Numerical Study of a Surface Confluent Jets Ventilation System Applied on a Virtual Occupied Chamber

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Abstract—The purpose of this numerical study is to evaluate the thermal comfort and indoor air quality provided by a surface confluent jets ventilation system applied on a virtual occupied chamber. This numerical study is carried out using a coupling of an integral numerical model, that simulates human thermal response systems, and differential numerical model, that simulates the computer fluid dynamics. The Draught Risk around the occupants, thermal comfort, indoor air quality and Air Distribution Index (ADI) are evaluated. The study was performed for winter and summer typical conditions. The results show that the surface confluent jet system presents, in general, an acceptable thermal comfort level and an acceptable indoor air quality, with carbon dioxide concentration values below the limit of 1800 mg/m^3. The ADI value is better in winter than in summer conditions.

Keywords—numerical simulation, confluent jets, thermal comfort, indoor air quality, draugt risk

I. Introduction

Confluent jets can be defined as "multiple interacting jets that issue from an array of closely spaced round nozzles" [1]. After their exit, these multiple interacting jets coalesce, combine between them and at a certain distance downstream they behave as a single jet. These confluent jets are applied on air supply devices of ventilation systems.

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Several studies have been conducted on the area of confluent jets ventilation systems. Most of the studies in this area fall under the category of experimental measurements [2-7] but are also available numerical studies on it [4,5,7-9]. In Yin *et al.* [2], an experimental method was used to visualize and investigate the airflow characteristics of a square column attached ventilation mode whose results show that this system has the advantages of mixing and displacement ventilation. Cho *et al.* [4] had investigated the characteristics of wall confluent jets in a compartment through Computer Fluid Dynamics (CFD) and experimental tests and concluded that this type of confluent jets have a greater spread over the floor than displacement flow. Similar conclusions were obtained in the experimental study developed by Janbakhsh and Moshfegh [6] in a mock-up office environment, where an acceptable draught in the occupied zone was also found. Good indoor environment with lower energy consumption Anderson *et al.* [7] and better performance than the conventional mixing systems Arghand *et al.* [3] would be obtained with confluent jets systems.

This numerical study considers a coupling of an integral numerical model, that simulates human thermal response systems, and differential numerical model, that simulates the CFD. The surrounding surfaces temperatures are previously calculated using an integral software that simulates the building thermal behavior. The human thermal response numerical model was initially developed and validated in Conceição [10,11] and Conceição *et al.* [12] by comparing experimental and numerical values. The CFD software was presented and validated in Conceição *et al.* [13]. Finally, these two software, coupling with the software that simulates the thermal response of buildings, were validated in Conceição *et al.* [14]. In these validations were used information provided by the standards ASHRAE 55 [15] and ISO 7730 [16].

This three software have been applied in several works over the years. For example, in Conceição and Lúcio [17], it was used to evaluate and improve the indoor air quality and indoor thermal conditions of a school building. The software was also applied on the simulation of the thermal comfort conditions that two virtual occupants are subjected in a virtual chamber equipped with localized radiant surfaces Conceição and Lúcio [18], and 25 occupants are subjected in a classroom equipped with radiant cooling systems Conceição and Lúcio [19]. The integral human thermal comfort model coupled with CFD was applied in the study of the thermal comfort and airflow characteristics of a space equipped with mixing ventilation and cold radiant floor Conceição *et al.* [20].

Indoor air quality can be assessed using various techniques. The quality of indoor air can be assessed using

various techniques, including the tracer gas method Conceição *et al.* [21]. Using this method, one can assess the concentration of carbon dioxide (CO_2) inside the compartments, which can be a good indicator of indoor air quality Asif *et al.* [22]. The ASHRAE Standard 62.1 proposes a CO_2 concentration below 1800 mg/m^3 as a reference for an acceptable indoor air quality ASHRAE [23].

The purpose of this numerical study is to evaluate the thermal comfort and indoor air quality in winter and summer conditions provided by a new surface confluent jets ventilation system applied on a virtual occupied chamber. This study is carried out using the three software referred to above and which has been developed and applied by the authors over the years.

II. Materials and Methods

The ventilation system was built with four ventilators coupled to four vertical ducts with a length of 1,700 mm and a diameter equal to 125 mm, located at the corner of the wall surfaces; each duct contains 136 nozzles divided into 4 rows of upright nozzles forming 34 jets in each row. The outlet of the jets is in the nozzles, whose diameter is 6 mm, 7.5 mm apart from their centers, occupying lines of 250 mm in the lower part of the duct, where the last nozzle is 10 mm above the floor level. The average air insufflation velocity used in the simulation was 1.85 m/s.

