Chapter 1
Solar Thermal Energy Production in DSF Applied in the Human Comfort Improvements

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Abstract This work presents a numerical study of solar thermal energy production in DSF applied in the human comfort improvements, in winter conditions. The study considers a solar thermal energy production made in a DSF system placed in the outdoor environment and the improvement of human comfort conditions, namely the thermal comfort and the indoor air quality in a virtual office provided with impinging jets ventilation and occupied by eight occupants seated around the table with eight seats. This study uses a Building Dynamic Response numerical model and coupling of the Computational Fluids Dynamics and Human Thermal Response numerical models. The impinging jets ventilation is built with an inlet system and an outlet system. The inlet system integrates 4 vertical ducts, installed near the corner of the walls, whose airflow direction is descendent, at 0.5 m from the floor. The outlet system integrated six vertical ducts, located above the head level, with ascendant airflow direction. The study considers a solar thermal energy production in DSF during all day and the detailed evaluation of comfort condition in the middle of the morning and afternoon. The indoor air quality, thermal comfort, Draught Risk and Air Distribution Index are evaluated. The results show that the energy production ensures acceptable indoor air quality and thermal comfort conditions.

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1.1 Introduction

A DSF, double skin façade, is frequently used in the solar thermal energy production, see Ghaffarianhoseini et al. (2016), Pasut and Carli (2012), Hazem et al. (2015) and Poirazis (2004). This equipment is built by an air cavity between two transparent glasses. The control of the cavity air ventilation can be performed by natural process, mechanical process or hybrid processes. The DSF is dependent on the characteristics of the skin coverage, the air ventilation topologies used, the eventual use of shading devices, its location in the building, among other details.

Several authors have investigated ventilation systems based on impinging jets in the last years. Example of this kind of study can be analysed in Karimipanah et al. (2008), Karimipanah and Awbi (2002), Cao et al. (2014), and Karimipanah et al. (2000). This study considers vertical ducts with descendent airflow. The ducts can be localized in the corner of the walls or in other placed.

The human comfort is evaluated by the thermal comfort level and the indoor air quality level (IAQ). The performance of the Heating, Ventilation and Air Conditioning (HVAC) system is evaluated by the Air Distribution Index (ADI). However, the local thermal discomfort eventually promoted by HVAC system is evaluated by the Draught Risk (DR).

The Predicted Mean Vote (PMV) index and the Predicted Percentage of Dissatisfied people (PPD) index are used to evaluate the occupants thermal comfort level. The PMV and PPD indexes, parameters developed by Fanger (1970), are applied to assess the thermal comfort conditions in spaces with HVAC system and they are presented in ISO 7730 (2005).

The carbon dioxide concentration is used in the IAQ evaluation (Conceição et al. 2008a). The carbon dioxide concentration, release by the occupants, can be used as reference of IAQ in occupied spaces (ANSI, ASHRAE Standard 2016).

ADI is used to assess simultaneously the air quality, thermal comfort, contaminants removal efficiencies and heat removal efficiencies. ADI was presented in detail in the work of Awbi (2003), for uniform environments, and in the work of Conceição et al. (2013), for non-uniform environments.

DR is used to assess the level of local thermal discomfort of occupants of an air-conditioned space. DR was developed by Fanger et al. (1988) and it is depending of air temperature, air velocity and air turbulence intensity.

The numerical software used in this work is based on a coupling between two numerical models, Computer Fluid Dynamics (CFD) and Human Thermal Response (HTR). This methodology can be seen in the studies of Conceição and Lúcio (2001, 2016), Conceição (2000), and Conceição et al. (2010a). The coupling methodology need inputs obtained from Buildings Dynamics software. Examples of this kind of software can be analysed in the studies of Yan et al. (2014), Sailor (2008), and Balaji et al. (2013).

In this study the inputs of the coupling methodology came from a Building Dynamic Response numerical model developed by the authors. Examples are shown in Conceição et al. (2000, 2008b), Conceição and Lúcio (2009, 2010a). The assessment of the air temperature distribution, surfaces temperature distribution and energy consumption was carried out. The surrounding building bodies, as tree, and others external details, can be see analysed in Conceição and Lúcio (2010b). This software considers the evaluation of thermal comfort through the PMV/PPD indexes (Conceição et al. 2018), the adaptive thermal comfort (Conceição et al. 2010b), and the temperature preferred control model (Conceição et al. 2009).

