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Influence of the Ceiling Mounted Localized Air Distribution System Performance in the Human Body

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Abstract

This work presents a numerical study of the influence of the ceiling mounted localized air distribution system performance in the human thermal behavior. In his study a coupling of the Computational Fluids Dynamics and the Human Thermal Modelling is used to evaluate the thermal comfort, the indoor air quality and the Draught Risk. The input data, of the coupling numerical models, are evaluated in the Building Dynamics Modelling. The virtual chamber geometry is generated using the Computational Aided Design system and the occupants' geometry is generated using empirical equations, based on occupant height and weight. The ADI (Air Distribution Index) and the ADTI (Air Distribution Turbulence Index), used to evaluate the Heating Ventilating and Air Conditioning system performance, depends of the thermal comfort level, the indoor air quality level, the Draught Risk level, the effectiveness for heat removal, the effectiveness for contaminant removal and the effectiveness for airflow removal. The study is made in a virtual chamber occupied by twelve virtual manikins and equipped with twelve seats, six desks and with a ceiling mounted localized air distribution system. The ceiling mounted localized air distribution system is equipped with an inlet system and an extraction system located above the head level.

Introduction

The ceiling mounted localized air distribution systems is based on descend jets located above the heat level. This kind of ventilation was being analyzed, as example, (Ghaddar, et al. 2013) and (Habchi, et al. 2016). (Ghaddar et al. 2013) analyzed the thermal comfort and the air quality in a ceiling-mounted personalized ventilation and (Habchi et al. 2016) analyze the reduction of the disease transmission between occupants using the ceiling-mounted personalized ventilation.

The impinging jets ventilation system is based on an airflow projected to a surface. Different authors work in this kind of ventilation. (Karimipanah and Awbi 2002) and (Karimipanah, et al. 2008), as example, presents works related with this topic. (Karimipanah and Awbi 2002) showed a comparative study between the impinging jets ventilation system and the wall displacement ventilation, while Karimipanah et al. showed a study that used the ADI, energy consumption and ventilation systems performance.

In this study the considered Heating, Ventilating and Air-Conditioning (HVAC) system is a combination of the ceiling mounted localized air distribution systems and the impinging jets ventilation system. The first one considers the inlet airflow located above the occupants' head level and the second one consider the airflow projected to the desk write table surface.

In this work the thermal comfort, indoor air quality, Draught Risk and HVAC system performance is evaluated numerically using the Building Thermal Modelling and the coupling of the Computational Fluids Dynamics and the Human Thermal Response.

In the thermal comfort, indoor air quality and Draught Risk is important to evaluate airflow around the occupants, see (Conceição, et al. 1997).

In the thermal comfort, evaluated numerically, developed by (Fanger 1972), which is presented in ISO 7730 (2005) and (ASHRAE-55 2017), can be analyzed in (Conceição et al. 2010). This numerical study considers an occupied school building and the thermal comfort is evaluated using the Building Thermal Modelling.

In the air quality, it is used the carbon dioxide concentration and the airflow rate as indicator of the indoor air quality, the ASHRAE 62.1 (2016), see examples, in (Conceição, et al. 1997) and in (Conceição et al. 2016).

In the Draught Risk, it is used the air velocity, air temperature and the air turbulence intensity, see (Fanger et al. 1988), being also present in ISO 7730 (2005), see an application in (Conceição et al. 2018). In this work the coupling of the Computational Fluids Dynamics and the Human Thermal Modelling.

Finally, in order to evaluate the HVAC system performance in this work the Air Distribution Index (ADI) and the Air Distribution Turbulent Index (ADTI) are evaluated. This calculus is developed using the coupling of the Computational Fluids Dynamics and the Human Thermal Modelling, see as example (Conceição and Awbi 2021).

