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Age-of-the-air in rooms according to the environmental condition of temperature: A case study

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ABSTRACT

The ventilation air in rooms is generally kept moving due to a constant difference in pressure. This gradient is generated through a general ventilation system (hybrid or mechanical), with minimum ventilation flow being established by the normative.

However, there are cases in which, even if the established flows are fulfilled, certain indoor areas exhibit an excess or shortage of ventilation. The excess or deficit depends on the flow pattern that the air follows in the room, and its characterisation is possible using the indoor local and mean calculation of the age of the air.

The flow pattern of air is conditioned by the energy transfer processes; therefore, analysis of air's behaviour under two extreme situations (summer and winter) was performed to compare the results with a previous isothermal model.

For the development of this work, a double study (numerical and experimental) was conducted. The numerical calculations were developed using a CFD tool, which is notably useful for this type of research work.

1. Introduction

In general terms, air quality in indoor spaces is an essential component for the well-being of the inhabitants, especially considering that in industrialised countries, people spend more than 90% of their time in an artificial environment [1]. Inhabitants can suffer certain illnesses related to indoor environments (human transmission, hypersensitivity reactions to bacteria and fungus, exposure to contaminants and toxic products) that can be avoided by establishing the correct ventilation airflow.

As a concept, building ventilation manages the quantity of air required in the indoor space under specific environmental conditions. The process implies managing the fresh air and extracting the contaminated air through the envelopment, distributing and circulating the incoming air and preventing the contamination of the indoor air.

The airflow moves following a pressure gradient generated, in the case of houses and as the Spanish regulation in this area establishes, using a general ventilation system that can be either hybrid or mechanical [2]. This Spanish regulation, as in other countries, studies the rooms from a comprehensive point of view by establishing minimum ventilation flow rates according to the typology, surface, possible contamination sources or the number of occupants of the room. However, despite fulfilling these prescriptive requirements, in certain cases, there are areas with excesses or deficits of ventilation. In these cases, the system is not efficient in "providing fresh air to those parts of a room where it is needed" [3], and its characterisation is possible by measuring local and room mean age of air [4].

Local mean age of the air τ_p is a statistical value of the time that all the particles of fresh air require to go from the supply point to the point of study. As well as lowering the time, local mean age of the air will improve the change of the air at point *p*. This local age is useful in the analysis of the room because fresh air distribution and also velocity of the air (draughts) and temperature maps can be deployed [5]. With the average value of all local mean age of the air in the room, the room average age of air value can be obtained [6].

The room average age of air $\langle\bar{\tau}\rangle$ is a number that characterises the treatment of the inlet air and its performance within the enclosure, as the room's average age of air depends on both the volumetric flow rate and the direction of its motion through the volume (i.e., the air flow pattern). Using this value, it is possible to obtain the air change efficiency of the room. The use of the air change efficiency ε^a is recommended for dwellings when no local source of contamination can be located, and at the same time, an adequate guarantee of air quality is desired throughout the entire volume of the room.

In an experimental and numerical study, the efficiency was calculated using the relationship between the local mean age of the air in the exhaust, τ_e, and the double of the room average age of

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Nomenclature

p	generic point
RH	relative humidity (%)
T	temperature (°C)
U	velocity (m/s)

Greek symbols

ε_a	air change efficiency (%)
τ	age of the air (s)
$\langle\bar{\tau}\rangle$	room average age of air (s)

Subscripts

e	exit
in	inside
iso	isothermal
oc	occupied zone
out	outside
p	generic point

the air, $\langle\bar{\tau}\rangle$, using as reference the theoretical optimum model or "piston flow model", where the air enters at one side of the room and flows straight through the room as a piston to the extraction point at the other side or the room. The time actually required to replace the air in the room can be compared to the shortest possible air change time [6,7]:

$$\varepsilon^{a} = \frac{\tau_e}{2 \cdot \langle\bar{\tau}\rangle} \times 100[\%] \quad (1)$$

Because the regulation establishes the volumetric air flows supposing a fully mixed model between the inlet air and the existing indoor air, i.e., $\varepsilon^{a} = 50\%$ [8], the calculation of the efficiency could even change the minimum air flows. This change in minimum air flows would allow energy savings (in case of efficiencies higher than 50%, by reducing the minimum volumetric air flow while maintaining the normative IAQ levels) or exhibit an insufficient level of ventilation (when the efficiency is lower than 50%, having to increase the air supply to ensure the appropriate IAQ levels) [9].

2. Objectives

The inlet air flow pattern is different for each room depending on, for instance, the geometry, furniture and occupation, ventilation system configuration (supply, exhaust and return), and hygrothermal conditions, and its calculation is essential in the calculation of the efficiency. The most efficient pattern allows fresh air circulation within the whole indoor space, not only in a fraction of the room, removing contaminants as rapidly as possible.

