APPLICATION OF INTEGRATED BUILDING SIMULATION AND CFD TO A CLASSROOM HEATING CASE STUDY IN A MEDITERRANEAN CLIMATE

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ABSTRACT

This study develops knowledge of the methodological analysis of indoor air distribution in high density rooms, allowing evaluation of the expected comfort level of the occupants. A typical classroom is presented as a case study, focusing on the influence of dedicated ventilation. The methodology established the boundary conditions using discretization and determination of values over time which defined the dynamic energy behaviour of the room, by means of a nodal model. The study incorporates sectional isothermal curves and air velocity analysis, the use of indicators to evaluate the thermal comfort of the occupants according to ASHRAE standards, and comparisons of alternative HVAC systems.

A case study application shows poor efficiency of traditional radiator heating systems versus those which incorporate a neutral ventilation air supply.

INTRODUCTION

HVAC systems are always designed to solve the equation of balance between energy demand and the power supplied to the space. Usually, this solution is carried out by assuming the transfer is between two discrete points, one internal and one external. However, the spaces to be dealt with are volumes where the occupants usually have freedom of movement or location, with multiple points where this energy load-contribution ratio does not behave as in the originally foreseen model. This problem is critical in evaluating two linked concepts: the efficiency of delivering energy of the system to the volume occupied, and the real comfort of the different occupants according to their spatial distribution in the volume.

Although there are many methods for calculating the transfer equations of a thermal system, these are achieved with a nodal model, where it is not possible to know what the energy distribution will be within the space, without establishing a spatial model based on CFD (Zhai, Z.J. *et al*). The generation of these models allows the energy efficiency of the building to be evaluated, and its energy distribution to be analysed, by considering the venues as three-dimensional spaces where occupants, furniture, equipment and other heat sources are active in the system.

This work is presented with this focus, and has sought to develop a methodology for connecting the nodal analysis results, representing the temporal evolution of the energy states of the building-HVAC-exterior system, and its impact on different states of the interior space.

A school building was chosen as the application model, because a classroom represents a space with problems that are typical of those to be analysed, due to its high internal load, high ventilation (ISO 13779:2008 on Ventilation for non-residential buildings) and high comfort needs and prolonged use over time. The evolution of its behaviour over a typical day is a particularly important factor, given the influence of the positive loads associated with the use of the space (Karimipanah, T. *et al*).

This study is presented as the next step in the working methodology begun in "Analysis of thermal emissions from radiators in classrooms in Mediterranean climates" and it incorporates new analytical tools and broadens the field of study to include the influence of mechanical ventilation. The work uses a series of indicators, among which the Fanger method is highlighted, and is supplemented with a series of linear graphs of thermal variations.

The final objective of this work is the development of a methodology to undertake comparative studies between HVAC systems, enabling decision making based on the results of energy distribution and the desired comfort of the occupants.

SIMULATION METHODOLOGY

Definition of the model under study

The characteristics of the base model for the study are as follows: a typical classroom of $50m^2$ corresponding to the non-university teaching centre type, accommodating 25 students with their teacher. Dimensions are 7.25 x 6.40 metres and 3.00 metres high, with the window to the left of the seats for easier reading with natural lighting. The space is defined, in addition to its north side (worst case orientation for the study of heating systems), by horizontal and vertical partitions in contact with other classrooms of similar size and use, and the common access corridor (Fig. 1).

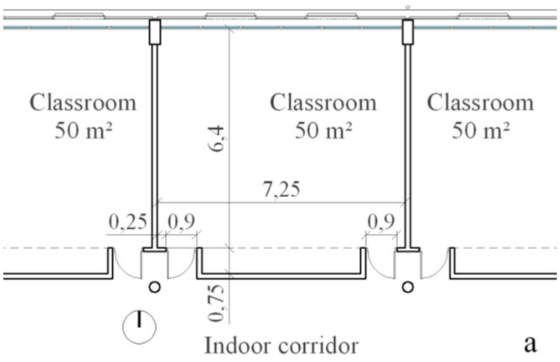

Figure 1 Floor plan of the classroom under study

A point to highlight is the incorporation of a laptop for each student.