The main objective of this work is to evaluate the thermal comfort, the indoor air quality, the Draught Risk and the HVAC system performance. The numerical study, using the Building Thermal Modelling, see (Conceição and Lúcio 2010), and the coupling of the Computational Fluids Dynamics and the Human Thermal Modelling, (Conceição and Awbi 2021), analyzed a new system based in the ceiling mounted localized air distribution systems coupled with the impinging jets ventilation system.

Numerical Models

The numerical software, developed by the author of this work, uses the Building Thermal Modelling, and the coupling of the Computational Fluids Dynamics and the Human Thermal Modelling. The Building Thermal Modelling evaluates the distribution of the temperature and mass in a building with complex topology, the Computational Fluids Dynamics evaluates the airflow around the occupants and inside the space, while the Human Thermal Modelling evaluates air temperature, air velocity and other parameters around each occupant. The Building Thermal Modelling equations generation is made using the CAD (Computer Aided Design) system. This methodology considers the different slices of the opaque bodies, the transparent bodies and the indoor bodies.

The Human Thermal Modelling equations generation considers only the occupant location and the geometry based in the weight and height. The human body and clothing thermal response equation, the human thermal physiology equations, the blood thermal equations and the water transport equations are considered for all occupants.

All equations system is resolved using the Runge-Kutta-Felberg. This resolution system, using the error control, is important in transient thermal conditions.

The numerical models of the Building Thermal Modelling and the Human Thermal Modelling, 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 Computational Fluids Dynamics, using Cartesian coordinates, with non-uniform grid generation refined in the inlet, outlet and near the surfaces. In all cell the following equations are considered:

- Mass continuity equation;
- Navier-Stokes equations (used to calculated the air velocity in x, y and z direction);
- Energy equation (used to calculate the air temperature);
- Turbulence kinetic energy equation;
- Turbulence energy dissipation rate equation;
- RNG turbulence model;
- Contaminant concentration equation (used to calculate the Carbon Dioxide concentration).
- SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) used in the velocity and pressure equations;
- TDMA (Tri-Diagonal Matrix Algorithm) used in the equations system resolution;
- Finite volume method;
- Hybrid scheme in the convective/diffusive fluxes;
- Grid refinement near the surfaces and in the airflow inlet and outlet;
- density changes with temperature;
- Impulsion term in the vertical air velocity equation.

The Building Thermal Modelling evaluates the surrounding temperatures, the surrounding geometry and inlet and outlet airflow. This information is used as input in the Computational Fluids Dynamics and in the Human Thermal Modelling.

The Human Thermal Modelling numerical model evaluates the thermal comfort level, using Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) indexes. The human body temperature distribution is used as input in the Computational Fluids Dynamics. This numerical model is used to evaluate the human thermal comfort level that the occupants are subjected.

The Computational Fluids Dynamics numerical model is used to evaluate the air temperature, the air turbulence intensity and the air velocity around the human body sections. This numerical model is used to calculate the indoor air quality and the Draught Risk that the occupants are subjected.

The Computational Fluids Dynamics numerical model was validated in steady-state conditions and isothermal conditions and in steady-state conditions and non-isothermal conditions. In the first validation only the Computational Fluids Dynamics numerical model was considered, however, in the second validation the coupling of the Computational Fluids Dynamics numerical model with the Human Thermal Modelling, using data from the Building Thermal Modelling numerical model, was made. Both validations were made in an experimental chamber. In the first one the occupation is not considered, however, in the second one the occupation was considered.

The Air Distribution Index and the Air Distribution Turbulent Index is used to evaluate the HVAC system performance.

The Air Distribution Index depends on the:

- Thermal Comfort Number;
- Air Quality Number.

The Air Distribution Turbulent Index depends on the:

- Thermal Comfort Number;
- Air Quality Number;
- Draught Risk Number.

While, the Thermal Comfort Number depends on the:

- PPD;
- 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;
- 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;
- Effectiveness for Airflow Removal (that depends on the Body Mean Velocity and the Occupied Mean Velocity.