The main objective of this numerical work is to develop a new situation where the production of energy is made in a DSF system using the solar renewable energy. The human comfort, in this work, is made by an impinging jet system. In the numerical simulation, made in winter conditions, it is used a coupling of the CFD, HTR and Building Dynamic Response numerical models to evaluate the thermal comfort, IAQ and DR levels, and the ADI.

1.2 Numerical Methodology

This work is made in a virtual office with $4.5 \times 2.55 \times 2.5\ \mathrm{m}^3$. The office is equipped with an internal impinging jets ventilation system and an external DSF system.

The impinging jets ventilation system is built with an inlet system and an outlet system. The inlet system integrates four ducts placed in the wall corners. The inlet airflow, with descendent direction, enters at 0.5 m from the floor. The outlet system uses six vertical ducts, located above the table level.

The numerical methodology used in grid generation of the CFD model is presented in Fig. 1.1. Figure 1.1a represents eight occupants, a table and eight chairs. Figure 1.1b includes the inlet ventilation and the outlet ventilation system. Figure 1.1c represents the inlet (light green arrows) and outlet (light blue arrows) airflow.

Figure 1.2 shows the numerical methodology used in the grid generation of the HTR model. Figure 1.2a represents eight occupants and a table. Figure 1.2b also includes the impinging jets ventilation, namely the incoming and exit system. The occupant location and identification number are presented in Fig. 1.3.

In Fig. 1.4 the scheme of the DSF system used in the energy production is presented. Figure 1.4a represents the office space equipped with a DSF system and Fig. 1.4b represents the DSF detailed.

In the numerical simulation is important to consider the occupation and the ventilation cycle.

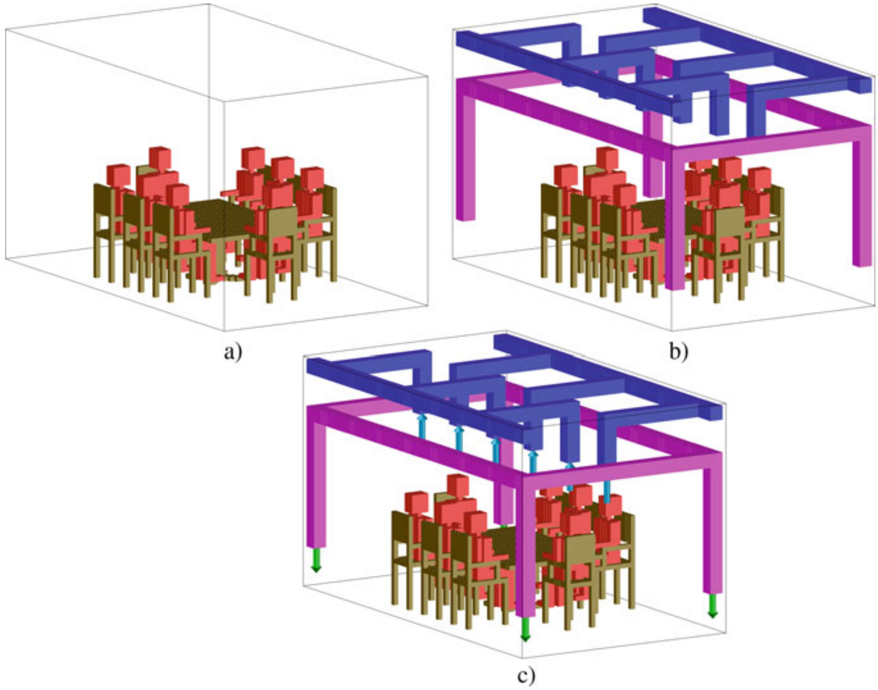

Fig. 1.1 Numerical methodology used in the CFD model grid generation: **a** Representation of eight occupants, a table and eight chairs. **b** Including the inlet ventilation and the outlet system. **c** With inlet (light green arrows) and outlet (light blue arrows) airflow used