The building was assumed to be located in a C3 zone (according to Spanish climatic zoning), which has moderately cold winters and hot summers, as can be seen on Table 1.

Table 1 Location data

Location	Granada (Spain)
Time zone	GTM +1:00
Longitude/Latitude	3.78º (W) / 37.18º (N)
Elevation above sea level	559.0 m
Exterior calculation template	1.9 ºC
Relative humidity for calculation	90%
Wind speed	10.1 m/s
Calculation date	21st of January
Climatic date template	ESP_Granada.swec

The building data on the thermal envelope comply with the current national standard for limiting energy demand, and are shown in Table 2.

Table 2 Envelope

ELEMENT	**TRANSMITTANCE (W/m^2·K)**
Façade	0.45
Vertical partitions	2.09
Slab	1.98
Insulated door	0.84
Fenestration	Double glazed window (4/6/4) with thermal break

Description of the systems studied

The study focuses on the modification of the behaviour of the classroom over a typical usage period, by adding a mechanical ventilation system to a radiator heating installation, which traditionally relied on uncontrolled venting through the envelope (model A). This original model is the most common in Southern Europe.

The radiator heat exchange system, common to both models, consists of three steel panels beneath the windows for model A and two steel panels for model B, marked red in Figure 2a and b, with an average emission temperature of 70 ºC and a a thermal difference of 20 ºC in the water I/O. The water flow varies according to the thermal requirements of the venue.

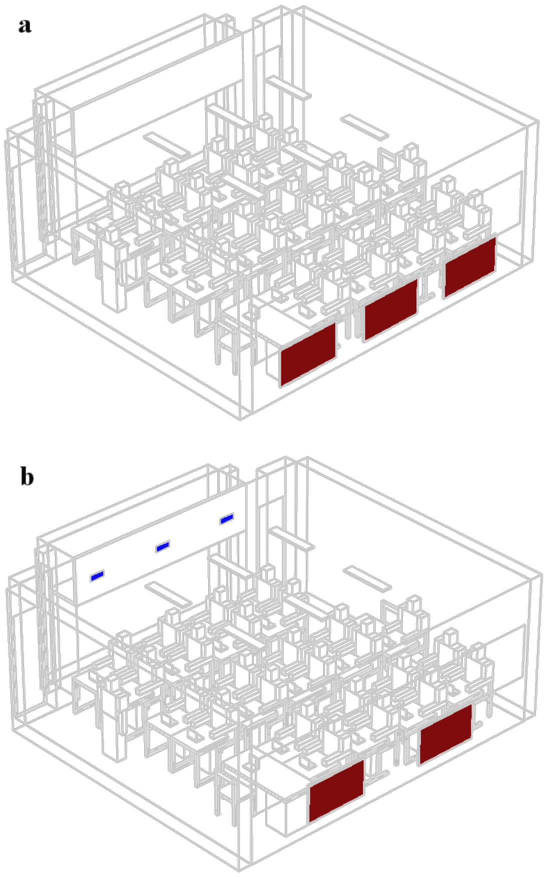

Figure 2 Positioning of HVAC elements in the models

The infiltration rate of model 1 is represented by a constant value of 1 air change per hour introduced into the venue through windows perimeter, adopted as a usual value as we have been able to appreciate in different field tests. The remaining air gets out of the venue throught the doorjambs.

The mechanical ventilation system introduced in the second model under consideration (model B) as a complement to resolve the indoor air quality, according to EN 13779 on ventilation for non-residential buildings, consists of a neutral primary air conditioner (dedicated outdoor air handler) which filters and heat treats 1170 m^3/h of outdoor air to level IDA2 at 21 °C, the interior temperature set-point. In addition, water vapour is introduced by a steam lance to reach 40% relative humidity at the quoted 21 °C.

The air is introduced in a typical fashion via the interior upper part of the classroom and collected in a perpendicular plane below that of the supply.

