Numerical Simulation of the Human Microenvironment Around the Occupants

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Abstract. In this study the numerical simulation of the human microenvironment around the occupants is carried out. This numerical work is made inside a virtual chamber, used as classroom, considers the ceiling mounted localized air distribution systems built with one inlet and one exhaust system. The virtual chamber has twelve chairs, each occupied by a virtual mannequin, and six tables. The software, developed by the authors, considers a differential CFD, an integral Human Thermal Modelling and an integral Building Thermal Modelling numerical model. The inlet and exhaust ventilation systems promote, respectively, a downward airflow and an upward airflow in the occupied zone. The study, made in winter conditions, evaluates the thermal comfort, the indoor air quality, the Draught Risk, the Air Distribution Index and Air Distribution Turbulent Index. The results obtained in this work allow us to infer that the thermal comfort, indoor air quality and Draught Risk are acceptable according to what is proposed in international standards.

1 Introduction

The application of Heating, Ventilating and Air-Conditioning (HVAC) system, to promote acceptable comfort and discomfort levels, is utilized in this work. Here the ceiling mounted localized air distribution systems are used as HVAC system. Applications, as example of this kind of ventilation, can be seen in the works of Ghaddar et al. [1] and Habchi et al. [2].

This kind of ventilation system, that promotes a downward airflow in the inlet ventilation system and promotes an upward airflow in the exhaust ventilation system, improves the thermal comfort, the Indoor Air Quality (IAQ) and the Draught Risk (DR).

In order to evaluate the comfort and discomfort levels, the human microenvironment around the occupants is important to be calculated. Examples of how to calculate the airflow around the occupants can be analysed in Conceição et al. [3].

Environmental variables, as air velocity, air relative humidity, air temperature and Mean Radiant Temperature (MRT), and personal parameters, as clothing insulation and activity levels, are used to calculate the thermal comfort level of the occupants in a ventilated conditioned space. The most common numerical model use to evaluate this level was developed by Fanger [4], which is presented in ISO 7730 [5] and ASHRAE 55 [6]. In the work of Conceição et al. [7], examples of the use of the software with application of the thermal comfort model mentioned above can be seen.

As a reference for indoor air quality, the ASHRAE 62.1 [8] standard proposes the concentration of carbon dioxide as an indicator. The recommended rate values, depending on the characteristics of the interior space, to ensure compliance with the previous standard can be seen in Conceição et al. [9] and Conceição et al. [10].

Turbulent variables around the human body, as air velocity, air temperature and the air turbulence intensity, are used to assess the DR. This index was developed in the work of Fanger et al. [11], being also present in ISO 7730 [5]. As example, the application of DR index in a virtual classroom provided by desk-type personalized ventilation systems was presented in Conceição et al. [12].

To evaluate the HVAC system performance, the Air Distribution Index (ADI) and the Air Distribution Turbulent Index (ADTI) can be used [13].

The main objective of this work is to assess the human microenvironment around the occupants in a virtual chamber equipped with ceiling mounted localized air distribution systems. These systems were built with one inlet and one exhaust systems. The thermal comfort, IAQ and DR are used to evaluate the comfort conditions provided to the occupants, while the ADI and ADTI are used to evaluate the HVAC system performance. In the present work three numerical software are used, particularly, a coupling between Computer Fluid Dynamics (CFD) and Human Thermal Modelling (HTM) numerical models and the Buildings Thermal Modelling (BTM) [14].

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2 Numerical Model

The software, developed by the authors, considers a differential CFD, an integral HTM and an integral BTM numerical models. The differential CFD and the integral HTM work in a coupling methodology and BTM is used to evaluate the surrounding environmental variables, whose obtained results are used as input in the coupling numerical model.

In the human microenvironment around the occupants, the HTM numerical model uses energy and mass balance integral equations. The equation system is resolved using the Runge-Kutta-Felberg with error control. The numerical models consider the following phenomena:

- Natural, forced or mixed convection between the skin and the environment and between the clothing and the environment;
- Conduction between skin and the clothing and between the clothing and the seats;
- Evaporation between the skin and the clothing, between the skin and the environment, between the clothing and between the clothing and the environment;
- Radiation between the skin and the clothing, between the skin and the surrounding surfaces, between the clothing and between the clothing and the surround surfaces;
- Respiration between the body and the environment.

