Development of a building thermal solution using solar renewable energy production

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Abstract. This paper presents a numerical study of the development of a thermal solution in buildings using solar renewable energy production in winter cold conditions. The Building Thermal Modelling numerical model, using solar sources through a DSF (Double Skin Facade) system, in a virtual small building, calculates the energy distribution, the internal variables and the thermal comfort level. The study considers a virtual small building equipped with two DSF systems, installed in south-facing windows, equipped with a duct system connected to an internal ventilation system, based on a mixing ventilation system. Each DSF is used to heat two or more spaces. The DSF systems are built with two transparent surfaces, forming an internal canal used to transport the warm air and to produce thermal energy, and are equipped with a set of internal lamella. The Building Thermal Modelling numerical model uses energy and mass balance integral equations for the opaque bodies, transparent bodies, internal bodies and internal air and contaminants. The study, made in winter cold conditions, in Mediterranean environment, evaluates the internal temperature and thermal comfort level evolution that the occupants are subjected. Without DSF system, the spaces equipped with windows turned south are thermally uncomfortable by positive PMV values, while the spaces equipped with windows turned North and East are thermally uncomfortable by negative PMV values. With DSF system, in general, all spaces are thermally comfortable. When the spaces with east and south facing windows are occupied the acceptable thermal comfort is verified by negative PMV values. When the north facing space is occupied the acceptable thermal comfort is verified in the noon by positive PMV values and in the final of the afternoon by negative PMV values.

Keywords. Energy production, Building Thermal Modelling, Double Skin Façade, Energy and mass integral equations, Thermal Comfort levels.
DOI: https://doi.org/10.34641/clima.2022.70

1. Introduction

In the development of a building thermal solution is frequent used solar renewable energy production in a Double Skin Facade (DSF) system. The DSF system is developed and implemented, mainly, in south-facing windows, is built with two transparent glasses, formed an internal channel, and works by natural, forced or hybrid ventilation.

Inside the air channel various types of devices, such as venetian blinds or photovoltaic cells, are frequently installed. Some studies about this topic can be seen in Pasut and De Carli [1], Ghadamian et al. [2], Hazem et al. [3], Parra et al. [4], Luo et al. [5], Ghaffarianhoseini et al. [6], Poirazis [7], Catto et al. [8], Xue et al. [9], Lee et al. [10], Lee et al. [11] and Li et al. [12]. Pasut and De Carli [1] analysed the CFD model in the evaluation of airflow in natural ventilated DSF system. Ghadamian et al. [2] studied the energy simulation of DSF system applied in buildings. Hazem et al. [3] analysed the numerical study of the airflow ventilation to evaluate the behaviour of the DSF system. Parra et al. [4] studied the thermal response of a ventilated DSF with Venetian-type blinds. Luo et al. [5] made a study of a DSF system in winter conditions. Ghaffarianhoseini et al. [6] analysed some advantages of DSF systems. Poirazis [7] made a literature review of DSF systems in office buildings. Catto et al. [8] presented a study about the simulation of DSF system. Xue et al. [9] analysed a method for thermal study of natural ventilation in a DSF system. Lee et al. [10] studied the natural ventilation system and energy of a DSF system. Lee et al. [11] analysed the natural ventilation and the acoustical systems in a DSF system. Finally, Li et al. [12] studied the thermal performance of an DSF system in buildings.

The numerical study presented in this study considers a Building Thermal Modelling numerical model. This model was developed by the authors over the last years, and it was applied, as example, on the studies of Conceição et al. [13] and Conceição and Lúcio [14].

The solar radiation, the glass radiative proprieties and the convection heat transfer coefficients were introduced in the study of Conceição et al. [15]. The results obtained in each space of the Building Thermal Modelling are used in software that simulates the coupling of Computer Fluid Dynamics and Human Thermal Modelling in order to evaluate the comfort (see Conceição et al. [16]).

The ventilation system, considered in occupied buildings, is used to improve the thermal comfort and indoor air quality. The thermal comfort is usually evaluated by the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) people indexes, presented in the work of Fanger [17], and making part of ISO 7730 [18] and ASHRAE Standard 55 [19]. In the Building Thermal Modelling numerical model, the thermal comfort is evaluated based on the human thermal physiology (see Conceição et al. [20]). The indoor air quality is frequently evaluated using the carbon dioxide concentration, used as indicator (see ASHRAE 62 [21]). In the Building Thermal Modelling numerical model, the evolution of carbon dioxide concentration is calculated in occupied spaces. Examples of this issue can be seen in Conceição and Lúcio [22], for buildings, and in Conceição et al. [23], for vehicles.