The ratio between the impulse and extraction flows is 80%, in order to achieve an overpressure state to stop the influence of natural infiltrations. This remaining air escapes from the venue thought doorjambs and the perimeter of the windows depending on their outlet surfaces.

Conditions for use and operation

The elements used in both study models are shown in Table 3.

Table 3 Elements included in the calculations

Thermal control	21 ºC set temperature
Tables and chairs	26 (table and chair per occupant)
Lighting	6 overhead lights, individual emission of 58 W (convective component only)
Netbooks	One per occupant, with an individual flow emission of 30 W (Lim, E. *et al* and Lee, J.M. *et al*).
Occupants	Teacher, standing, and 25 students, sitting, with an individual flow emission of 45 W (convective component only) and clothing 1.2 clo. 0.52 people/m^2.
Openings	Model A: Infiltration rate of 1.0 air change per hour through the windows perimeter. Model B: Infiltration rate of 0.0 air changes per hour.
Radiators	Model A: Three steel radiator panels. Model B: Two steel radiator panels.
Mechanical Ventilation	Model A: None Model B: Neutral ventilation air supply of 1170 m^3/h (IDA 2).
Area occupied	According to EN 13779 on ventilation for non-residential buildings (fig 3).

Tool for energy simulation

The software chosen both for nodal calculations and for the CFD was Design Builder 2.36.007. This program was designed as the nodal simulation engine EnergyPlus by the U.S. Department of Energy, and also incorporates a steady-state type CFD module, validated by the University of Northumbria (Newcastle), which calculates snap-shot of the studied model using nodal simulation data as boundary conditions.

For this study, a simulation tool with low computational needs but reliable results was adopted, to allow for an easier methodology development, although the process applied is usable under all types of CFD calculation engines.

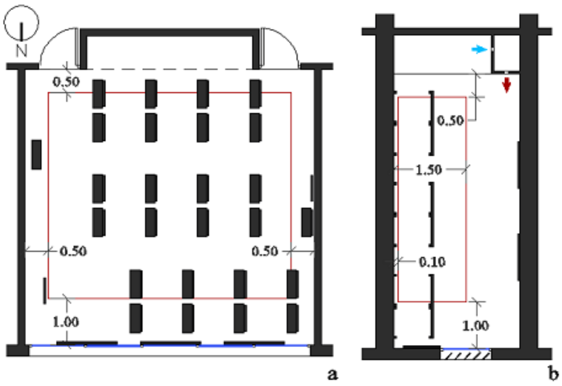

Figure 3 Occupied zone in horizontal (a) and vertical (b) section of the classroom (EN 13779)

Properties of calculation and derived geometrical considerations

When building the study model in the program to make the nodal calculation, it is necessary to create the boundary conditions (Figure 4), i.e., the spaces with which the classroom makes contact, they are:

- The classroom on its left (P1)
- The classroom on its left (P1)
- The classroom immediately above (P2)
- The classroom immediately below (PB)
- Access corridor (P1)

The characteristics of these spaces will be the same as the study location, except the hall, which represents an area without air conditioning and zero occupation and activity.

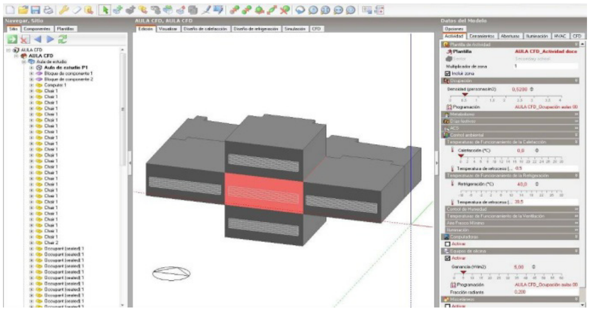

Figure 4 Model under study and adjacent venues

The boundaries of these adjacent areas, which are the exterior and the other classrooms. The latter connection is represented by adiabatic partitions, since the energy exchange with these other rooms is not of great relevance, given the predominance of energy flows to the exterior via the envelope compared to those that occur between the partitions.