This numerical study considers a coupling of a differential numerical model, that simulates the CFD and an integral numerical model, that simulates human thermal response systems. The integral human response model, that simulates the human thermal and thermoregulatory and clothing thermal response, evaluates the tissue, blood and clothing temperatures distribution Conceição *et al.* [12]. The differential CFD model evaluates the air velocity, air temperature, air turbulence intensity and CO_2 concentration Conceição *et al.* [13]. In this study the Draught Risk (DR) around the occupants, the thermal comfort, the air quality and the Air Distribution Index (ADI) are evaluated. The ADI is used to evaluate simultaneously the occupant thermal comfort, occupant air quality and ventilation effectiveness for heat and contaminants removal levels [20,24].

In the numerical simulation of three-dimensional flows, the virtual chamber is equipped with the surface confluent jets ventilation system with four vertical ducts located near the wall surfaces corners and with an air extractor installed in an extraction duct placed in the center of the room ceiling (Fig. 1). In Fig. 1 the air velocity field at the nozzles outlet of the surface confluent jets system can be seen in yellow. The virtual camera is equipped with a square table and 4 virtual manikins (occupants) sitting on each side of the table. Each manikin is 1.70 m high and 70 kg weight.
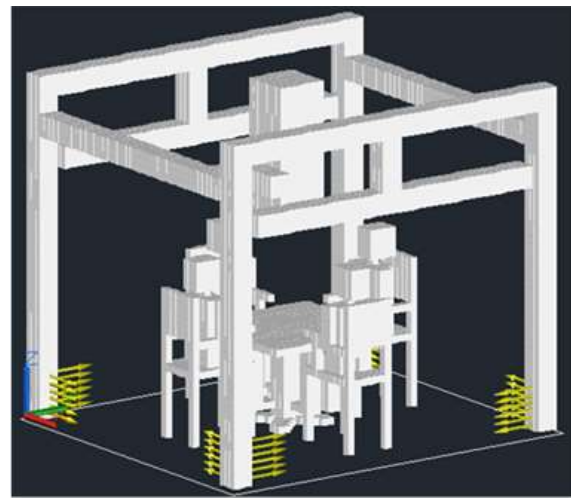

Figure 1. Virtual chamber used on the numerical model. The yellow arrows represented the air velocity field at the nozzles outlet.

Numerical simulations were performed for a winter and summer typical day conditions with inlet air temperatures of 20ºC and 25ºC, respectively, and with 50% indoor air relative humidity for both cases. The outdoor temperatures were 10ºC and 30ºC, respectively, for winter and summer conditions. It was considered a typical clothing level of 0.5 clo for summer conditions and 1 clo for winter conditions, with a typical level of activity of 1.2 met for both winter and summer conditions.

III. Results and discussion

Fig. 2 shows the vertical plan located at 1.30 m in the Y direction selected to present the results of the numerical simulation. This plan was chosen to show some key aspects of this numerical simulation, namely the air velocity field, the air turbulence intensity field, the air temperature field, and the draught risk field.
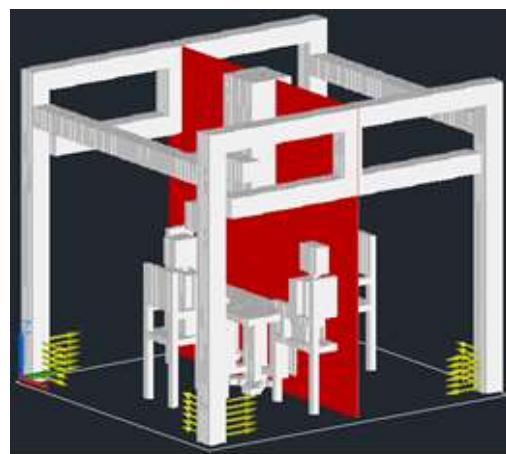

Figure 2. Virtual chamber used on the numerical model. The yellow arrows represented the air velocity field at the nozzles outlet.