The main objective of this numerical work is to evaluate the influence of two DSF, located in facing-south windows, on the building thermal response and thermal comfort inside an occupied virtual building. Each DSF system is connected by ducts with two or more spaces: one space facing south and others facing north. The comparative study, for winter conditions, is made with and without DSF system.

2. Numerical Model

The Building Thermal Modelling numerical model, presented in this work, was developed by the authors in the last years. This numerical model considers a building design and an energy and mass balance integral equations system.

The building design is developed by the Computer Aided Design, CAD, numerical methodology. All geometry of the building is considered. The building geometry, developed previously and used as input in the numerical model, is used to developed the energy and mass balance integral equations for the opaque, transparent and indoor bodies and for the indoor spaces:

- Each opaque body considers a group of energy equations for the different layers (doors, floor, brick, double brick, roof and others);
- Each transparent body, namely the glass, considers one energy equation;
- Each indoor body considers one energy equation;
- Each space considers one energy equation and a group of mass equations for all contaminants (carbon dioxide concentration and others) and water vapour.

In the geometry is also necessary to introduce the boundary conditions. These boundary conditions define the heat transfer fluxes inside the building. The numerical model is nodal, except when calculating radiation and radiative exchange, in which the numerical model is discretized using, at least, meshes with 10×10 elements.

Building Thermal Modelling numerical model considers energy and mass balance integral equations. These equations are used to calculate, in transient conditions, the temperature fields of the opaque, transparent and internal bodies and internal air, and the water and contaminants mass fields inside the spaces. The energy and mass balance integral equations are solved by the Runge-Kutta-Felberg method with error control

The energy balance linear integral equations consider the convection, conduction and radiation phenomena as follows:

- Heat transfers by natural, forced and mixed convection are evaluated using dimensionless coefficients, which are used in the opaque and transparent bodies;
- Heat transfer by conduction is verified within the opaque bodies, between the different layers;
- In the incident solar radiation, the numerical model considers a sun trajectory during all day, for all days in the year. In this calculus all contaminants in the atmosphere are considered;
- In the absorbed, transmitted, absorbed and reflected solar radiation in transparent (glasses) bodies the numerical model considers all radiative proprieties of the grass;
- In the absorbed solar radiation by opaque bodies the numerical software considers the surface proprieties.

The radiation phenomenon considers all shading devices. In this calculus all surfaces of the building geometry are considered. The study calculated the shading devices considered in the external surfaces and the shading devices considered in the internal surfaces. In the second situation, for each indoor space, the external surfaces are also considered.

The energy balance integral equations are used to evaluate the temperature opaque bodies (door, walls, floor and ceiling), transparent (glazed) bodies, indoor bodies and internal air of the virtual buildings. In the DSF system, the Building Thermal Modelling numerical model calculates the temperature in Venetian-type blind, inner and outer glasses, DSF surrounding structure and air inside the ventilated DSF.

The mass balance integral equations consider the convection and diffusion phenomenon. This equation system is used to evaluate the mass concentration of the water vapour and contaminants concentration inside the building indoor space. In the DSF system this equation system is also used to evaluate the mass concentration of the water vapour and contaminants concentration

As input data, the numerical model considers the geographical data, the environmental data, and other details. In the environmental conditions the external air temperature, air relative humidity, air velocity and wind direction, for all day, are considered.

All numerical models were validated in winter conditions and in summer conditions, with different conditions, for school buildings and experimental chamber:

- In school buildings the indoor air temperature calculated by the numerical model and measured experimentally was considered in transient conditions (see Conceição and Lúcio [24] for winter conditions and Conceição et al. [25] for summer conditions);
- In the experimental chamber the surrounding surfaces (floor, ceiling, wall and indoor bodies temperatures), in steady state conditions, are considered (see Conceição and Lúcio [26]).

3. Methodology

The building geometry, considered in this work is presented in Fig. 1. Fig. 1a) represents the building scheme, while Fig. 1b) and Fig. 1c) represents the building grid generation. The grid generation considered in the numerical simulation, namely in the calculus of the solar radiation field in external and internal surfaces, can be analysed in Fig. 1. The main facade of the building (including the door and two windows, one larger and the other smaller) faces south. The building also has two more windows: a small one facing north and another facing east.