To study the temporal evolution of both models, it was chosen to perform an hourly simulation hypothesis after the start at 8:00 until 11:00, when the daily break time occurs, thus breaking the thermal cycle (Table 4), obtaining the characterization of each of these instants for later evaluation.

Table 4 Description of the adopted assumptions

HEATING SYSTEM	VENTILATION SYSTEM	DIALY EVOLUTION
3 radiators under the windows	Infiltrations through the envelope	8:00; 9:00; 10:00; 11:00
2 radiators under the windows	Mechanical ventilation system	8:00; 9:00; 10:00; 11:00

For CFD simulation considerations, the boundary conditions of each scenario were given by the previous nodal calculation, also made by the Design Builder program.

A two-equation (Standard k-ε) turbulence model was chosen because it is the most complete model included in this software, despite of it assumes fully turbulent flow. A Renormalisation Group (RNG) k-ε model could solve laminar flow with more accuracy, but the relative deviation between both models results is acceptable for this type of indoor environment (Srebric, J. *et al*). Also, "Upwind" was chosen as a discretization method because of its greater simplicity of calculation for a hypothesis with air as the sole working fluid, under non-extreme conditions, without significant losses in the expected results.

When designing the mesh a hexahedral structure with straight, uniform sides was chosen, with a maximum spacing of 5 cm, being progressively reduced near surfaces and objects and uses a junction tolerance of 1 cm and a maximum ratio between the edges of the resulting cells of 1 to 10.

This maximum spacing was reduced to 2.5 cm in a test model in order to evaluate divergences, and was concluded that this spacing decrease did not affect significantly to the overall results but high increased computational time, as expected for those grid densities (Srebric, J. *et al*).

The maximum number of iterations of each simulation was established at 10,000.

Method of comparison of results

Two different methods were used, one based on numerical indicators and the other on graphs.

The recommendations of Standards EN ISO 7730 and EN ISO 11079 on Ergonomics of the thermal environment, were followed by using a number of indicators of thermal sensation and clothing associated with an array of evaluation points of 3x3 with three heights, corresponding to the legs (0.1 m), torso (0.6 m) and head (1.1 m) of a seated occupant, (Fig. 5), with which the results of the calculation were analysed from the perspective of a typical user. Of these points, nine of them (corresponding to the series C, F and I) were close to radiators, thus simulating the possibility of an occupant permanently seated near them, which is quite common in teaching classrooms and not recommended by the Standard EN ISO-13779.

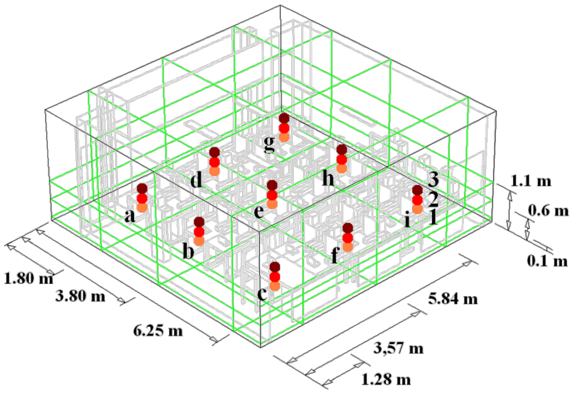

Figure 5 Array of evaluation points of 3x3x3 in the classroom under study

These indicators are:

- Fanger method
  - Predicted Mean Vote (PMV)
  - Predicted Percentage of Dissatisfied (PPD)
- Level of local thermal discomfort due to Draught Rate (DR).
- Level of local thermal discomfort due to vertical air temperature difference (PD).
- Required clothing insulation (IREQ).
  - To maintain thermal equilibrium with high physiological response ($IREQ_{minimum}$)
  - To maintain thermal equilibrium with no physiological response ($IREQ_{neutral}$)

All these indicators were applied at a height of 0.6 meter, corresponding to the chest of a seated occupant.

Parallel to these indicators, a series of linear graphs of thermal variations were created in support, and in which were generated a set of slices of the isothermal curves contained in the vertical section to be studied (Fig. 6), and chosen for being highly representative. Through the superimposition of the graphs of the instants studied for each model of thermal system, it was possible to perform the analysis of their evolution, as well as the comparative study between the two systems.