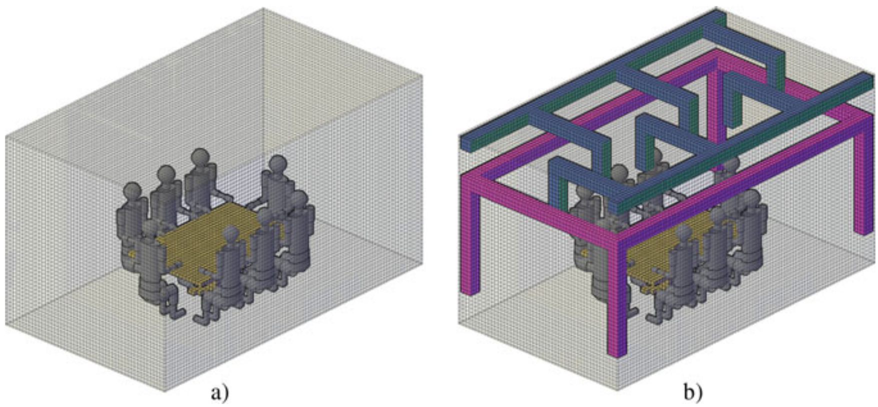

Fig. 1.2 Numerical methodology used in the grid generation of the HTR model: **a** Representation of eight occupants, a table and eight chairs. **b** Including the impinging jets ventilation

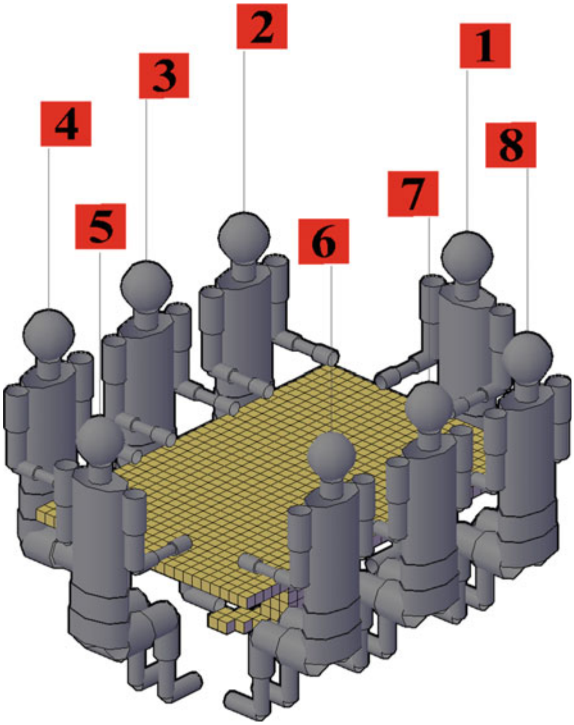

Fig. 1.3 Location of the occupants and identification number of each occupant

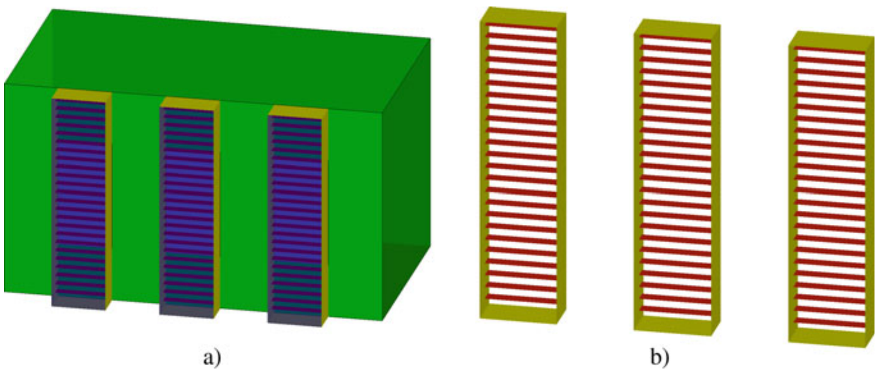

Fig. 1.4 Design of the DSF system used in the production of energy: **a** Office space equipped with a DSF system. **b** DSF detailed

The occupation cycle of the virtual chamber is the following:

- 8h00 to 12h00, during the morning time, is occupied by eight persons;
- 12h00 to 14h00 is not occupied (lunch time);
- 14h00 to 18h00, during the afternoon time, is occupied by eight persons.

The ventilation cycle, that is used to transfer the energy from the DSF system to the office space and to improve IAQ and thermal comfort levels, namely:

- 0h00 to 8h00, one air renovation;
- 8h00 to 12h00, airflow rate acceptable for eight occupants;
- 12h00 to 14h00 one air renovation;
- 14h00 to 18h00, airflow rate acceptable for eight occupants.
- 16h00 to 24h00 one air renovation.