Previous studies published regarding local and room average age of the air, τ_p, and $\langle\bar{\tau}\rangle$, and efficiency, ε^{a}, refer to rooms as a function of the parameters of the architectural design (room shape and dimensions [10], relative location of supply and exhaust openings [10,11], variables in design of openings [12–14]), all considering isothermal conditions. The knowledge about these variables allows modelling the air flow such that the air flow could move in the most efficient manner, ensuring an adequate IAQ while reducing the minimum volumetric flow rate. Under these premises, generally it is recommended [10]:

- To establish cross ventilation (both vertical and horizontally);
- To enhance the design of rooms which volume is lower than 25 m^3 or irregular shape, because it is on them where the air change efficiencies range is wider;
- To increase the number of openings in each room (both inlet and exhaust);
- To use devices that make the flow enter perpendicularly to the wall (90°) or direct it towards the ceiling (45°), avoiding solutions where the flow moves parallel to the walls, as occurs with air curtains (0 and 180°).

By means of experimental tests, it was verified that these variables can be isolated in order to be studied separately and that the results obtained through overlapping of effects are coherent [10]. This paper is focused on how the difference of indoor/outdoor temperatures in rooms with fresh air demand (bedrooms and living rooms) in houses affects the value of the age of the air and its efficiency. The importance of the age of the air depends on the significant influence that outdoor environmental conditions have on these rooms (by means of convective and radiant air processes). Once the inlet air is conditioned, it assimilates into an isothermal model, being affected only by local presence of cold or heat sources [15].

3. Experimental setup

This study reproduced, in both experimental and numerical ways, a bedroom (for two occupants) exposed to winter and summer climatic conditions. The experimental tests were developed in the full-scale test chamber of the Ventilation Laboratory HS3 in the School of Architecture of Valladolid [16,17], fulfilling the conditions established in the European Norm EN 13141-1:2004 [18] (that defines the performance of externally and internally mounted air transfer devices in terms of air temperature differences and, particularly, the specific conditions to analyse the air movement in the occupied area).

The full-scale test chamber is divided into two spaces [19]. The main space simulates a room bounded by an outdoor wall with one window and three indoor walls with dimensions of 3.00 m × 4.00 m × 2.50 m (ceiling height) and a second subchamber for reproducing external climate conditions.

Outdoor conditions of constant temperature and humidity were tested using the values of 43 °C and RH 50% (for summer conditions) and 3 °C and RH 50% (for winter conditions), using one installed air handling unit. The inlet air flow to the indoor space is constant through the depression created on the bottom side of a supposed door, establishing the gradient through a fan with a frequency variator adjusted by software.

At the same time, the indoor temperature remains constant at 23 °C by conditioning the other parts of the envelopment (walls, floor and ceiling) and controlling the process through the use of ambient temperature sensors. The temperature of the surfaces of the envelopment does not influence the indoor air movement in a significant way by means of the absence of appreciable temperature differences or radiant effects.

The window (1.06 m × 1.06 m and ledge height from the floor level of 0.88 m) is considered a constant thermal surface that influences (mainly in terms of convection) the inlet air flow pattern (Fig. 1). The gradient of temperatures is achieved by a frame working as the internal unit of a split system of cooling-heat pump, and the value of this temperature gradient varies depending on the difference in temperatures between the indoor and outdoor spaces, as established in the norm EN 13141-1:2004:

23 °C (T_{in}) – 23 °C (T_{out}) = 0 °C → T_{window} = 23 °C → isothermal study
23 °C (T_{in}) – 43 °C (T_{out}) = 20 °C → T_{window} = 28 °C → summer conditions

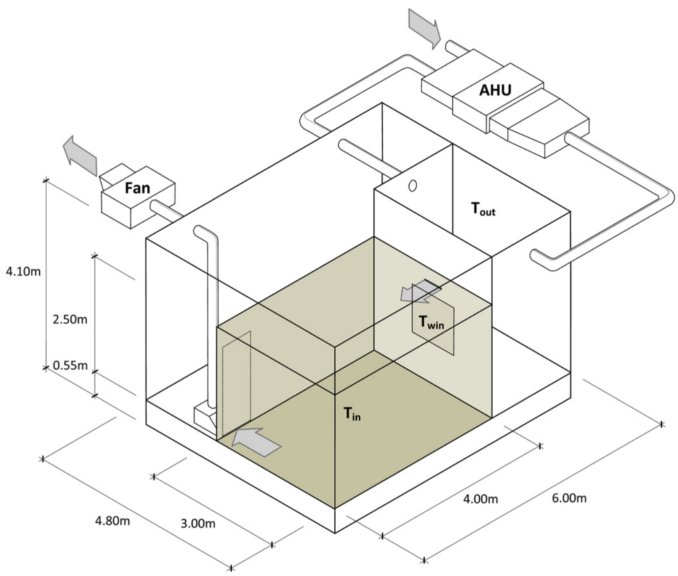

Fig. 1. Shaping of the experimental full-scale test chamber.

