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DEVELOPMENT AND APPLICATION OF AN INTEGRATED VIRTUAL THERMAL-ACOUSTIC MANIKIN DESIGN USED INSIDE VENTILATED OCCUPIED SPACES

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Resumo

Neste estudo é desenvolvido e aplicado um manequim virtual termo-acústico integrado utilizado em espaços ventilados e ocupados. A componente do manequim virtual térmico avalia o sistema térmico, termorregulatório e do vestuário dos ocupantes e calcula o nível de conforto térmico. A componente do manequim virtual biauricular avalia o som direto e indireto e calcula o tempo de reverberação.

Neste estudo, efetuado numa sala de aula ocupada por seis alunos e um professor e equipada com um sistema de jatos confluentes, o nível de conforto térmico dos ocupantes e o tempo de reverberação do espaço são avaliados. De acordo com os resultados obtidos, em geral, os valores estão de acordo com a normalização em vigor.

Palavras-chave: manequim virtual termo-acústico, conforto térmico e tempo de reverberação.

Abstract

In this study an integrated virtual thermal-acoustic manikin design used inside ventilated and occupied spaces is developed and applicated. The component of the virtual thermal manikin evaluates the occupants' thermal, thermo-physiology and clothing systems and calculates the thermal comfort. The component of the virtual binaural manikin evaluates the direct and indirect sound and calculates the reverberation time.

In this study, performed in a classroom occupied by six students and a teacher and equipped with a confluent jets system, the thermal comfort level and the space reverberation time is evaluated. In accordance with the obtained results the values are, in general, in accordance with the actual standards.

Keywords: virtual thermal-acoustic manikin, thermal comfort and reverberation time.

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1 Introduction

In this work a virtual manikin used in the evaluation, in occupied spaces, of integral thermal acoustic study is made. In this study the geometry of the virtual manikin and the surrounding room surfaces, used in the occupied space, is developed. The virtual manikin evaluates the environmental variables around the occupants (see as example Conceição et al. [1]), the occupants' thermal comfort (see as example Conceição [2]) and the acoustic level (see as example Conceição et al. [3]).
The occupants' presence is developed using numerical equations, for the dimensions and positions of the occupants, and the space geometry was developed using Computational Aid Design (CAD). The CAD system is used in the vehicle and building thermal systems and in the human thermal response, while the human generation equations are used in the human thermal response and CFD.
In the numerical study is important to calculate the room surface temperature, using the vehicle or building thermal response, the airflow around the manikins, using the CFD, the thermal comfort, using the thermal manikin, and the acoustic reverberation time, using the acoustic manikin.
The building or vehicle thermal behaviour numerical model is used to evaluate the surrounding room temperature. This vehicle numerical model was developed in Conceição et al. [4] and Conceição [5], while the building numerical model was developed in Conceição and Lúcio [6-8]. The validation of these models were made for vehicles in Conceição et al. [4] and Conceição [5], and for buildings in winter conditions in Conceição et al. [9] and summer conditions in Conceição and Lúcio [10].
The thermal component considers the Human Thermal Response and the CFD. In Conceição [2, 11], Conceição and Lúcio [12, 15, 17], and Conceição et al. [13, 14, 16], the Human Thermal Response was considered. In Conceição et al. [18] the CFD was developed and applied. In Conceição et al. [19, 20] the coupling of CFD and the Human Thermal Response are considered. The coupling considers simultaneously the human geometry and the compartment geometry and the input of the Human Thermal Response are the output of the CFD and the input of the CFD are the output of the Human Thermal Response.
The sound propagation, in indoor spaces, is function not only to the internal geometry, but also the internal temperature level. The evaluation of sound propagation can be made numerically or experimentally. However, in this paper only the numerical component is developed (see also Schetelig and Rabenstein [21], Savioja et al. [22], Funkhouser et al. [23, 24, 26], and Taylor et al. [25]).
This work is a continuation of the work of Conceição et al. [3]. The preliminary work was used in the evaluation of thermal acoustic phenomena in high density occupied spaces with complex geometry. In the previous work was presented the grid generation details, sitting room internal thermal airflow field, the occupants' thermal distribution and the space reverberation time. The surrounding space surfaces and the occupants' surfaces geometry are applied. In the previous work the software develops, namely, the CFD, the radiative heat exchanges and the Sound Propagation. The space geometry is obtained using a Computer Aid Design (CAD), while the occupants' geometry are obtained using geometric equations. Previous work considered that all occupants were seated. However, in the present work, six students are seated, but the teacher are stand. This new configuration need special attention in the Heating, Ventilation and Air-conditioning (HVAC) system in order to guarantee acceptable thermal comfort levels for all occupants and need special attention in the acoustic virtual manikins in the sound propagation numerical model.
In order to evaluate the thermal acoustic phenomena is important to evaluate the occupants' thermal phenomena, the internal airflow and the sound propagation. In this study three geometries are considered: one for the occupants' thermal response, used to evaluate the thermal comfort level, ISO 7730 [27], other for the internal airflow and another for the internal acoustics, used to evaluate the reverberation time DL [22].
This concept, using the Predicted Percentage of Dissatisfied people, can be analysed in accordance with ISO 7730 [27] and the adaptive thermal comfort level can be evaluated in Conceição et al. [28]. However, others concepts in order to guarantee acceptable thermal comfort level, as the internal