In order to evaluate the thermal comfort and indoor air quality, the coupling numerical software as used at 10:00 h and 16:00 h, namely:

- 10 h, evaluation of human comfort conditions at morning;
- 16 h, evaluation of human comfort conditions at afternoon.

1.3 Results and Discussion

In this point, the results obtained of the DSF numerical simulation and of the occupants and environment variables determination are presented.

1.3.1 Energy Production in the DSF System

In Fig. 1.5, the DSF system indoor air temperature and outdoor environment temperature evolution is presented.

In accordance with the results, the three DSF system presented the same internal temperature and the DSF air temperature increases during the morning and decreases during the afternoon. This fact is associated with the solar radiation.

The Building Dynamics Response numerical model calculates the results presented in the Fig. 1.5. The obtained results at 10:00 h and at 16:00 h are transferred to the coupling system, in order to be used in the thermal comfort and IAQ evaluation.

1.3.2 Air Velocity

The distribution of the air velocity around the sections of the human body is depicted in Fig. 1.6. At 10 and 16 h, the evolution is presented, respectively, in Fig. 1.6a and b.

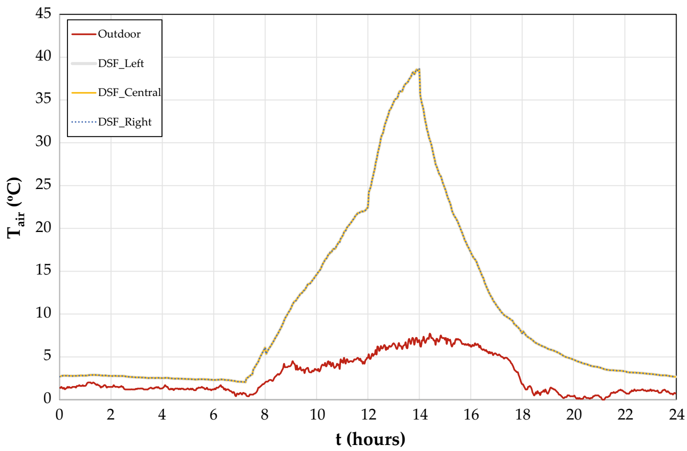

Fig. 1.5 Evolution of DSF system indoor air temperature and of outdoor air temperature

According to the obtained results, the air velocity is higher in the lower human body sections than in the upper human body sections.

1.3.3 Air Temperature

In Fig. 1.7 is possible to verify the evolution of the air temperature distribution around the human body sections at 10 h, in Figure a), and at 16 h, in Figure b). The air temperature is higher in the upper body sections than in the lower body sections.

1.3.4 Draught Risk

In Fig. 1.8, it is shown the DR distribution around the human body sections at 10:00 h and at 16:00 h, respectively in figures a and b.

DR is higher in the lower sections than in the upper sections. The DR is slightly highest in the lower sections for the occupants located in the top of the table than for the occupants located in the side of the table. The DR level is acceptable, regarding to ISO 7730 (ISO 2005).

1.3.5 Air Distribution Index

ADI values are presented in Tables 1.1 and 1.2. The Table 1.1 is associated with 10:00 h, while Table 1.2 is associated with 16:00 h.