A. *Environmental variables field*

In Fig. 3 to 5 are presented, respectively, the air velocity field, air temperature field and CO_2 concentration field for winter (point a) and summer (point b) conditions.
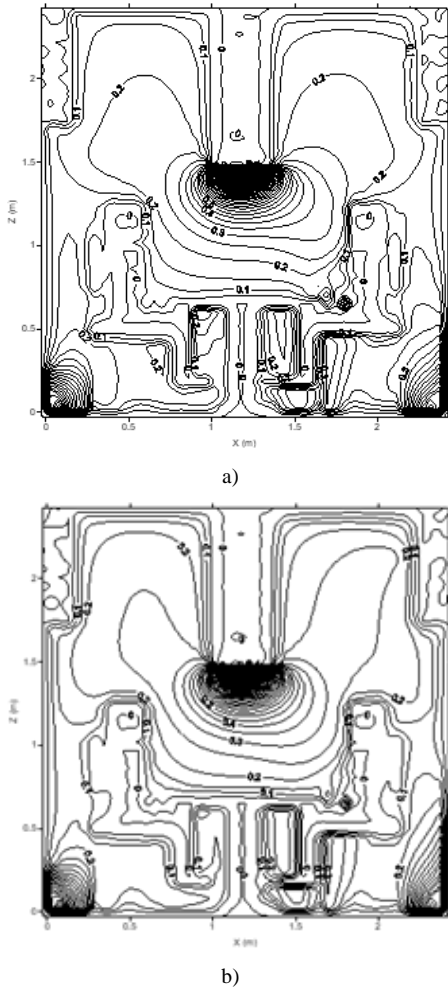

a)

b)

Figure 3.   Air velocity field in a vertical plane located at 1.30 m in the Y direction for a) winter conditions and b) summer conditions.

The results obtained allow us to verify that:

- The air velocity around the occupants is about 0.2 m/s;

- The highest air velocities are checked in the extraction zone;

- The air temperature in the room around the occupants is approximately 21.5ºC for winter conditions and approximately 27.5ºC for summer conditions;

- In both conditions, the air temperature values are higher in the occupied zone than in the unoccupied zone;

- The CO_2 concentration values are higher in the breathing zone, but these are acceptable values, below 1800 mg/m^3 ASHRAE [23];

- The location of the extraction system near the occupied zone allows exhaled air to be directed to the extraction,

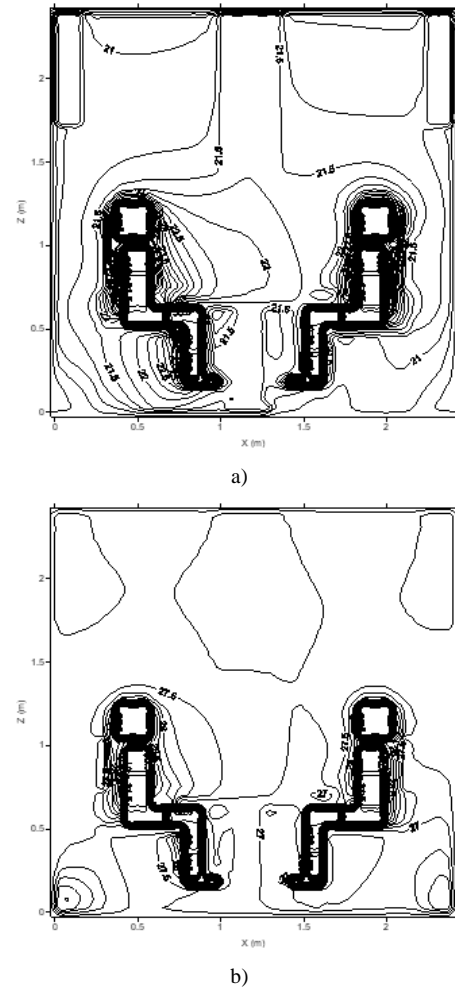thereby reducing the level of contaminants present in the room.

a)

b)

Figure 4.   Air temperature field in a vertical plane located at 1.30 m in the Y direction for a) winter conditions and b) summer conditions.

B. *Environmental variables distribution around the occupants*

In Fig. 6a) and 6b), it can be observed the air velocity distributions (V_{air}) around the occupants for winter and summer conditions, respectively. The results show that the air velocity distribution does not present significant differences between winter and summer conditions.