The HTM numerical model evaluates the thermal comfort level, using Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) indexes, through the heat flux between the body and the environment.

In the human microenvironment around the occupants, the CFD numerical model is used to evaluate the air temperature, the air turbulence intensity and the air velocity around the human body sections.

Finally, in the human microenvironment around the occupants, BTM numerical model evaluates the surface temperature around the occupants. These temperature values, with the internal human and room geometry, are used to calculate the MRT. In this calculus the view factors between the human body and the surrounding surfaces are evaluated.

The ADI depends on the Thermal Comfort Number and the Air Quality Number, while the ADTI depends on the Thermal Comfort Number, the Air Quality Number and the Draught Risk Number. On the other hand, Thermal Comfort Number depends on PPD and Effectiveness for Heat Removal (that depends of the Inlet Temperature, Outlet Temperature, Body Mean Temperature). Air Quality Number depends on the Percentage of Dissatisfied with Indoor Air Quality and the Effectiveness for Contaminant Removal (that depends on the Inlet Carbon Dioxide Concentration, Outlet Carbon Dioxide Concentration and Carbon Dioxide Concentration in the Respiration Area). Draught Risk Number depends on the Body Mean Draught Risk and the Effectiveness for Airflow Removal (that depends on the Body Mean Velocity and the Occupied Mean Velocity.

3 Numerical Methodology

The new ceiling mounted localized air distribution systems consider an inlet and one exhaust system:

- The inlet system, placed above the head occupant level, is made with a horizontal rectangular duct;
- The exhaust system, placed above the head occupant level, is made with two horizontal ducts placed in the lateral area of the rectangular duct.

In the study the following numerical simulation are considered:

- External air of 0ºC;
- Air mean internal temperature of 20ºC;
- Inlet air temperature of 16.8ºC;
- Inlet air velocity of 5 m/s.

This numerical study is done in a virtual classroom chamber. The virtual chamber has twelve chairs, each occupied by a virtual mannequin, and six tables.

The virtual chamber, similar to a real experimental chamber, which simulates the virtual classroom, has the dimensions of $4.5 \times 2.55 \times 2.5$ m³. This virtual chamber consists of a wood structure equipped isolated by a material with a thickness of 3 cm.

Fig. 1 shows the scheme of the classroom equipped with ceiling mounted localized air distribution systems, Fig. 2 presents the localization of the occupants in the virtual classroom, Fig. 3 and Fig. 4 show two views of the scheme of the airflow detail in the ceiling mounted localized air distribution systems.

Note that the inlet air velocity was chosen to have a high enough value so that there is no short circuit in the airflow due to the proximity of the supply and exhaust vents.
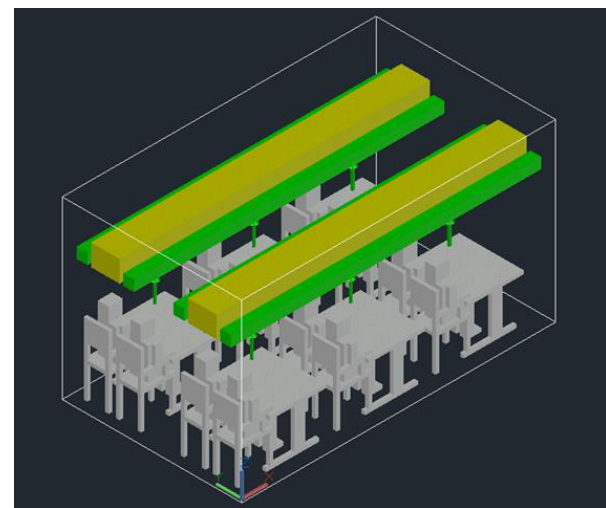

Fig. 1. Scheme of the classroom equipped with ceiling mounted localized air distribution systems.