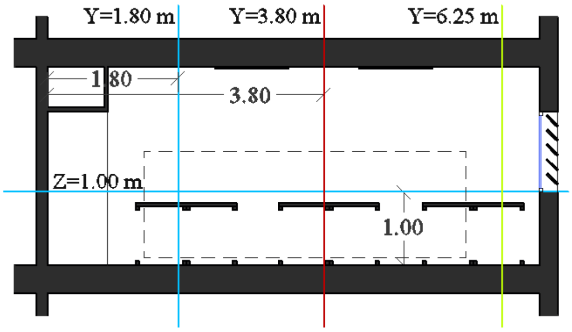

Figure 6 Lineal graphs of thermal variations on vertical section on 3.57 m

DISCUSSION AND RESULT ANALYSIS

Node calculations

The results of the structural thermal demand of the classroom (without mechanical ventilation loads) as a function of time for 21 January for both models, are shown in Table 5, whereby the radiators deliver a proportional amount of thermal energy if it is required.

In model B, due to the pressurization created by the neutral temperature ventilation air supply, from 10:00 internal loads (occupation, lighting and computers) are enough on their own to compensate thermal losses through the envelope whitout a heating system support.

Similarly, the average temperatures of the air and radiant faces were measured for each of the instants of calculation, and are listed in Table 6.

All these data were used as boundary conditions in the CFD calculation of each of the hypotheses of the models.

Table 5 Nodal results of local time structural heating demand (January)

TIME	**STRUCTURAL HEATING DEMAND**	
	MODEL A W	**MODEL B W**
8:00	2291	1414
9:00	1158	331
10:00	696	0
11:00	321	0

Table 6 Air and surface average temperatures for both models (January)

ELEMENT	**m^2**	**AVERAGE TEMPERATURE ºC**			
		8:00	9:00	10:00	11:00
Outdoor air	-	1.7	2.8	4.4	7.2
External wall	23.8	14.0	15.9	16.6	17.2
Windows	7.3	8.5	12.3	13.2	14.2
Partition 1	18.1	13.6	12.8	13.1	16.5
Partition 2	5.7	13.9	19.3	20.0	20.4
Door 1	1.3	11.6	11.6	11.6	13.8
Door 2	1.3	11.6	11.6	11.6	13.8
Partition 3	21.5	13.5	16.0	16.9	17.4
Partition 4	21.5	13.5	16.0	16.9	17.4
Floor	45.1	14.6	15.9	16.9	17.8
Ceiling	45.1	15.4	16.6	17.5	17.8
TOTAL	190.8	14.1	15.6	16.5	17.4