The numerical simulation considers one external space, five internal spaces, a loft and two DSF systems, namely:

- Space 1 – external space. The air temperature and relative humidity, wind velocity and wind direction are used as input data.
- Space 2 – non-permanent occupation. Is equipped with a door facing south.
- Space 3 – two occupants between 19 to 24 hours. Is equipped with a window facing south.
- Space 4 – two occupants between 12 to 14 hours and one occupant between 18 to 19 hours. This space is equipped with a window facing north.
- Space 5 – two occupants between 0 to 8 hours. This space is equipped with a window facing east.
- Space 6 – one occupant between 18 to 19 hours. This space is equipped with a window facing south.
- Space 7 – loft. This space is used to regulate the temperature in the building.
- Space 8 – Small DSF system. This space is used to heat two spaces: the space 6 (with window equipped with this DSF system) and the space 5.
- Space 9 – Large DSF system. This space is used to heat two spaces: the space 3 (with window equipped with this DSF system) and the space 4.

A comparative study, with and without DSF system, is made. This work is divided into two parts:

- Without DSF system: the heating process is made using only direct solar radiation;
- With DSF system: the heating process is made using direct solar radiation and heat transported by ducts from the DSF located in the south window to the uncomfortable cold spaces located in the north-facing area of the building, in order to improve the thermal comfort conditions of these spaces.

The two DSF systems, in the present study, consider an airflow from the:

- DSF number 8 to the space number 6 during all day with an airflow rate of 0.005 m^3/s;
- DSF number 8 to the space number 5 during all day with an airflow rate of 0.02 m^3/s;
- DSF number 9 to the space number 3 between the 14 to 24 hours with an airflow rate of 0.01 m^3/s;
- DSF number 9 to the space number 4 between the 0 to 14 hours, with an airflow rate of 0.02 m^3/s and between the 14 to 24 hours, with an

airflow rate of 0.01 m^3/s;

- DSF number 9 to the space number 5 between the 0 to 14 hours with an airflow rate of 0.02 m^3/s.

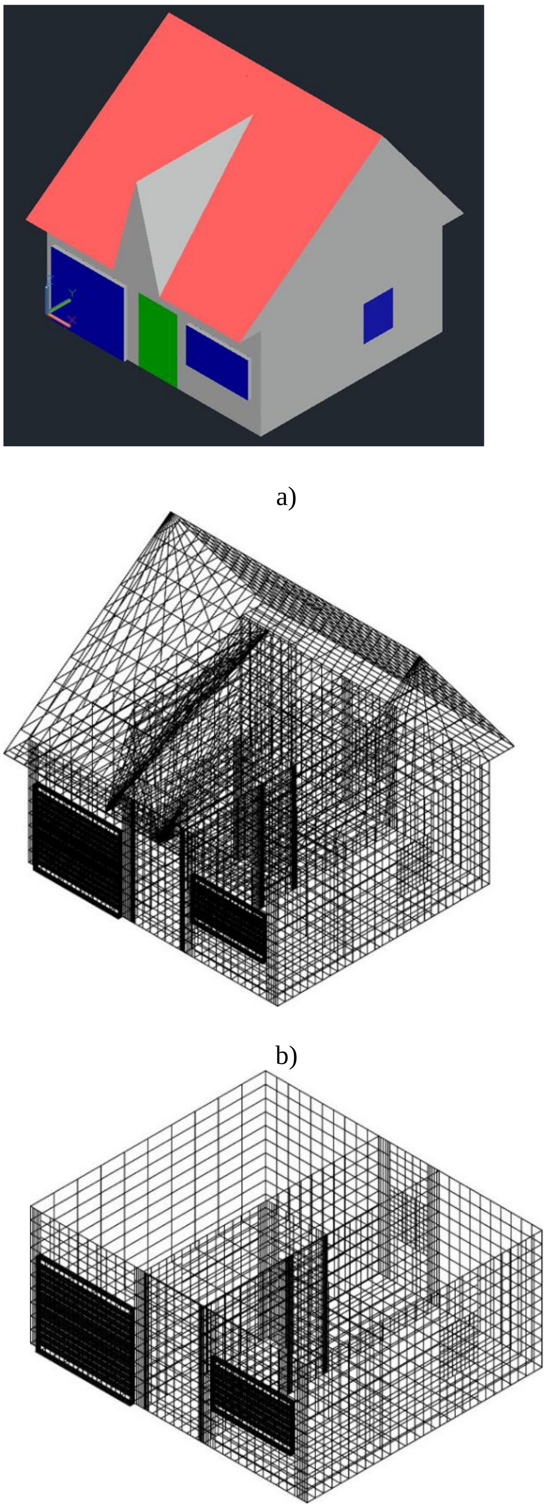

a)
b)
c)

Fig. 1 – Building occupied space. External surface a), grid generation in all building b), and grid generation in occupied building spaces c).