temperatures, can be seen in Portuguese Decreto-Lei No. 118/2013 [29], the Portaria No. 349-D/2013 [30] and in Conceição et al. [31].
In this work, the design and geometry used in this type of study will be generated and analysed in detail, in order to reduce the calculation time and increase the accuracy of the results. The building thermal behaviour, used to evaluate the room surface temperature around the occupants, introduces the room design. The coupled software, using the previous information to evaluate the internal airflow variables and occupants comfort levels, generates obstacles around the occupants (such as chairs and desk) and obstacles related to the HVAC system (located above the level of people's heads). The coupled software, in order to significantly reduce the number of surfaces used in the acoustic calculation, group the coplanar surfaces. In the acoustics numerical model, in order to evaluate the reverberation time, the numerical model generates the emission source (mouth) and the receptor (ears), for all occupants.

2 Numerical models

The numerical model considers the integral vehicle and building thermal response numerical models, the coupling of integral Human Thermal Response and differential CFD numerical models and the integral Sound Propagation numerical model.

Integral vehicle and building thermal response numerical model
This numerical model considers the integral energy balance equations used to calculate the air temperature inside the spaces, the temperature on the indoor bodies, the temperature on the glasses and the temperature distribution in the opaque surfaces. These equations take into account the convection, conduction and radiation phenomena. The heat transfer is calculated by natural, forced and mixed convection, through the use of dimensionless coefficients. In the radiative exchanges, the incident solar radiation, the solar radiation absorbed by glasses and opaque surfaces and the solar radiation transmitted through the glass are considered.

Integral Human Thermal Response numerical model
The Human Thermal Response numerical model evaluated the thermal variables in the occupants and clothing, namely the body temperature, the clothing temperature, the skin water vapour and the clothing water vapour. These variables are used as input data in the CFD numerical model. The Human Thermal Response numerical model, based in mass and energy integral equations, works in transient conditions and simulates simultaneously a group of occupants. The body is divided into 24 cylindrical and 1 spherical elements. Each element is divided in core, muscle, fat and skin layers and could be protected from external environment using clothing layers. This numerical model also evaluates the thermal comfort level that the occupants are subjected.

Differential Computational Fluids Dynamics numerical model
The CFD numerical model evaluates the environmental thermal variables inside the spaces and around the occupants, namely the air temperature, air velocity and carbon dioxide concentration around the occupant. These variables are used as input data in the Human Thermal Response numerical model. This numerical model is based in Navier-Stokes differential equations in Cartesian coordinates and works in steady-state conditions and in non-isothermal conditions. In the turbulence simulation is applied the RNG model. This numerical model also evaluates the draught risk (based in empirical models) and the air quality level (based in carbon dioxide released from the respiration process).