Fig. 2. Position of the occupants in the virtual classroom.

Fig. 3. Scheme of the airflow detail in the ceiling mounted localized air distribution systems (rear view). Green arrows refer to exhaustion and yellow arrows to inlet.

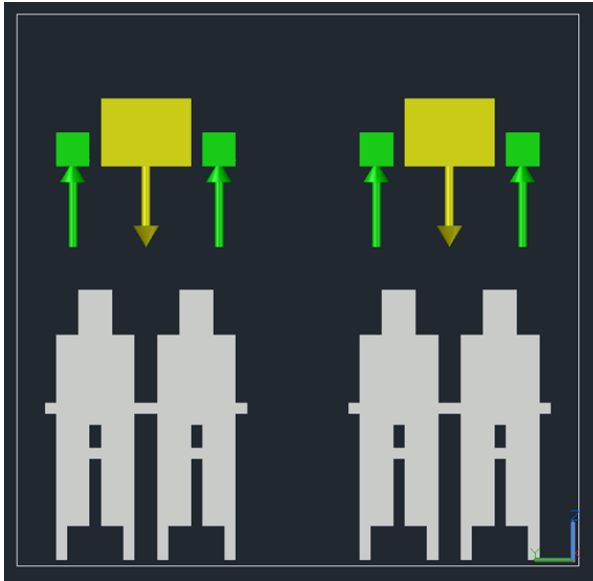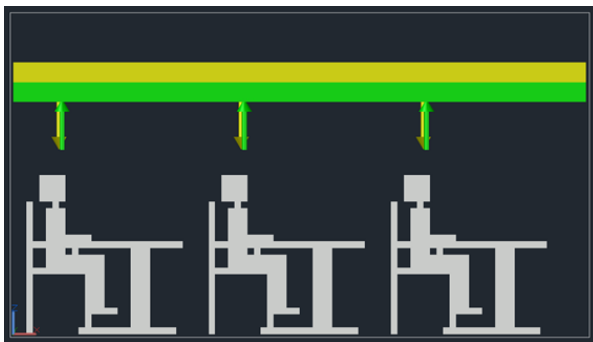**Fig. 4.** Scheme of the airflow detail in the ceiling mounted localized air distribution systems (side view). Green arrows refer to exhaustion and yellow arrows to inlet.

4 Results and Discussion

In this section, the results obtained for ADI and ADTI are presented in Tables 1, 2 and 3. Table 1 shows the ADI and ADTI for the first six occupants, Table 2 presents ADI and ADTI for the last six occupants, and Table 3 shows the mean values of ADI and ADTI. These Tables show also the body mean temperature, effectiveness for heat removal, PPD, thermal comfort number, carbon dioxide concentration in the respiration area, effectiveness for contaminant removal, percentage of dissatisfied with indoor air quality, air quality number,

effectiveness for airflow removal, body mean draught risk and draught risk number.

In this study the thermal power, used to heat the air, from external thermal conditions with an air temperature of 0ºC to the mean internal value of air temperature of 20ºC, is 5390.2 W.

Table 1. ADI and ADTI for the first six occupants.

Occupant	1	2	3	4	5	6
Body Mean Temperature (ºC)	23.41	23.47	23.40	23.52	23.50	23.77
Effectiveness For Heat Removal (%)	60.24	59.62	60.25	59.21	59.41	57.07
PPD (%)	11.07	10.48	11.63	10.92	11.36	9.55
Thermal Comfort Number	5.44	5.69	5.18	5.42	5.23	5.97
Inlet CO2 (mg/m3)	500.00	500.00	500.00	500.00	500.00	500.00
CO2 in the respiration area (mg/m3)	796.94	836.63	784.33	807.00	820.27	824.46
Effectiveness For Contaminant Removal (%)	100.00	90.80	100.00	99.57	95.44	94.21
PD (%)	6.19	6.19	6.19	6.19	6.19	6.19
Air Quality Number	16.16	14.68	16.16	16.09	15.43	15.23
Effectiveness for Airflow Removal (%)	50.03	59.20	53.39	54.85	53.24	57.48
Body Mean Draught Risk (%)	18.55	18.90	21.06	20.46	20.90	19.05
Draught Risk Number	2.70	3.13	2.54	2.68	2.55	3.02
Air Distribution Index (ADI)	9.38	9.14	9.15	9.34	8.98	9.54
Air Distribution Turbulent Index (ADTI)	6.19	6.40	5.97	6.16	5.90	6.50

Table 2. ADI and ADTI for the last six occupants.