Numerical Methodology

This Heating, Ventilating and Air Conditioning System, is based on ceiling mounted localized air distribution systems and impinging jets ventilation system. The first one, main ventilation system, considers the inlet airflow located above the head level, while the second one considers the airflow projected to a surface of the desk writing table.

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

- The inlet system, placed above the head occupant level, is made with a horizontal rectangular duct. This duct transport clean air from the external to the internal environment;
- The exhaust system, placed above the head occupant level, is made with two horizontal ducts placed in the lateral area of the rectangular duct. This duct transport poluted air from the internal to the external environment.

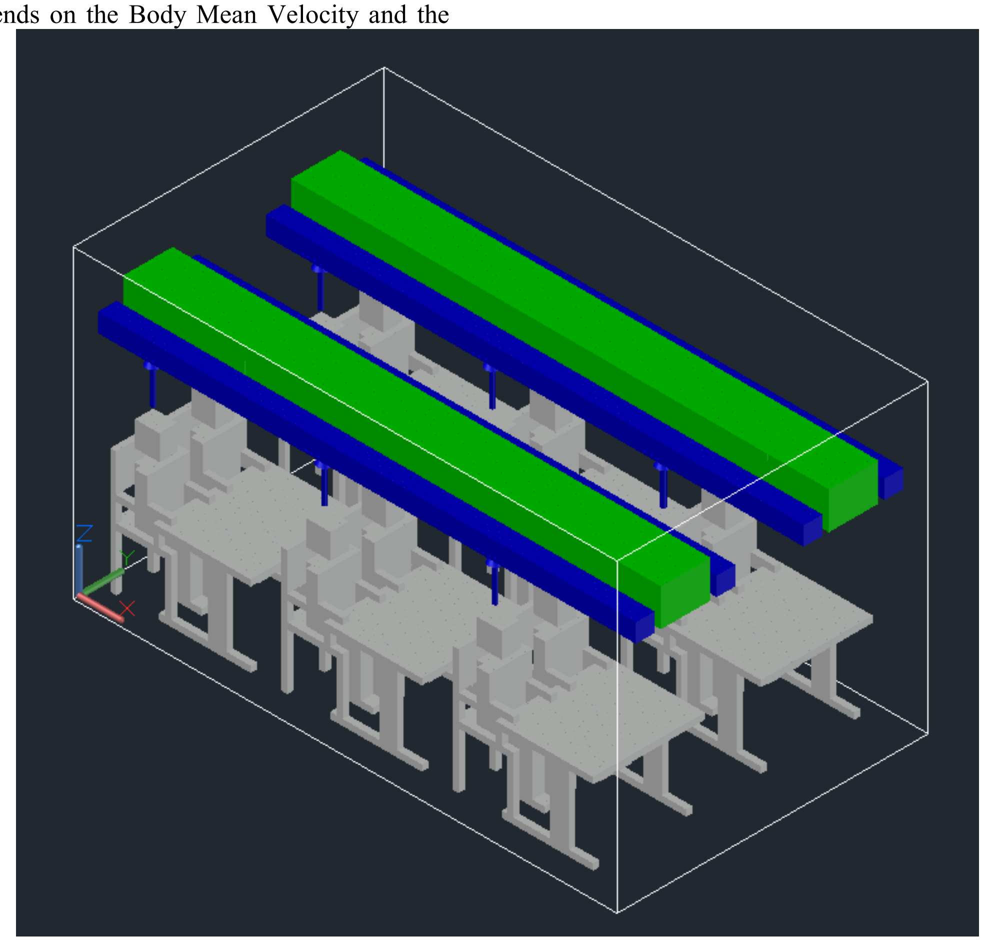

Figure 1: Scheme of the classroom occupied with twelve students and equipped with twelve chairs, six desks and a ceiling mounted localized air distribution systems. The inlet airflow ducts is presented in green color and outlet airflow ducts is presented in blue color.