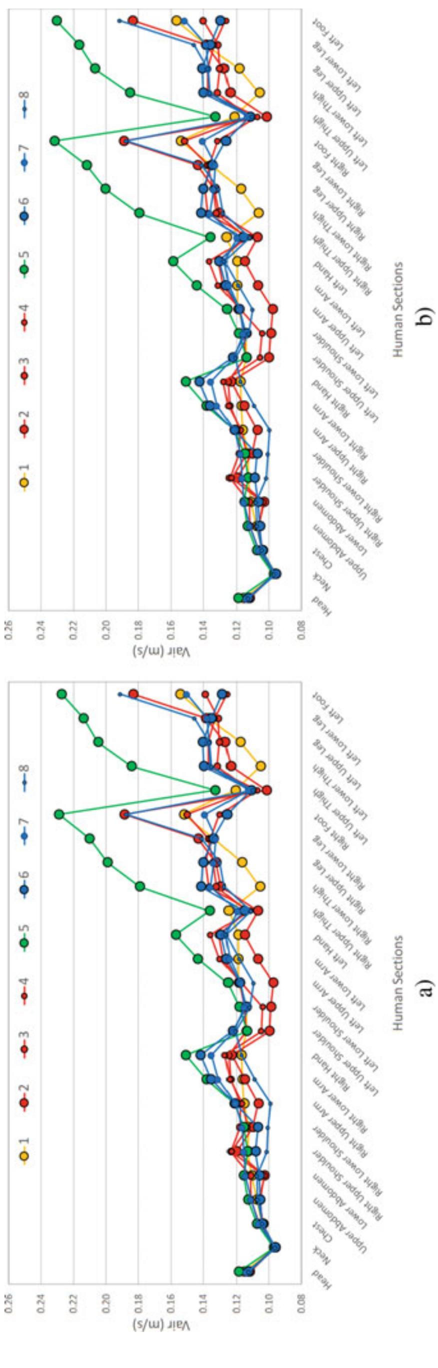

Fig. 1.6 Air velocity distribution around the human body sections at **a** 10 h, and **b** 16 h

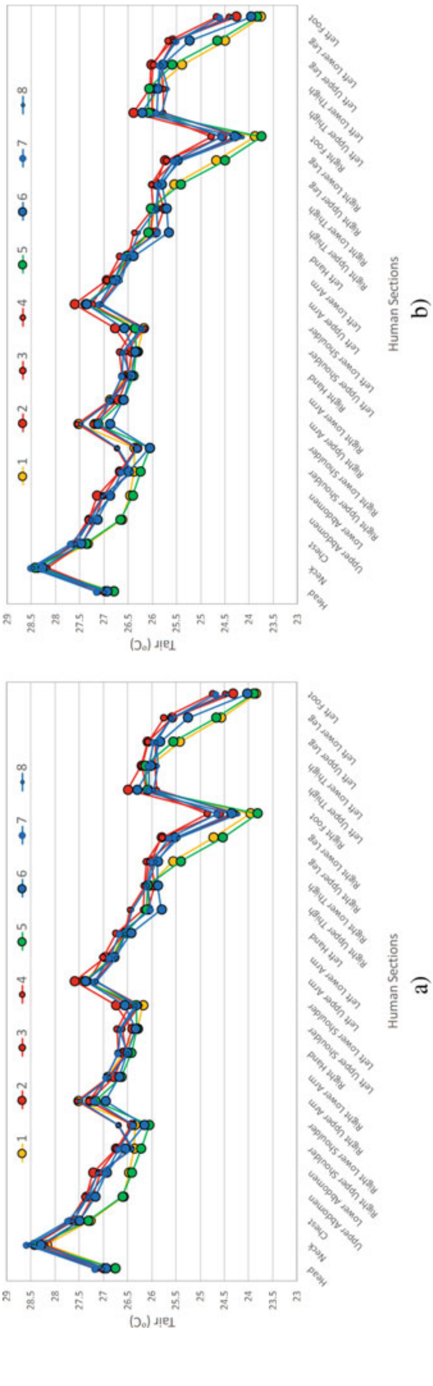

Fig. 1.7 Air temperature distribution around the human body sections at **a** 10 h, and **b** 16 h