The values of the previous airflows were selected in order to guarantee conditions of thermal comfort when the spaces are occupied.

The study considers a virtual small building equipped with two DSF systems, installed in windows facing south, equipped with a duct system connected to an internal ventilation system, based on a mixing ventilation system.

Without DSF system, an airflow rate of 35 m^3/h by person, only when the space is occupied, suggested by the standards for an occupation of two persons, was used in the numerical simulation.

Each DSF is built with two glazed surfaces and a surrounding structure. The Venetian-type blind is constituted by an adjustable set of six aluminium lamellae and it is installed in the air cavity of the DSF system (see Fig. 2). The small DSF system is equipped with six lamellas, while the larger DSF system is equipped with twelve lamellas.

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. In the numerical simulation the five previous days were considered in order to obtained the real build thermal behaviour.

In the assessment of the PMV index, a metabolic rate of 1.2 met and a clothing insulation level of 1 clo were used [18].

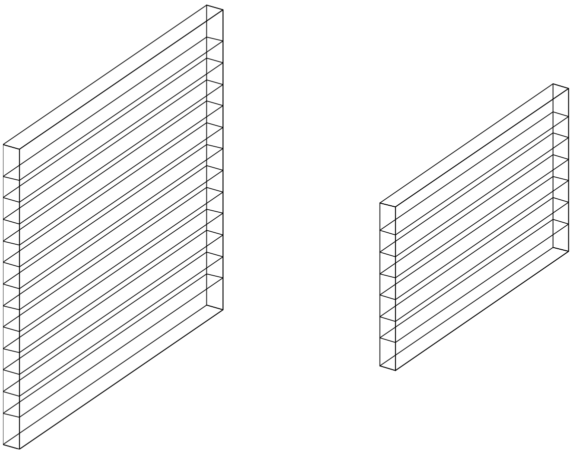

a) b)

Fig. 2 – DSF used in the numerical simulation. Small a) and large b) DSF.

In Fig. 3 the existing air flows can be seen when the DSF are not used (Fig. 3a) and when the DSF are used (Fig. 3b and Fig. 3c), the latter in the situation existing after 14 hours).