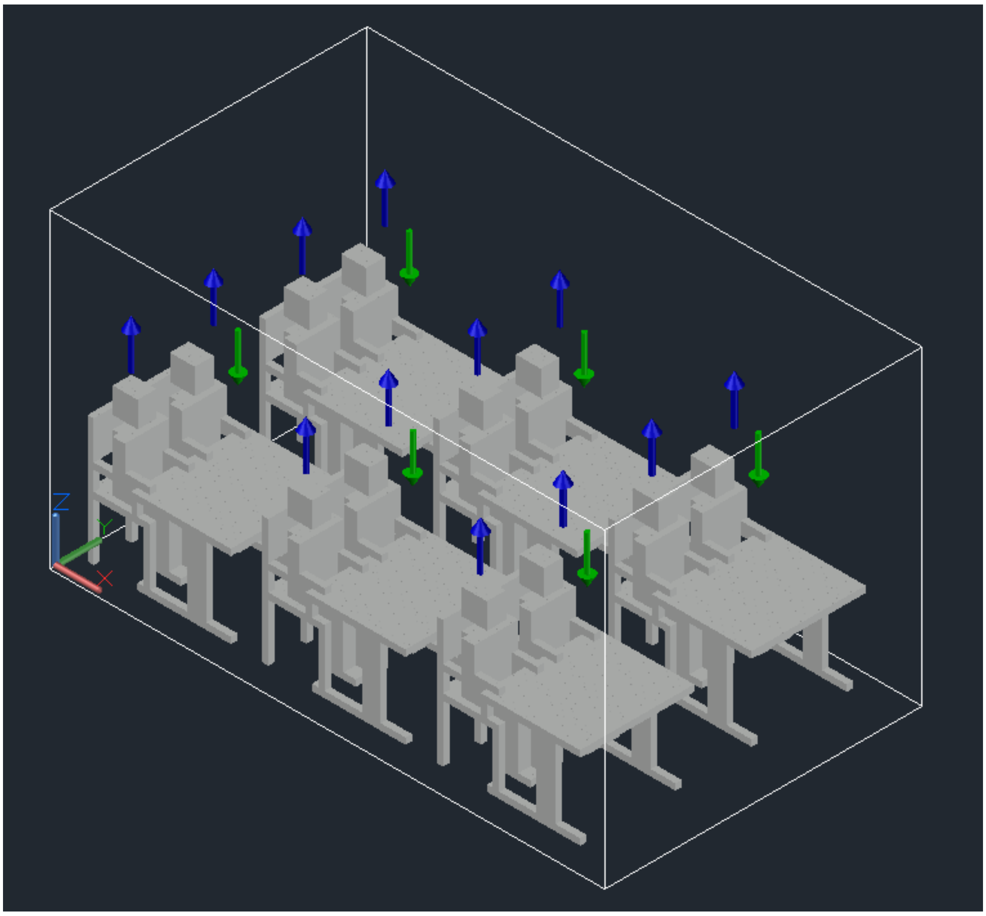

Figure 2: Scheme of the classroom occupied with twelve students and equipped with twelve chairs, six desks and a ceiling mounted localized air distribution systems built with an inlet airflow (green color) and outlet airflow (blue color).

The impinging jets ventilation system considers the projection of the airflow in the desk-writing table.
In the study the following numerical simulation are considered:

- External air temperature of 0ºC;
- Internal air 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, similar to a real experimental chamber, which has the dimensions of 4.5×2.55×2.5 m^3. This virtual chamber consists of a wood structure isolated by a material with a thickness of 3 cm.
The virtual chamber has:

- twelve seats;
- twelve occupants;
- six tables.

Figures 1 and 2 shows the scheme of the classroom occupied with twelve students and equipped with twelve chairs, six desks and a ceiling mounted localized air distribution systems. The ceiling mounted localized air distribution systems is built with an inlet airflow (green color) and outlet airflow (blue color) (see figure 2).