Integral Sound Propagation numerical model
The Sound Propagation numerical model is based in geometrical methods and mathematical numerical models. The acoustical geometrical methods, developed graphically the path between the source and the

receiver, considering the multi reflections, diffractions and refractions at surfaces of the occupied room, using an image source method. This ray tracing method find the reverberation paths between the source and the receiver. This numerical model, between other variables, in this work, is used to evaluate the reverberation time. In this numerical simulation the mouth is used as source and the left and right ears as used as receivers.

Grid generation numerical model

The space geometry with complex topology is developed using CAD, while the occupants' geometry is done using geometric equations. The grid generation, in the surrounding space surfaces and around the external occupants' surfaces geometry, is developed to be used by the CAD software, to calculate the radiative heat exchanges and the sound propagation.

In the CFD, the geometry is based in volume elements, while in the Human Thermal Response numerical model the geometry is based in surfaces. The surfaces generated in the Human Thermal Response numerical model is used to evaluate heat exchanges by radiation between the occupants and the surrounding surfaces and the incident solar radiation.

3 Numerical methodology

The study presented in this work is performed in a virtual chamber, similar to an existing experimental chamber, with dimensions of 4.50×2.55×2.50 m^3. The chamber, occupied with seven virtual manikins (six seated and one stand), is equipped with six tables, six chairs, one exhaust system and one inlet system, based in confluents jets system (see figure 1). In figure 1 the first occupant (seated student) is located in the beginning of the x and y coordinates and the last one (stand teacher) is located at the furthest x coordinate.

This simulation considers the descendent inlet airflow, near the lateral walls. The airflow is distributed in the ground floor. The ascendant airflow transport all bioefluents and heat release by the occupants to the exit system located above the head level. This kind of airflow topology promotes good air quality levels, because remove the bioeffluents contaminants release in the respiration process, promote acceptable thermal comfort levels because remove the heat emanated from the body and promotes low Draught Risk levels because the higher air velocity levels are located near the wall, in the non-occupied space, and low air velocity in the occupied area.

In the exhaust system are considered six air ducts, located above the head level, connected to the ceiling area. This innovative structure improves the thermal comfort and air quality levels and reduces the risk of airborne disease transmission. The inlet system, based in two horizontal ducts, with 0.15 m diameter, located 1.8 m above the floor level, are equipped with consecutive holes, that promote vertical descendent jets near the wall.

In table 1 is presented the thermal conditions used in the numerical simulation in Winter and Summer conditions. In this simulation the renovation airflow is 20 l/s/occupant, the activity level is 1.2 Met and the clothing level is 1 Clo (in winter conditions) and 0.5 Clo (in summer conditions). In the Sound Propagation numerical model, the surface absorption coefficient of 20 % is considered.

Table 1: Thermal conditions used in the numerical simulation in Winter and Summer conditions. Positive power are associated to heating system and negative power are associated to air-conditioning system

	Winter	Summer
External temperature (ºC)	10.0	30.0
Power (W)	834.5	-1465.9
Mean Internal temperature (ºC)	20.0	25.0
Wall temperatures (ºC)	18.8	25.7
Floor temperature (ºC)	19.0	25.6
Ceiling Temperature (ºC)	18.3	26.0

The CFD numerical model is based in boxes with 5 cm of dimension. In the present situation a grid box, made by 90×51×50 units is considered. The input, introduced in the coupling numerical model, considers the:

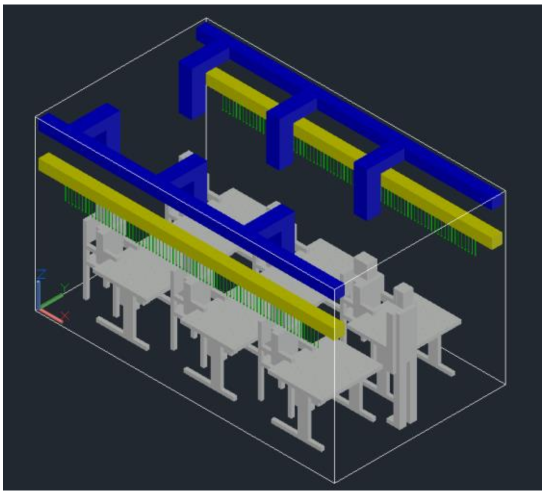
- interior bodies, like tables, desks, inlet horizontal, used as HVAC system, and outlet vertical exhaustion systems. In this information is used a CAD software;
- occupants' presence is made numerically using equations after an occupant location is identified. The occupant is divided in twenty-five elements, namely, head, neck, chest, upper abdomen, lower abdomen, right upper shoulder, right lower shoulder, right upper arm, right lower arm, right hand, left upper shoulder, left lower shoulder, left upper arm, left lower arm, left hand, right upper thigh, right lower thigh, right upper leg, right lower leg, right foot, left upper thigh, left lower thigh, left upper leg, left lower leg and left foot. In the CFD numerical model each element is represented by a box, while in the Human Thermal Response numerical model each element is represented by a cylinder or a sphere.

In figure 1 is presented the geometry used in the CFD. In figure 2 is presented the geometry used in the Human Thermal Response. The geometry of the Sound Propagation numerical model is presented in figure 3. Inlet and outlet system and occupation area are presented in these figures. In the CFD, the occupants, inlet and outlet systems and desks boxes are considered. In the Human Thermal Response, the occupants cylindrical and spherical elements, the inlet and outlet systems and desks surfaces are considered. In the Sound Propagation, the occupants, the inlet and outlet systems and desks surfaces are also considered.

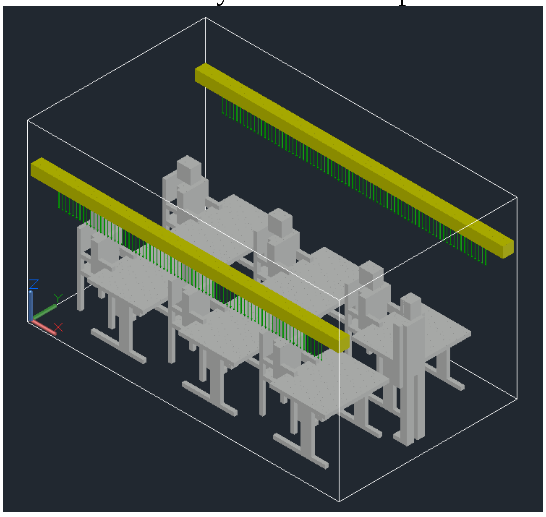
The geometry of the sound propagation is exported from the CFD numerical model. The geometry of the Sound Propagation numerical model, being calculated before the sound path, is simplified, in order to reduce the number of considered surfaces. The strategy used in the model considers grouping a set of coplanar surfaces on the same planes. Thus, in the present simulation (see figure 3), with initial 41666 surfaces:

- the grouping of planes with the same x values reduces the number of surfaces to 32852;
- the grouping of planes with the same y values reduces the number of surfaces to 17842;
- the grouping of planes with the same z values reduces the number of surfaces to 1180.

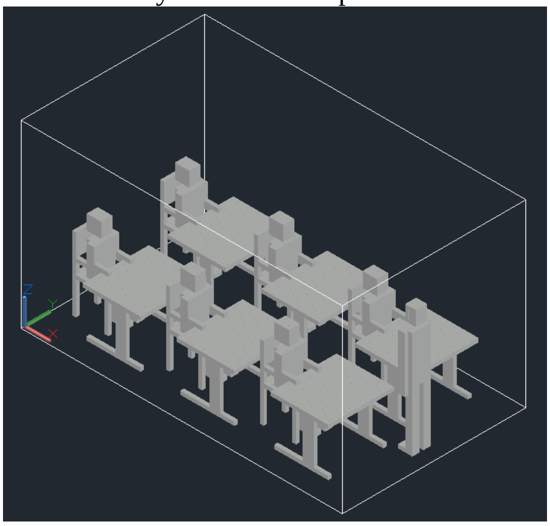
In figure 3 are presented the 41666, 32852, 17842 and 1180 surfaces considered in the Sound Propagation numerical model in the sound evaluation.



