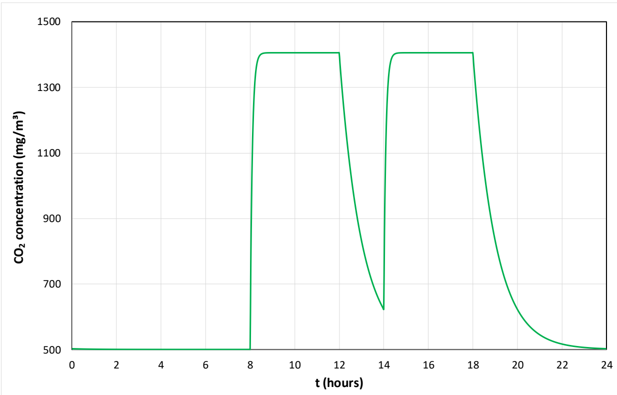


Figure 3. Evolution of the CO_2 concentration inside the virtual chamber

The evolution of the CO_2 concentration inside the virtual chamber presents values below the limit of 1800 mg/m^3, so it can be concluded that, during the occupation cycle, the indoor air quality is acceptable for the occupants.

Air temperature

Figure 4 shows the evolution of the MRT inside the virtual chamber and the air temperature outside, inside the DSF and inside the virtual chamber. Note that the values shown correspond to the average of the values obtained inside the space.

Throughout the day, the MRT varies between the minimum value of 15.9°C and the maximum value of 18.6°C, values obtained during the occupation period.

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During the occupation period, the indoor air temperature of the virtual chamber varies between 16.3°C and 21.1°C in the morning and between 19.7°C and 22.2°C in the afternoon. The air temperature inside the virtual chamber is higher during the afternoon, generally above 20°C, than during the morning, most of the time below 20°C.

Under the effect of solar radiation, the indoor air temperature in the DSF increases between 8.3°C, calculated in the early morning, and 21.4°C, obtained at 1.30 pm, and then decreases until 10.8°C, calculated in the late afternoon. As the façade where the DSF are located faces south, so the evolution of the air temperature inside the DSF follows the evolution of solar radiation, typically obtained from facades facing south in the region where the simulated building is located. The DSF system allows to heat the outside air that is insufflate into the interior space of the virtual chamber between 0.8°C (early morning) and 8.4°C (around 1 p.m.).

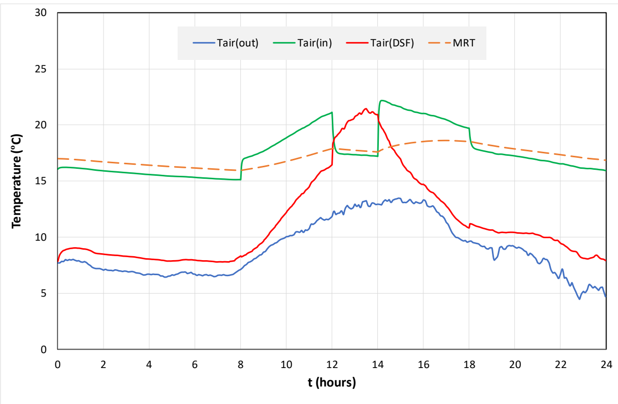

Figure 4. Evolution of the MRT, outdoor air temperature (Tair(out)), indoor air temperature (Tair(in)) and air temperature inside the DSF (Tair(DSF))

The MRT is lower than the air temperature inside the virtual chamber, which shows that the building's surroundings (walls, ceiling) are cooled by the outside air, which will negatively affect the level of thermal comfort of the occupants. Therefore, it is necessary to improve the insulation of the building envelope by, for example, increasing the thickness of the insulating material.

The use of the DSF system allows passively heating the air blown inside the virtual chamber, thus contributing to an improvement in the thermal conditions of that space in winter conditions. In these conditions, between 8 a.m. and 6 p.m., the average temperature of the interior space is around 19.4°C.

Thermal comfort

Thermal comfort of the occupants is assessed by the PMV index (ISO 7730:2005). Figure 5 shows the evolution of the average PMV index inside the virtual chamber to which the occupants are subjected.

During the occupation period, the PMV index values are in the range between -0.7 and 0 from mid-morning. Until mid-morning, the PMV index values gradually increase until they enter this range, which is associated to category C of ISO 7730:2005. This increase follows the increase in the indoor air temperature of the DSF. The gradual increase in the thermal energy provided by the DSF, whose value is highest around the middle of the day, allows to ensure acceptable levels of thermal comfort during the afternoon occupation period.