The occupants numbers 1, 3 and 5 are located near the right wall, the occupants number 2, 4 and 6 are located near the right corridor. The occupants numbers 7, 9 and 11 are located near the left corridor, the occupants number 8, 10 and 12 are located near the left wall. The low occupant numbers are located in low x values, while high occupant numbers are located in high x values

Results and Discussion

In this study the air velocity, air temperature, air turbulence intensity, Draught Risk, carbon dioxide concentration, amount others variables, are calculated inside the space and mainly around the occupants. The air velocity, air temperature, air relative humidity and Mean Radiant Temperature are used in the evaluation of the PPD index, the temperature is used to calculate the effectiveness for heat removal, the carbon dioxide concentration is used to calculate the Percentage of Dissatisfied due the carbon dioxide concentration and the effectiveness for contaminant removal. The air velocity is used to calculate the effectiveness for airflow removal. The air velocity, air temperature and air turbulence intensity are used to calculate the Draught Risk.

This section presents the results obtained for each occupant and respective mean value regarding the following parameters: CO_2 (carbon dioxide) concentration in the respiration zone (Figure 3); PPD (Predicted Percentage of Dissatisfied people) and DR (Draught Risk) (Figure 4); TCN (Thermal Comfort number), AQN (Air Quality Number) and DRN (Draught Risk Number) (Figure 5); ADI (Air Distribution Index) and ADTI (Air Distribution Turbulence Index) (Figure 6).

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.

The concentration of CO_2 in the respiration area of all occupants is acceptable because all values obtained there are below the 1800 mg/m3 recommended as an acceptable limit by the standard (AHRAE, 2016). Occupants 2 and 5 have, respectively, the highest and lowest CO_2 concentration values in the respiration area.

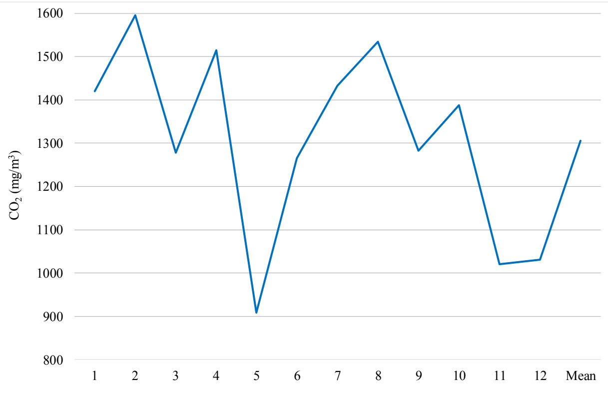

Figure 3: CO_2 concentration in the respiration zone of each occupant for an inlet air velocity of 5 m/s.

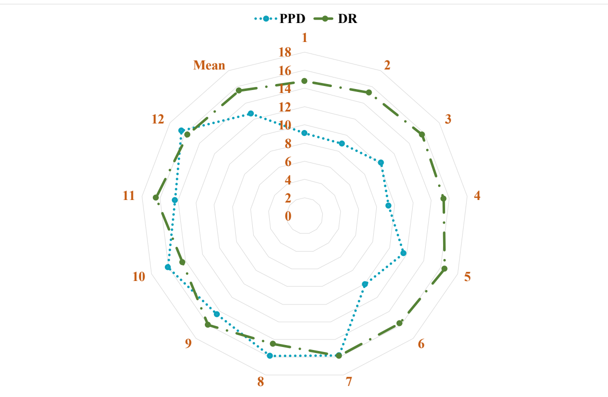

Figure 4: PPD (%) and DR (%) by occupant number for an inlet air velocity of 5 m/s.