Inlet and outlet system and occupation area



Inlet system and occupation area



Occupation area

Figure 1: Geometry used in the Computational Fluids Dynamics: inlet and outlet system and occupation area.

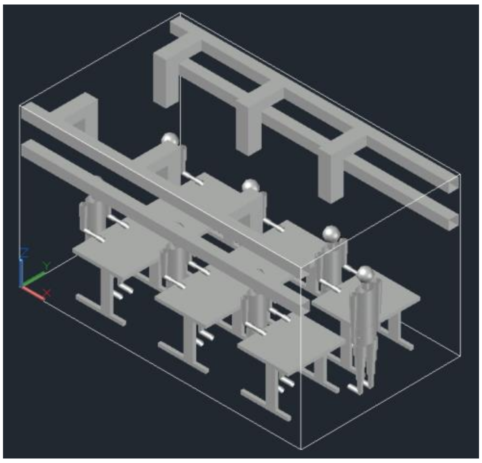


Figure 2: Geometry used in the Human Thermal Response.

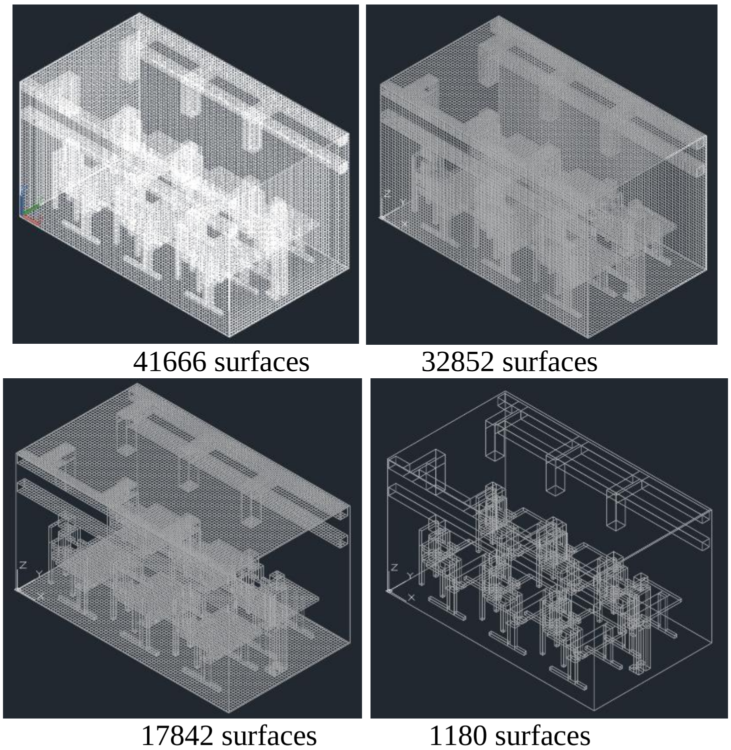


Figure 3: The 41666, 32852, 17842 and 1180 surfaces considered in the Sound Propagation numerical model.

4 Results

The Predicted Percentage of Dissatisfied (PPD) of people and the Predicted Mean Vote (PMV), that the occupants are subjected, are presented in table 2. In accordance with the ISO 7730 [27] the indoor thermal conditions are acceptable. In winter conditions are near the optimal conditions (PMV equal to 0), while in summer conditions is acceptable by positive Predicted Mean Vote.

Table 2: Comfort PMV and PPD parameters.