In Fig. 7a) and 7b), it can be observed the air temperature distributions (T_{air}) around the occupants, for winter and summer conditions, respectively. The results show that the air temperature distribution around the occupants is usually uniform and is lower in winter conditions than in summer conditions, with values around 23.5ºC. In summer conditions the air temperature is approximately 28ºC. For both winter and summer conditions, occupant 1 is also observed to have the highest air temperature distribution values, especially in the neck area and lower abdomen areas.
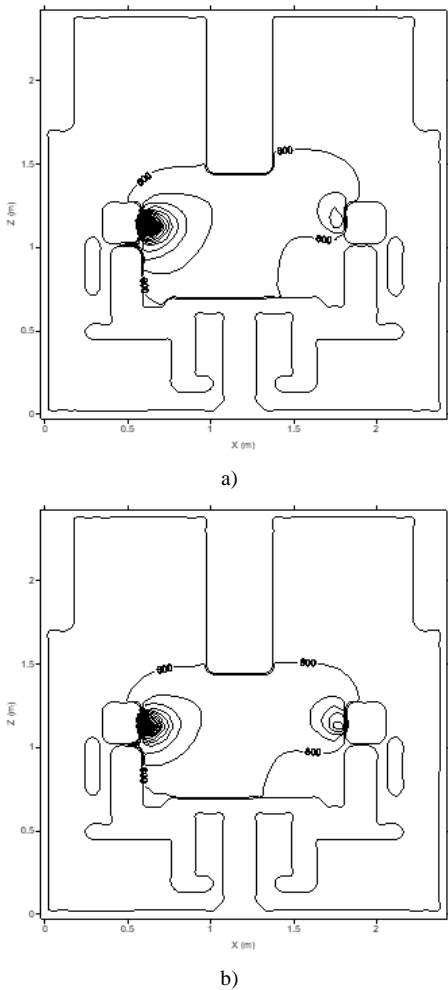
a)

b)

Figure 5. CO_2 concentration field in a vertical plane located at 1.30 m in the Y direction for a) winter conditions and b) summer conditions.
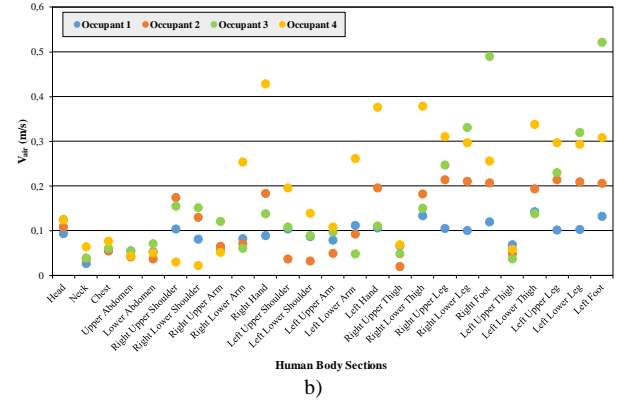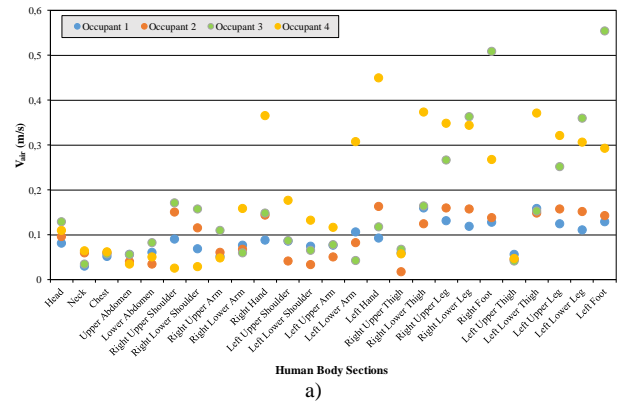

a)

b)

Figure 6.   Air velocity (V_{air}) distribution around the occupants for a) winter conditions and b) summer conditions.

a)

b)
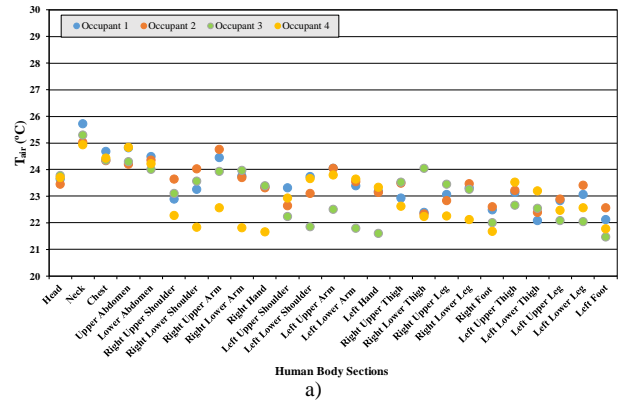
Figure 7.   Air temperature (T_{air}) distribution around the occupants for a) winter conditions and b) summer conditions.