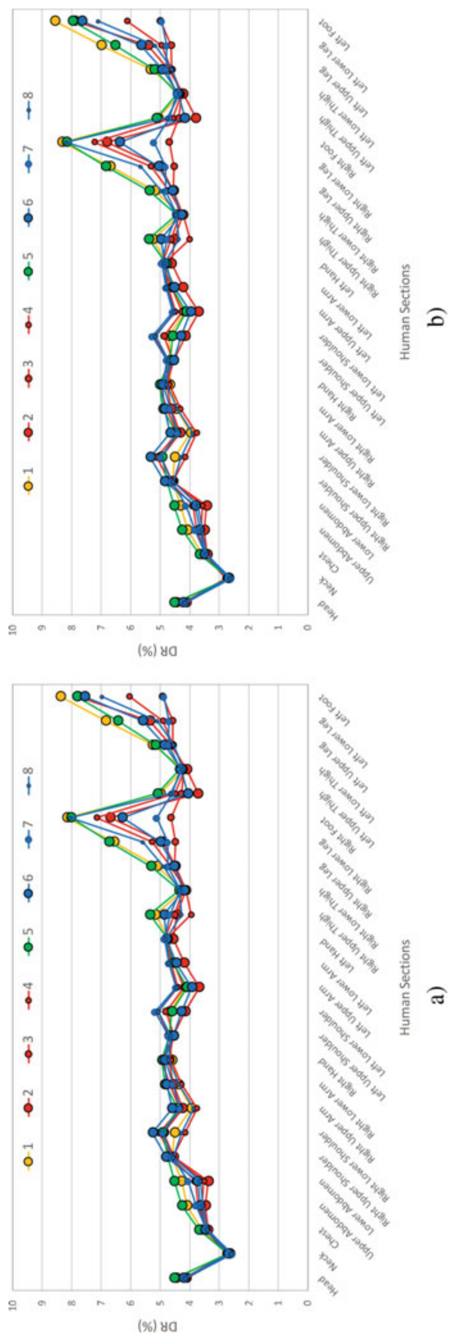

Fig. 1.8 DR distribution around the human body sections at **a** 10 h, and **b**) 16 h

Table 1.1 ADI value obtained at 10 h

People number	1	2	3	4	5	6	7	8	Mean
Body mean temperature (°C)	26.4	26.8	26.8	26.7	26.4	26.6	26.8	26.7	26.6
Effectiveness for heat removal (%)	79.2	76.0	75.6	76.8	79.3	77.5	76.1	76.5	77.1
PPD (%)	15.0	17.5	17.7	17.1	14.1	16.8	17.4	17.2	16.6
Thermal comfort number	5.3	4.3	4.3	4.5	5.6	4.6	4.4	4.5	4.7
CO_2 in the respiration area (mg/m^3)	1524.2	1642.8	2023.1	1704.7	1510.3	2050.2	2296.3	1808.9	1820.1
Effectiveness for contaminant removal (%)	36.6	32.8	24.6	31.1	37.1	24.2	20.9	28.6	29.5
Air quality number	2.5	2.2	1.7	2.1	2.5	1.6	1.4	1.9	2.0
Air Distribution Index (ADI)	3.6	3.1	2.7	3.1	3.8	2.7	2.5	2.9	3.0

Table 1.2 ADI value obtained at 16 h

People number	1	2	3	4	5	6	7	8	Mean
Body mean temperature (°C)	26.4	26.7	26.7	26.6	26.4	26.5	26.7	26.6	26.6
Effectiveness for heat removal (%)	79.9	77.3	77.0	78.0	79.8	78.6	77.5	77.8	78.2
PPD (%)	15.0	17.2	17.4	17.0	14.1	16.6	17.1	16.9	16.4
Thermal comfort number	5.3	4.5	4.4	4.6	5.7	4.7	4.5	4.6	4.8
CO_2 in the respiration area (mg/m^3)	1538.3	1652.1	2054.7	1720.6	1526.4	2105.5	2354.0	1840.3	1849.0
Effectiveness for contaminant removal (%)	36.2	32.6	24.2	30.8	36.6	23.4	20.3	28.0	29.0
Air quality number	2.4	2.2	1.6	2.1	2.5	1.6	1.4	1.9	2.0
Air Distribution Index (ADI)	3.6	3.1	2.7	3.1	3.7	2.7	2.5	2.9	3.1

In general. all variables and parameters are similar both at 10:00 h and 16:00 h. The thermal comfort and IAQ levels are acceptable regarding to the international standards. The level of the thermal comfort is near the Category C (ISO 2005), and the value of carbon dioxide concentration is near the acceptable limit (ANSI, ASHRAE Standard 2016).

The results of the production of energy in the DSF system reveals that this system can promote acceptable thermal comfort and IAQ conditions, in accordance with the international standards.

1.4 Conclusion

In this work a numerical study of solar thermal energy production in DSF applied in the human comfort improvements, in winter conditions, is developed and presented. This DSF system, located in the office space outdoor environment and used in the energy production, uses solar renewable energy. The HVAC system, founded in an impinging jet system, is used to improve the human comfort conditions.

A coupling of CFD and HTR and a Building Dynamic Response numerical models were used in the numerical simulation to evaluate the human comfort and discomfort conditions. ADI was used to evaluate the performance of the HVAC system.

In accordance with the obtained results, the energy production guarantees acceptable thermal comfort and IAQ conditions. The HVAC system, applied in this work, promotes, inclusively, low DR levels to the occupants.

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