	Winter		Summer	
Occupant number	**PMV**	**PPD**	**PMV**	**PPD**
1	-0,09	5,2	0,56	11,5
2	-0,08	5,1	0,59	12,3
3	-0,12	5,3	0,51	10,4
4	-0,11	5,3	0,55	11,2
5	-0,12	5,3	0,53	10,8
6	-0,12	5,3	0,55	11,3
7	0,05	5,1	0,76	17,3
Mean Value	**-0,08**	**5,21**	**0,58**	**12,12**

In this section, after the evaluation of the temperature filed inside the space, the Sound Propagation numerical model is applied. In the study a sound impulse in the source, in the mouth of the seven occupants, is made and in the receiver, in the right and left ears of the seven occupants, is monitored. Figure 4 shows the sound propagation paths from a source to a receiver. In this calculus, the direct paths, first reflections paths and second reflections paths are considered.

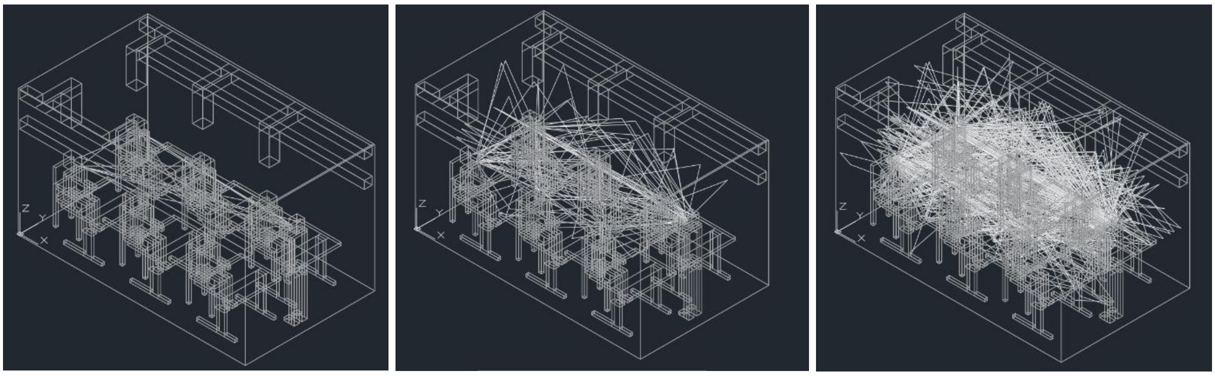


Figure 4: Sound propagation paths from a source to a receiver. Direct paths (left image), first reflections paths (central image) and second reflections paths (right image).

The reverberation time is numerically calculated using a regression of the sound intensity level evolution, using an exponential equation, when the receiver is located in the left and right ears. Thus, the reverberation time is calculated, for the left and right ears, using the necessary time to decay 60 dB from the beginning of the test. The exemplification of the present method is shown in Conceição et al. [3].

Reverberation time calculation when the source is located in the mouth of the seven occupants and the receiver is located in the left and right ears of other seven occupants are presented in table 3. The calculated mean reverberation time is 0.364638 s for the left ear and is 0.329631 s for the right ear. The mean reverberation time for the left and right ears is 0.3471345 s. In accordance with DL [22] the suggested reverberation time, used as reference a furnished and non-occupied school space, is lower than 0,454 s. Thus, the calculated reverberation time is lower the suggested value. The reverberation time is highest when is using as source the mouth of teacher.

Tabela 3 – Reverberation time.

Occupant	Left	Right
1	0,327802	0,597901
2	0,616732	0,3731
3	0,18531	0,208435
4	0,311659	0,256675
5	0,235261	0,247873
6	0,349592	0,290735
7	0,526111	0,641354
Mean	0,364638	0,373725

5 Conclusions

In this study an integrated virtual thermal-acoustic manikin design used inside ventilated and occupied spaces is developed and applicated.
In accordance with the thermal obtained results and in accordance with the international standards, the indoor thermal conditions are acceptable. In winter conditions are near the optimal conditions and in summer conditions is acceptable by positive Predicted Mean Vote.
In the acoustical results, in accordance with national standards the obtained reverberation time is lower than the suggested reverberation time. The reverberation time is highest when is using as source the mouth of teacher.

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