In Fig. 8a) and 8b), it can be observed the DR index distributions around the occupants, for winter and summer conditions, respectively. The results demonstrate that the DR index distribution around the occupants is generally uniform and is acceptable for all occupants according to category B [16] in winter conditions, and according to category A [16] in summer conditions. The DR index is slightly higher in winter conditions than in summer conditions, with values around 18% in winter conditions and 10% in summer conditions for some areas of the body. Occupants 3 and 4 have a higher DR index than occupants 1 and 2, with discomfort values on the left shoulder, arm, hand and legs, both in winter and summer conditions.

a)

b)

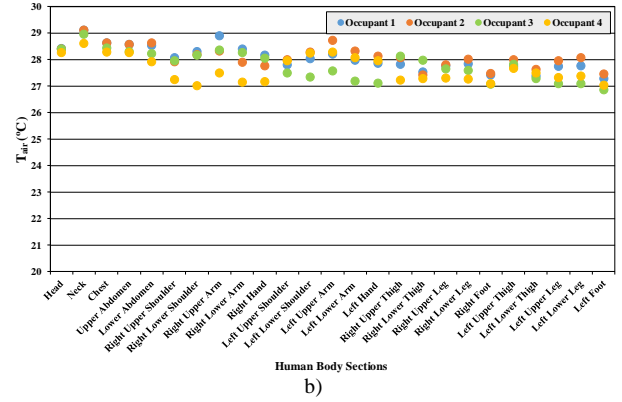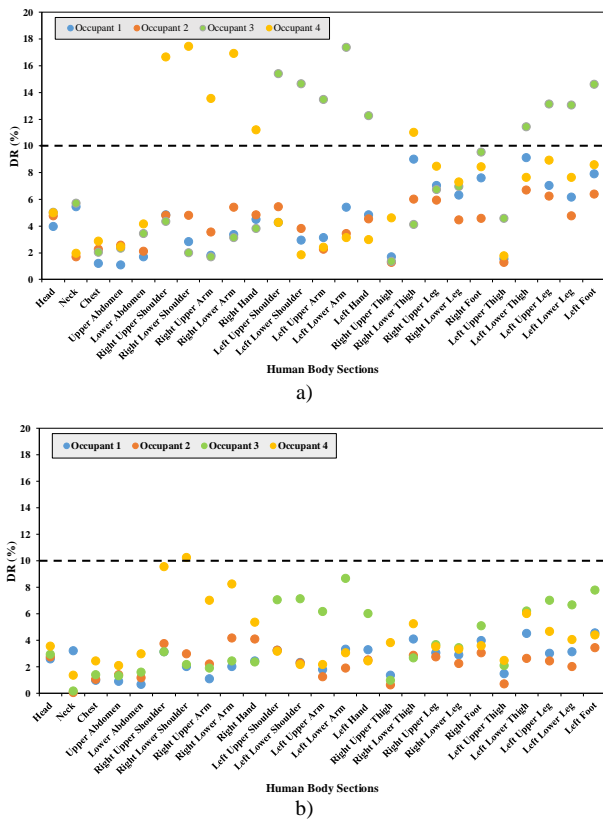Figure 8. Draught Risk (DR) distribution around the occupants for a) winter conditions and b) summer conditions. The dashed line in the figure defines the maximum limit of category A (10%) of ISO 7730 [16]; above this line up to 20% is the category B [16].

C. *Air distribution index*

Table I and Table II present the results of the effectiveness for heat removal, the Percentage of People Dissatisfied (PPD), CO_2 concentration in the breathing area, the effectiveness for contaminants removal, the percentage of dissatisfied (PD) people with indoor air quality and the ADI index for winter and summer conditions, respectively.

The numerical simulation obtained results demonstrate that:

- The effectiveness of heat removal is higher in summer conditions than in winter conditions;

- The PPD index is better in winter conditions than in summer conditions, with values within category B [16]; in summer conditions, the occupants are slightly uncomfortable because the PPD index is up from 15%;

- The thermal comfort number is higher in winter conditions than in summer conditions;

- The effectiveness of contaminants removal in the breathing area presents better results in summer conditions than in winter conditions. However, both CO_2 concentration values are below the recommended value required by ASHRAE 62.1 [23];

- The air quality number is higher in summer conditions than in winter conditions;

- The ADI is better in winter conditions than in summer conditions.