CFD calculations

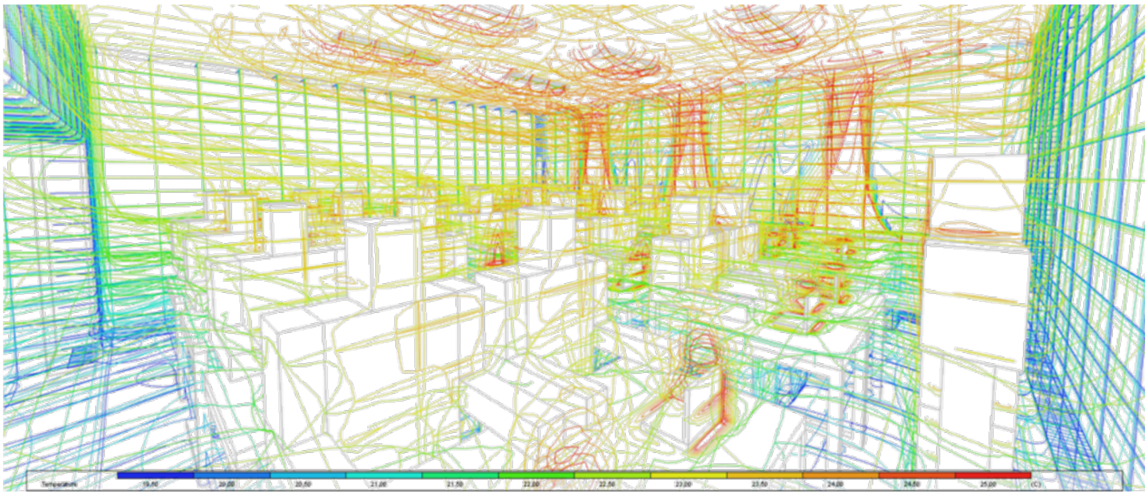

Figure 7 3D view of the classroom with mesh of isotherm curves. Model B.

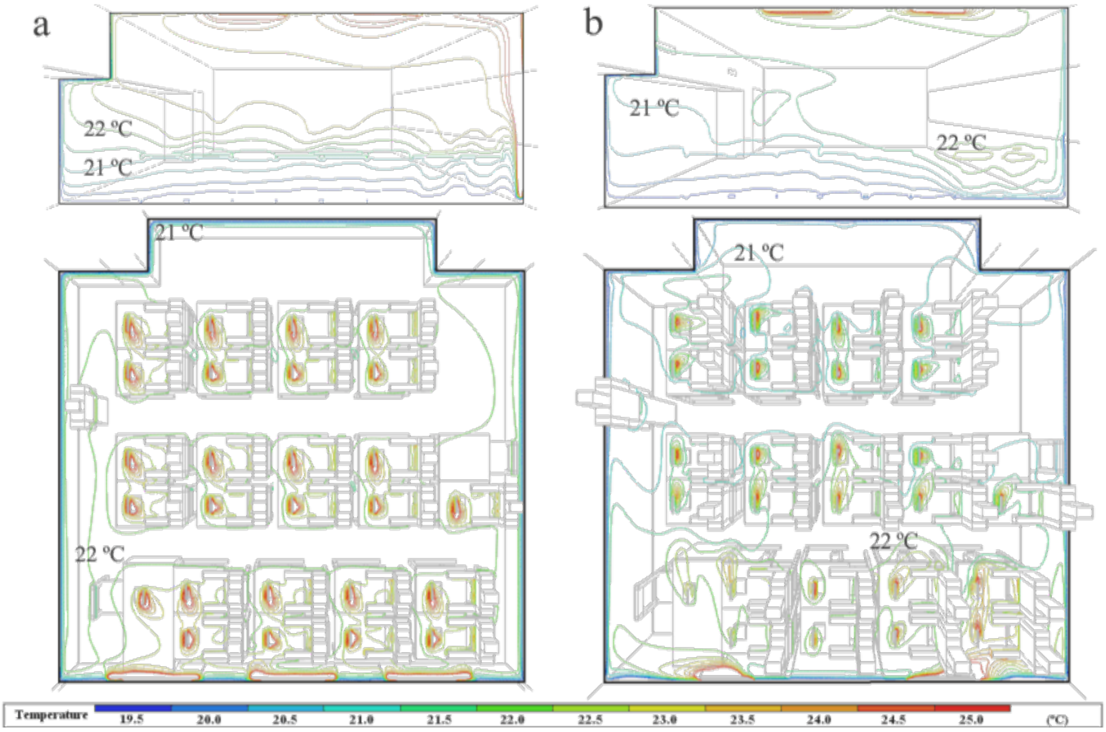

Figure 8 Transversal vertical section (X = 3,57 m) and horizontal section (Z = 1 m) of model A and B at 8:00

The results of CFD calculation can be shown as a 3D matrix of isothermal lines (fig. 7) which can be cut with horizontal and vertical sections for being easier analyzed (fig. 8).

To analyse the behaviour of the two systems studied, the central transverse vertical section was taken, after checking by means of a horizontal section at 1 meter and the array of evaluation points that the other two transverse vertical sections which cover the remaining points behave similarly to the study object.

To calculate the various indicators, air temperature, velocity and relative humidity data were taken over time in the evaluation points D1+2 +3, E1+2 +3 and F1 +2 +3 of both models.