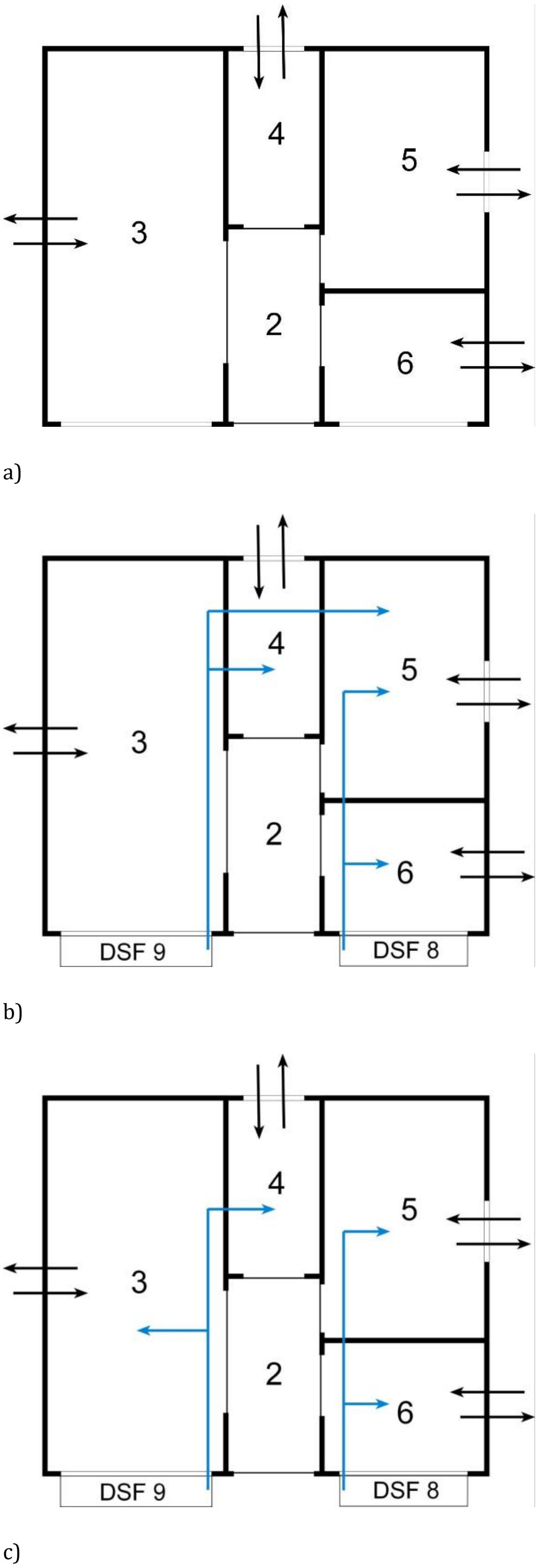


Fig. 3 – Airflow without DSF a) and airflow with DSF until b) and after c) 14 hours.

4. Results and discussion

In Fig. 4 is presented the evolution of the air temperature in the internal space without (point a) and with (point b) DSF system. In the Fig. 4, the spaces numbers 2, 3, 4, 5, 6 and 7 are presented.

Without DSF, the evolution of temperature is higher in spaces facing-south (number 3 and 6). Spaces numbers 2 (without window), 4 (with window facing-north), 5 (with window facing east) and 7 (loft without window) present internal air temperature evolution with low values.

Thus, in accordance with obtained results, two DSF systems were developed in order to improve the temperature distribution. In order to increase the internal air temperature in occupied spaces numbers 4 and 5 a DSF system was installed in each window of the space 3 and 6. The internal air temperature spaces 4 and 5 increase, mainly when the spaces are occupied, to values near the space number 3. The internal air temperature of the space number 3 and 6 decreases.

Fig. 5 shows the evolution of the air temperature in the external environment (space 1) and DSF spaces (8 and 9) system.

In accordance with the obtained results, the larger DSF space present higher internal air temperature than the small DSF system.

Fig. 6 shows the evolution of the PMV index in the internal spaces, namely the spaces number 3, 4, 5 and 6. The point a) is associated without a DSF system, while point b) is associated with a DSF system.

The thermal comfort level, evaluated by the PMV index, when is not used a DSF system, is uncomfortable by positive values in spaces with windows facing south (3 and 6) and is uncomfortable by negative values in the space with window facing north (space number 4) and in the space with window facing east (space number 5).

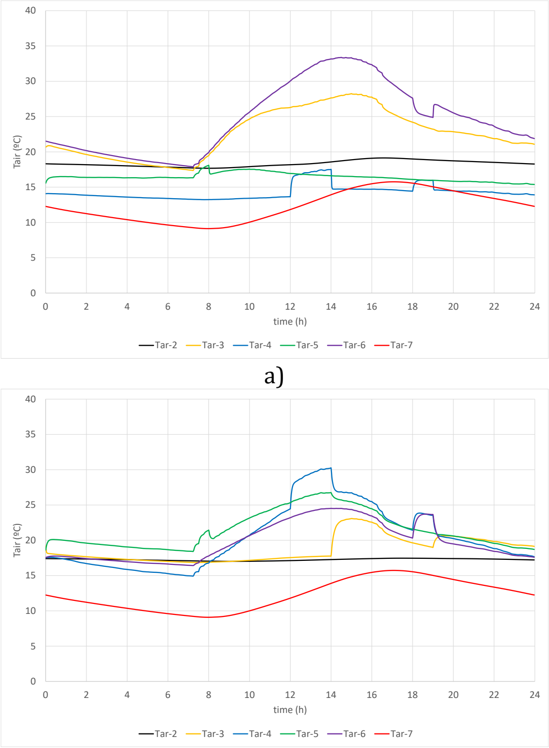
However, in accordance with the obtained results, with DSF system, the following conclusions are verified:

- The thermal comfort level is acceptable, by negative PMV values, in the space number 3 during the afternoon and the night, mainly, when the space is occupied during the night. In this space the DSF system improves the thermal conditions to acceptable values;

- The space number 4 presents comfortable thermal comfort levels, by negative PMV values, in the morning, in the evening and at night. On the other hand, it presents comfortable thermal comfort levels, by positive PMV values, in the early afternoon. Thus, when the space is occupied at noon the thermal comfort level is acceptable, by positive PMV values, and in the early night the thermal comfort level is acceptable, by negative PMV values;