TABLE I. ADI OBTAINED IN WINTER CONDITIONS

Occupant	1	2	3	4	Average
Inlet temperature (ºC)	20.0	20.0	20.0	20.0	20.0
Outlet temperature (ºC)	21.7	21.7	21.7	21.7	21.7
Body mean temperature (ºC)	23.7	23.6	23.5	23.4	23.6
Effectiveness for heat removal (%)	44.5	45.6	47.7	48.3	46.5
PPD (%)	7.4	8.9	7.6	7.8	7.9
Thermal comfort number	6.1	5.2	6.3	6.2	6.0
Inlet CO_2 concentration (mg/m^3)	500.0	500.0	500.0	500.0	500.0
Outlet CO_2 concentration (mg/m^3)	647.4	647.4	647.4	647.4	647.4
CO_2 concentration in the breathing area (mg/m^3)	952.3	973.3	945.3	1105.3	994
Effectiveness for contaminants removal (%)	32.6	31.2	33.1	24.4	30.3
PD (%)	3.0	3.0	3.0	3.0	3.0
Air quality number	10.8	10.3	11.0	8.1	10.1
ADI	**8.1**	**7.3**	**8.3**	**7.1**	**7.7**

TABLE II. ADI OBTAINED IN SUMMER CONDITIONS

Occupant	1	2	3	4	Average
Inlet temperature (ºC)	25,0	25,0	25,0	25,0	25,0
Outlet temperature (ºC)	27,3	27,3	27,3	27,3	27,3
Body mean temperature (ºC)	28,2	28,2	28,0	27,8	28,1
Effectiveness for heat removal (%)	72,9	71,5	77,6	82,2	76,1
PPD (%)	22,5	23,4	21,1	21,1	22,0
Thermal comfort number	3,2	3,1	3,7	3,9	3,5
Inlet CO_2 concentration (mg/m^3)	500,0	500,0	500,0	500,0	500,0
Outlet CO_2 concentration (mg/m^3)	638,5	638,5	638,5	638,5	638,5
CO_2 concentration in the breathing area (mg/m^3)	902,8	966,3	923,7	989,9	945
Effectiveness for contaminants removal (%)	34,4	29,7	32,7	28,3	31,3
PD (%)	3,0	3,0	3,0	3,0	3,0
Air quality number	11,4	9,8	10,8	9,4	10,4
ADI	**6,1**	**5,5**	**6,3**	**6,0**	**6,0**

As final conclusion, the surface confluent jet system exhibits a good indoor thermal comfort level, but with the indoor thermal comfort level is slightly better in winter conditions than in summer conditions. Indoor air quality is slightly better in summer conditions than in winter conditions.

The electrical energy consumption values were also numerically obtained. Considering that the ventilation system works for 8 hours, the electrical energy consumption is 3,766 kWh on a typical winter day and 1,870 kWh on a typical summer day.

IV. Conclusions

In this numerical study the evaluation of the thermal comfort and indoor air quality provided by a surface confluent jets ventilation system applied on a virtual occupied chamber was done. A coupling of an integral numerical model, that simulates human thermal response systems, and a differential numerical model, that simulates the computer fluid dynamics, was used in the simulation. A typical winter day conditions and a typical summer day conditions were considered in the simulation. Parameters as thermal comfort, indoor air quality, DR around the occupants and ADI were evaluated.

The results of environmental fields variables demonstrate that the highest air velocities are verified in the extraction zone and air temperature values are higher in the occupied zone than in the unoccupied zone. The DR distribution around the occupants is generally uniform and is acceptable for all occupants according to category B [16] in winter conditions, and according to category A [16] in summer conditions.

The surface confluent jet system exhibits a good thermal comfort level, but with thermal comfort level slightly better in winter conditions than in summer conditions. In winter conditions, the PPD value is within category B [16], but in summer conditions the PPD value is slightly above the limit considered acceptable (15% corresponding to category C [16]). Therefore, it is recommended that the inlet temperature of the virtual chamber be slightly lowered in summer conditions. An acceptable indoor air quality, with CO_2 concentration values below the limit of 1800 mg/m^3 [23], for both winter summer conditions, was also obtained.

The performance of the surface confluent jets system is better in winter conditions than in summer conditions, because the ADI value is the highest in winter conditions.

Acknowledgment

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