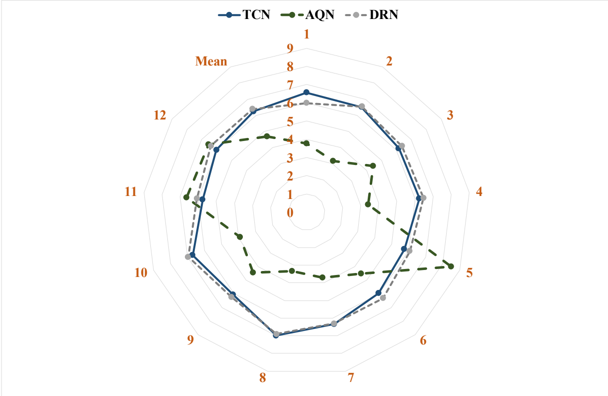

Figure 5: TCN, AQN and DRN by occupant number for an inlet air velocity of 5 m/s.

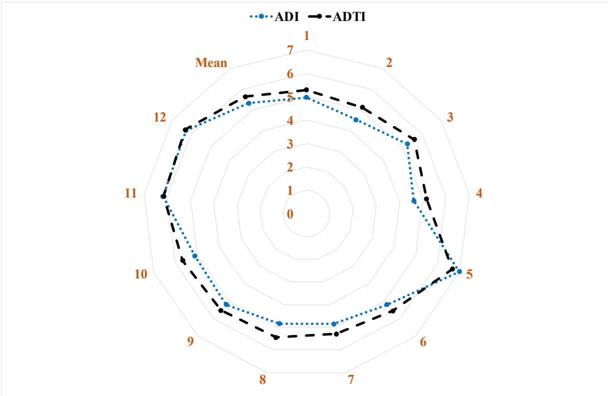

Figure 6: ADI and ADTI by occupant number for an inlet air velocity of 5 m/s.

In general, the values obtained for PPD per occupant show that most occupants have an acceptable level of thermal comfort according to category C (PPD < 15%) of the standard (ISO, 2005). The exception is occupants 7, 8, 10 and 12; however, their PPD values are slightly above acceptable (less than 2%). The most thermally comfortable occupant is number 2 (whose PPD equals 8.9%). All occupants have acceptable DR values according to category B of the standard (ISO, 2005). Their values are very similar, varying between 14.4% (occupant 10) and 16.5% (occupant 5).

The mean values of TCN and DRN are very similar. The mean value of the AQN is lower than the other two. This means that the ventilation system is more efficient at removing heat and airflow than it is at removing contaminants. Occupant 10 has the best TCN and DRN values. Occupants 5 and 11 have the lowest TCN value and occupant 1 the lowest DRN value. Occupant 11 has the best AQN value and occupant 2 has the worst AQN value.

The mean value of ADTI (5.7) is slightly above the mean value of ADI (5.3). These results show that the ventilation system performs well in terms of ensuring acceptable levels of thermal comfort, draught risk and air quality in the respiration area. The best values of ADI and ADTI are obtained in the position of occupant 5. The worst values of ADI and ADTI are obtained in the position of occupant 2.

This ventilation system, when the inlet air velocity is located above the desk area, promote an ascendant airflow near the occupant. The thermal comfort is acceptable, due the ascendant airflow around the body, the air quality is acceptable, due the ascendant airflow near the face, and the Draught Risk is acceptable, due the low levels of air velocity and turbulence intensity levels around the body. Thus, in accordance the obtained results, this is ventilation system present some advantages.

Conclusion

In this article a new ventilation system based on a ceiling mounted distribution system and an impinging jet system was presented. A numerical study was carried out in order to evaluate its performance using its own research software. The most significant conclusions are the following:

- The air quality in the breathing zone of all occupants meets the requirements imposed by the standard for CO_2 concentration values below the suggested limit;
- The thermal comfort of the occupants is, in general, acceptable for almost all of them by PPD values within the C category of the standard;
- Occupant Draught Risk is acceptable to all for DR values within category B of the standard;
- The mean value of ADTI is slightly above the mean value of ADI;
- Overall, the performance of this system guarantees acceptable levels of air quality, thermal comfort and Draught Risk for the occupants.