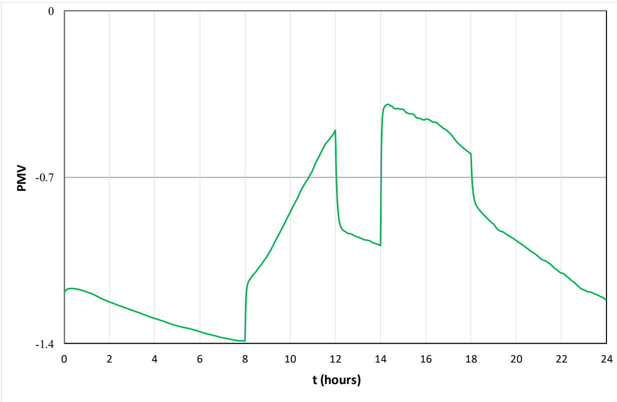

Figure 5. Evolution of average PMV index inside virtual chamber

It can thus be said that the use of DSFs ensures from mid-morning acceptable levels of thermal comfort for the occupants. The level of thermal comfort is achieved by negative values of the PMV index within the category C of ISO 7730: 2005.

Thermal power

Figure 6 shows the evolution of the thermal power inside each DSF.

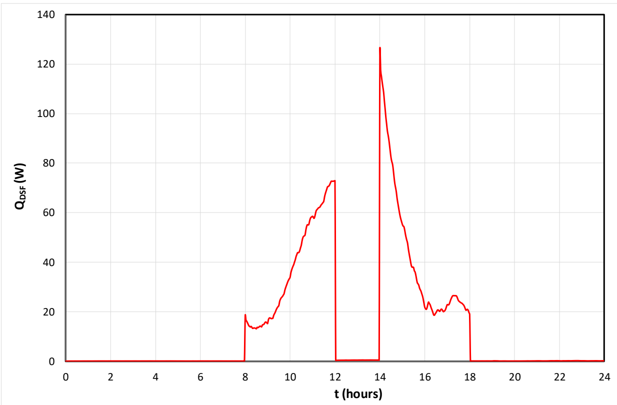

Figure 6. Evolution of thermal power (Q_{DSF}) inside each DSF

The thermal power increases during the morning and decreases during the afternoon. The maximum thermal power of 125.8 W is obtained at about 2 p.m. The evolution of thermal power throughout the day is proportional to the difference between the air temperature inside the DSF and the temperature of the outdoor air. It is also found that the availability of thermal power is much greater when the virtual camera is occupied than when it is unoccupied, because the airflow rate also increases significantly. In this way, DSF's contribution to the significant increase in the availability of thermal power for heating the interior space of the virtual chamber is confirmed.

Thermal energy

Figure 7 shows the evolution of the thermal energy accumulated throughout the day by the system made up of the six DSF.

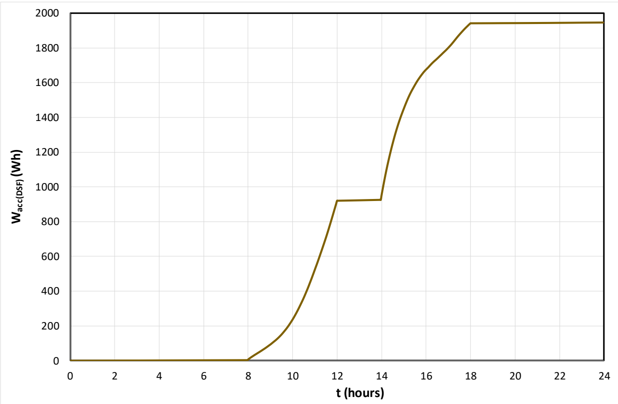

Figure 7. Evolution of the thermal energy accumulated ($W_{acc(DSF)}$) throughout the day by the DSF system

The total daily energy provided by the DSF system is 1946 Wh, of which about 47% (921 Wh) are available by the end of the morning. This value corresponds to about 85% of the value needed to heat this space during the occupation time. Therefore, the availability of this energy obtained through a passive solar device allows to obtain energy gains, since it is not necessary to have to resort to electrically driven ventilation systems during about 85% of the occupation time.

CONCLUSIONS

In this article was introduced a numerical model to project and construct a DSF system in windows located on the south facade of a building. This passive solar technique will be used, in winter conditions, to produce thermal energy used to heat the interior spaces of the building in order to guarantee acceptable conditions of thermal comfort for the occupants. At the same time, the ventilation system associated with it will have a sufficient airflow rate to guarantee acceptable levels of indoor air quality.

The proposed solution makes it possible to guarantee these three objectives at the same time. As the results show, indoor air quality is acceptable throughout the occupation period by CO_2 concentration values below 1800 mg/m^3 (ASHRAE 62.1: 2016). The evolution of the PMV index inside the occupied space presents values within category C (ISO 7730: 2015) during most of the day. Only until mid-morning, these values are below, although close to, the acceptable limit. Therefore, it can be concluded that it is possible to guarantee acceptable levels, or close to that, of thermal comfort for the occupants during the day. The daily energy gains obtained are equal to 1946 Wh.

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