Applying the Ergonomics of the Thermal Environment regulations

With the data above, each of the indicators described (Table 7) were calculated, and evaluated according to EN ISO 7730 in three categories, from best to worst comfort: A (green), B (orange) and C (red). Where out of the range, the value is in **black**.

The final classification of the thermal environment was equal to the least favourable of the four indicators.

From this table we can see that although both systems evolve in a similar way, the thermal perception of the occupants in the radiators only model (model A) is slightly better.

Table 7 Expected comfort indicators for model A and model B (0.6 meters high)

POINT		PMV	PPD	DR	PD	IREQ	
		-3 to 3	%	%	%	min clo	neu clo
D 2	A	-0.63	13.2	4.24	8.5	0.92	1.28
8:00	B	**-0.70**	**15.3**	6.05	2.4	0.93	1.29
E 2	A	-0.67	14.5	0.00	**12.5**	0.95	1.31
8:00	B	-0.68	14.6	5.09	6.3	0.92	1.28
F 2	A	**-0.70**	**15.3**	1.64	**19.1**	0.96	1.32
8:00	B	-0.41	8.5	3.13	1.4	0.77	1.13
D 2	A	-0.51	10.4	1.18	4.5	0.86	1.23
9:00	B	-0.67	14.3	5.23	2.4	0.92	1.28
E 2	A	-0.55	11.2	0.00	5.5	0.88	1.24
9:00	B	-0.67	14.4	5.42	4.7	0.92	1.28
F 2	A	-0.57	11.7	2.94	**17.9**	0.88	1.24
9:00	B	-0.42	8.6	4.76	1.1	0.77	1.13
D 2	A	-0.42	8.7	0.00	3.2	0.85	1.18
10:00	B	-0.60	12.6	5.00	2.0	0.89	1.25
E 2	A	-0.45	9.2	0.00	4.2	0.86	1.22
10:00	B	-0.61	12.7	4.38	3.6	0.89	1.25
F 2	A	-0.5	10.3	3.72	4.2	0.86	1.22
10:00	B	-0.35	7.6	4.43	1.0	0.74	1.11
D 2	A	-0.34	7.4	0.00	2.6	0.79	1.15
11:00	B	-0.54	11.2	4.92	2.0	0.85	1.22
E 2	A	-0.37	7.8	0.00	3.9	0.82	1.18
11:00	B	-0.55	11.3	5.48	3.4	0.85	1.22
F 2	A	-0.40	8.4	0.00	**12.1**	0.83	1.19
11:00	B	-0.53	11.1	4.77	0.9	0.85	1.08

This is mainly due to the divergence in the relative humidity of the air, which increased over time in model A and was more stable in the model B due to its hygrothermic treatment. This humidity variation is also more sharply perceived in the increasing divergence between the two systems when assessing the level of insulation of the clothing, it becoming somewhat excessive at 11:00 in the first case, because of the high humidity. Draught rate values are higher in model B than model A, due to the ventilation system working, but despite this both models obtain category A in this indicator. Finally, the PD indicator demonstrates greater stratification in the occupied area of the first series of the model.

Lineal graph analysis of thermal variations according to section

The resulting graphs are shown in figure 9, according to the previously selected cuts included in figure 5.