Acknowledgement

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References

ANSI/ASHRAE Standard 62-1: Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers."

ISO 7730: Ergonomics of the Thermal Environments—Analytical Determination and Inter-Pretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. Geneva, Switzerland: International Standard Organization.

ASHRAE-55. 2017. "Thermal Environmental Conditions for Human Occupancy." *ANSI/ASHRAE Standard -55*.

Conceição, E., M. Lúcio, V. Vicente, and V. Rosão. 2016 "Evaluation of Local Thermal Discomfort in a Classroom Equipped with Crossed Ventilation." *International Journal of Ventilation* 7(3):267–277.

Conceição, E. Z. E., and M. M. J. R. Lúcio. 2010. "Numerical Study of the Influence of Opaque External Trees with Pyramidal Shape on the Thermal Behaviour of a School Building in Summer Conditions." *Indoor and Built Environment* 19(6).

Conceição, E. Z. E., A. R. L. Nunes, J. M. M. Gomes, and M. J. R. Lúcio. 2010. "Application of a School Building Thermal Response Numerical Model in the Evolution of the Adaptive Thermal Comfort Level in the Mediterranean Environment." *International Journal of Ventilation* 9(3).

Conceição, E. Z. E., C. I. M. Santiago, M. M. J. R. Lúcio, and H. B. Awbi. 2018. "Predicting the Air Quality, Thermal Comfort and Draught Risk for a Virtual Classroom with Desk-Type Personalized Ventilation Systems." *Buildings* 8(2).

Conceição, E. Z. E., M. C. G. Silva, and D. X. Viegas. 1997. "Air Quality inside the Passenger Compartment of a Bus." *Journal of Exposure Analysis and Environmental Epidemiology* 7(4).

Conceição, E. Z. E., M. C. G. Silva, and D. X. Viegas. 1997. "Airflow around a Passenger Seated in a Bus." *HVAC and R Research* 3(4).

Conceição, Eusébio, and Hazim Awbi. 2021. "Evaluation of Integral Effect of Thermal Comfort, Air Quality and Draught Risk for Desks Equipped with Personalized Ventilation Systems." *Energies*.

Fanger, P. O., A. K. Melikov, H. Hanzawa, and J. Ring. 1988. "Air Turbulence and Sensation of Draught." *Energy and Buildings*.

Fanger, P. Ol. 1972. "Thermal Comfort: Analysis and Applications in Environmental Engineering." *Applied Ergonomics* 3(3):181.

Ghaddar, Nesreen, Kamel Ghali, and Alain Makhoul. 2013. "Performance of Coaxial Ceiling-Mounted Personalized Ventilator for Comfort and Good Air Quality." in *ASME 2013 Heat Transfer Summer Conf. Collocated with the ASME 2013 7th Int. Conf. on Energy Sustainability and the ASME 2013 11th Int. Conf. on Fuel Cell Science, Engineering and Technology, HT 2013*.

Habchi, Carine, Kamel Abou Ghali, and Nesreen Ghaddar. 2016. "Chair Fans or Desk Fans to Aid Performance of Ceiling Personalized Ventilation for Reduced Disease Transmission between Occupants?" in *International Conference on Efficient Building Design: Material and HVAC Equipment Technologies*.

Karimipanah, T., and H. B. Awbi. 2002. "Theoretical and Experimental Investigation of Impinging Jet

https://doi.org/10.1051/e3sconf/202236214002

Ventilation and Comparison with Wall Displacement Ventilation.” *Building and Environment*.

Karimipanah, T., H. B. Awbi, and B. Moshfegh. 2008. “The Air Distribution Index as an Indicator for Energy Consumption and Performance of Ventilation Systems.” *Journal of the Human-Environment System*.