- The space number 5 presents acceptable thermal comfort conditions, by negative PMV values, during the night, in the early morning and in the late afternoon and presents acceptable thermal comfort conditions, by positive PMV values, during the late morning and during the early afternoon. Thus, when the space is occupied (during the night) the thermal comfort conditions, by negative PMV values, is verified;

- Finally, the space number 6 presents acceptable thermal comfort conditions, by negative PMV values, during the afternoon and morning and unacceptable thermal comfort conditions, by negative PMV values, during the night. When the space is occupied (in the late afternoon) the acceptable thermal comfort conditions are verified.



a)

b)

Fig. 4. Evolution of the air temperature in the internal spaces (2, 3, 4, 5, 6 and 7), without a) and with b) DSF system.

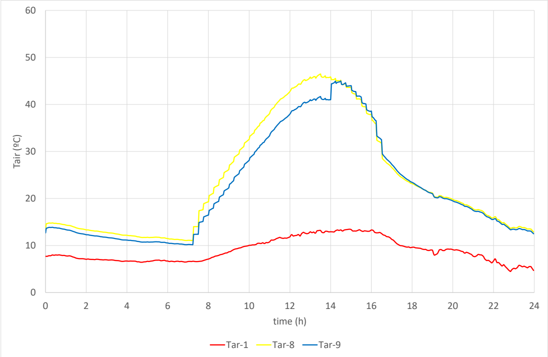
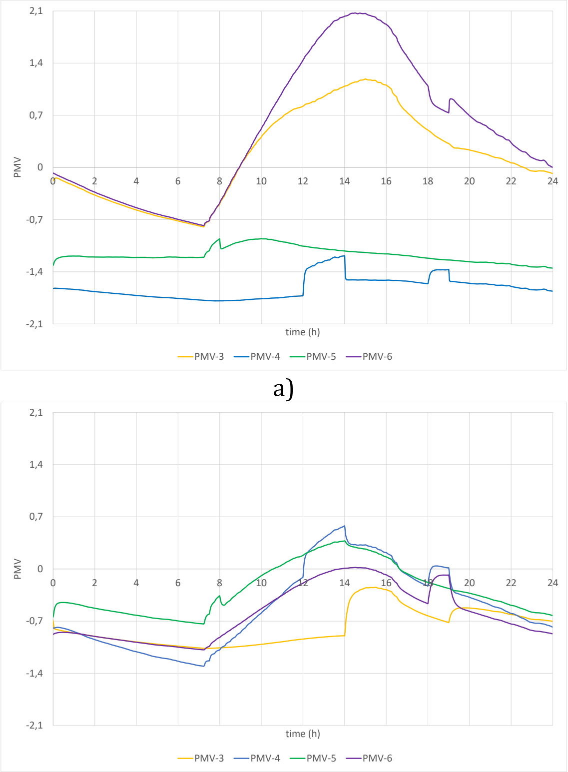


Fig. 5. Evolution of the air temperature in the external and DSF spaces (1, 8 and 9) system.



a)

b)

Fig. 6. Evolution of the PMV index in the internal spaces (3, 4, 5 and 6), without a) and with b) DSF system.

5. Conclusions

In this paper is presented a numerical study of the development of a sustainability thermal solution in buildings using solar renewable energy production in winter cold conditions. The comparative study is done considering the building without DSF system and equipped with two DSF systems, each one connected by ducts to two spaces.

In general, without DSF system the spaces equipped with windows facing south are thermal uncomfortable by positive PMV values, while the other spaces are thermal uncomfortable by negative PMV values.

When is used the DSF systems, in general, all spaces are thermal comfortable when the space is occupied. When the spaces number 3, 5 and 6 are occupied the acceptable thermal comfort is verified by negative PMV values. When the space number 4 is occupied the acceptable thermal comfort is verified in the noon by positive PMV values and in the late afternoon by negative PMV values.

In accordance with the obtained results, the larger DSF transports higher energy level than the necessary, while the small DSF transports lower energy level than the necessary. Thus, in future work is important to implement and developed new energy management in order to optimize the energy distribution promote by the DSF system.

6. Acknowledgement

The authors acknowledge to the project (SAICT-ALG/39586/2018) from Algarve Regional Operational Program (CRESC Algarve 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF) and the National Science and Technology Foundation (FCT). The authors grateful the collaboration of the Margarida Conceição in the project design development.

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