Occupant	7	8	9	10	11	12
Body Mean Temperature (ºC)	23.57	23.38	23.48	23.50	23.69	23.57
Effectiveness For Heat Removal (%)	58.74	60.47	59.52	59.39	57.78	58.77
PPD (%)	10.40	11.13	11.71	10.88	10.30	10.56
Thermal Comfort Number	5.65	5.43	5.08	5.46	5.61	5.56
Inlet CO2 (mg/m3)	500.00	500.00	500.00	500.00	500.00	500.00
CO2 in the respiration area (mg/m3)	801.85	801.74	764.46	823.36	797.66	857.88
Effectiveness For Contaminant Removal (%)	100.00	100.00	100.00	94.53	100.00	85.41
PD (%)	6.19	6.19	6.19	6.19	6.19	6.19
Air Quality Number	16.16	16.16	16.16	15.28	16.16	13.81
Effectiveness for Airflow Removal (%)	58.35	58.17	51.54	55.34	54.73	55.19
Body Mean Draught Risk (%)	18.89	19.30	21.64	20.39	20.03	20.16
Draught Risk Number	3.09	3.01	2.38	2.71	2.73	2.74
Air Distribution Index (ADI)	9.56	9.37	9.06	9.13	9.52	8.76
Air Distribution Turbulent Index (ADTI)	6.56	6.42	5.80	6.09	6.28	5.95

Table 3. ADI and ADTI mean values.

Occupant	Mean value
Body Mean Temperature (ºC)	23.52
Effectiveness For Heat Removal (%)	59.21
PPD (%)	10.83
Thermal Comfort Number	5.48
Inlet CO2 (mg/m3)	500.00
CO2 in the respiration area (mg/m3)	809.71
Effectiveness For Contaminant Removal (%)	96.66
PD (%)	6.19
Air Quality Number	15.62
Effectiveness for Airflow Removal (%)	55.13
Body Mean Draught Risk (%)	19.94
Draught Risk Number	2.77
Air Distribution Index (ADI)	9.25
Air Distribution Turbulent Index (ADTI)	6.19

The results show that the thermal comfort level of all occupants is acceptable at least within category C [5, 6].

The carbon dioxide concentration levels obtained in the breathing zone of all occupants show that the IAQ is acceptable since its values are below 1500 mg/m^3, therefore below the limit considered acceptable by the standards [8].

The mean body Draught Risk value, obtained in the numerical simulation, is acceptable at least within the category B provided for in the ISO 7730 standard [5].

The effectiveness for contaminant removal is significantly higher than the effectiveness for heat removal and effectiveness for airflow removal.

Finally, the air quality number is the highest and the Draught Risk number is the lowest. Thus, ADI is higher than ADTI, because ADTI is influenced by DR.

5 Conclusions

In this study the numerical simulation of the human microenvironment around the occupants was applied using ceiling mounted localized air distribution systems consisting of an inlet system and an exhaust system. Numerical simulation was performed assuming winter conditions.

As can be seen from the results obtained, the proposed ventilation system presents a good performance in terms of thermal comfort and IAQ conditions provided to the occupants. His ventilation system guarantees acceptable levels of thermal comfort, at least within category C [5, 6], and of IAQ, for values of carbon dioxide concentration in the breathing zone below the acceptable limit of 1800 mg/m^3 [8], for all occupants. In addition, it also manages to guarantee average DR values around the occupants acceptable at least within category B [5].

Acknowledgement

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