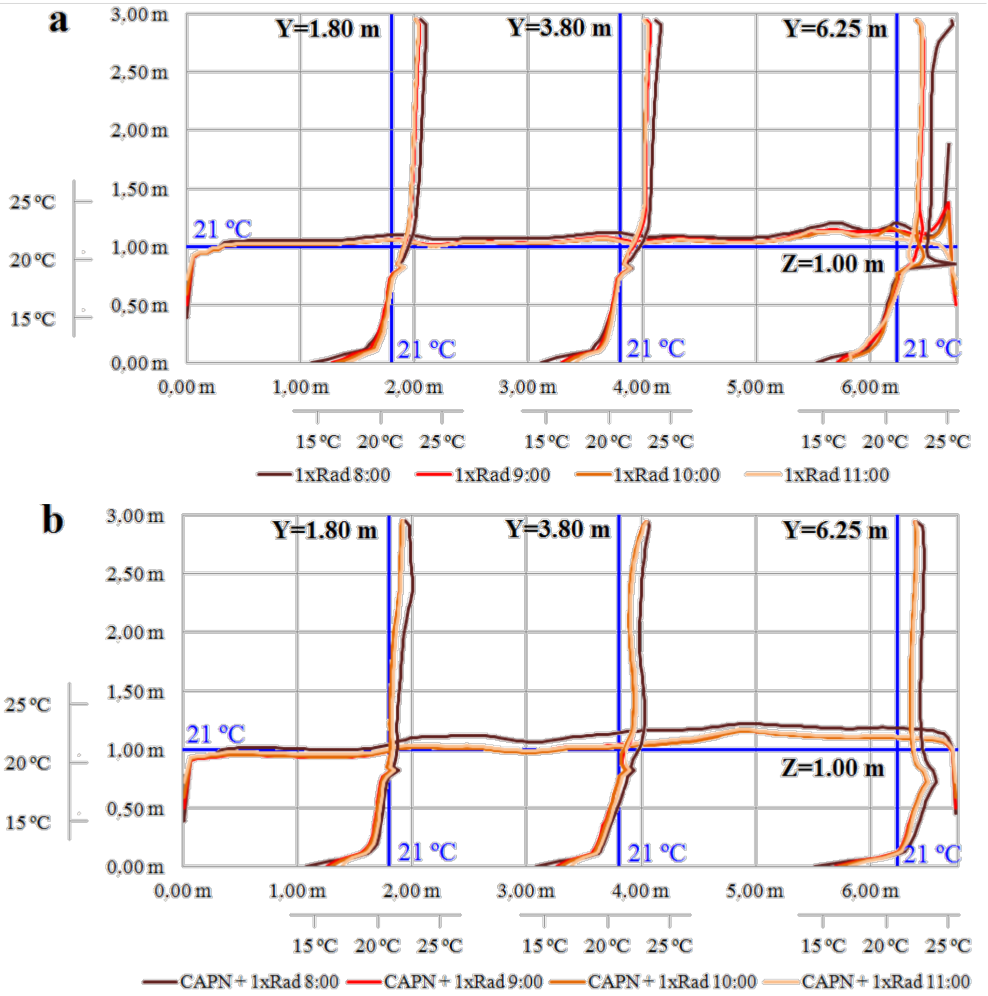

Figure 9 Lineal graphs of thermal variations on vertical section of model A and model B

In the graphs it can be seen again that there is strong thermal homogeneity in the horizontal plane, broken only by approach to the radiating elements. On the other hand, a more pronounced stratification phenomenon reappears in the model A, a fact which favours a better energy distribution and a greater tendency to approach the 21ºC air temperature being seen in the ventilation hypothesis (model B).

CONCLUSION

About the methodology

The process of creating the working model described, despite having been performed with a software with low computational requirements but enough accurate results, is fully exportable to other programs with greater requirements and features because it was focused on establishing the initial and boundary conditions, and it is presented as a methodological guide for the generation of any kind of model for studying air-conditioned locations.

Moreover, the dual analysis of these calculation data by using combined indicators of proven reliability as the Fanger method, the indicators of local thermal discomfort and the IREQ index, as well as the series of linear graphs of thermal variations, allow objective and detailed characterization of the thermal behaviour simulated with CFD of the HVAC systems in the given locations, in order to compare them with alternative systems in these locations.

About the results

The radiators only system, despite allowing somewhat higher average air temperatures to be reached than in the system incorporating mechanical ventilation, it suffers from a higher degree of stratification and thermal heterogeneity, while suffering from excessive build-up of humidity derived from occupation. On the other hand, it helps to slightly increase thermal perception and gradually decrease the amount of insulation by clothing.

In any case, these differences are not marked, because the effect of the introduction of mechanical ventilation on the selected temperature of the occupied area does not significantly influence the overall thermal variation of the enclosure, although it is evident that there is a need for humidification to improve the level of occupant comfort.

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