23 °C (T_{in}) − 3 °C (T_{out}) = 20 °C → T_{window} = 18 °C → winter conditions

For this research, the following boundary conditions were fixed:

- The opening of windows or doors has not been considered, nor have other elements causing a non-constant regime (the objective is to analyse the efficiency under conditions of the fulfilment of the minimum ventilation requirements without being conditioned by the behaviour of the occupants);
- Incompressible flow: the Mach number is approximately 0.00734 with a higher velocity around the inlet jet. The density variation due to the pressure gradient is notably small and can therefore be considered negligible;
- The age of the air in the inlet is set to zero;
- The direction of the inlet air flow has been designed to be perpendicular to the wall, through a device with dimensions 0.40 m × 0.01 m (40 cm^2), with a volumetric flow of 10 l/s (value imposed by the Spanish regulation for a two-occupant bedroom) and constant air velocity of 2.50 m/s. The inlet device has no mobile elements, so change in the volumetric flow that crosses the opening is not possible;
- For the turbulence intensity and length scale in the inlet, the imposed values are 5% and 0.01 m, respectively.
- The outlet air opening has been designed with dimensions 0.70 m × 0.01143 m (80 cm^2) and constant velocity of 1.25 m/s (to avoid the existence of draughts) that simulate the bottom space of the door of the tested bedroom. The age of the air calculated for this air outlet is 3000 s in this case study.

4. Experimental procedure and calculation

To characterise the air flow under summer and winter conditions, an experimental study was developed to measure the local mean age of the air and its temperature at different check points (75) inside the full-scale test chamber: fifteen of the check points were placed in a grid distributed in the floor and with records at five different heights, ranging from 0.10 to 1.80 m above the floor level (Fig. 2).

To obtain the age of the air values, 60 tests were developed following the decay method for tracer gases, calculating local mean age of the air τ_p in six point series [20]: five that correspond to the check points and the sixth related to the air outlet, which is allowed because non-dimensional results obtain the real results. At the same time, from these points, the test calculates the room average age of air $\langle\bar{\tau}\rangle$ and from this value, gets the air change efficiency ε^a [21].

In the process, a multipoint sampler and doser (Brüel & Kjær 1303 model) and a multi-gas monitor (Brüel & Kjær 1302 model) were used to measure the concentrations of tracer gas contained in the air samples collected in the room (through the photoacoustic method of infrared detection) [22].

Although the design of the test chamber minimises infiltrations that are not desired (pressurisation test $n_{50} \approx 0.05$), the decay procedure was modified to avoid the problem of a non-controlled air inlet. This method consists of injecting the tracer gas (sulphur hexafluoride) directly inside the room, utilising a mixing fan to create a uniform initial concentration for reference (200 mg of SF_6/m^3 of air) and, when this level is reached, the fan is turned off and concentrations are measured [23].

Under these premises, average testing deviations relative to the experimental measurements are quantified as ±2.71%, with local maximum values of +5.32% and −6.76% [24], being considered adequate to characterise the existing flow pattern (Fig. 3) [25].

Temperature values were measured simultaneously at these check-points through the use of thermal transducers for multiple validations of values obtained in the numerical study.

All these experimental procedures were completed with a previous study developed under isothermal conditions, considering no temperature differences between the inlet air from the exterior and the air contained inside the room [10]. This isothermal analysis was carried out with a methodology similar to the mentioned previously, developing 30 tracer gas tests in this case.

5. Numerical study

Complementary to the experimental testing, numerical studies were carried out using the Computational Fluid Dynamics.

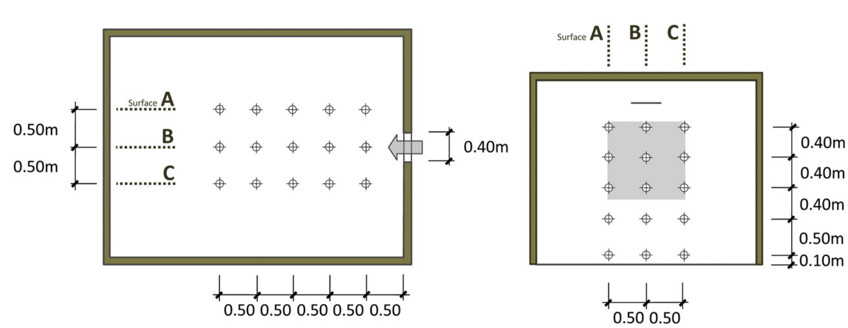

Fig. 2. Validation check-points (floor-plan and cross-section).

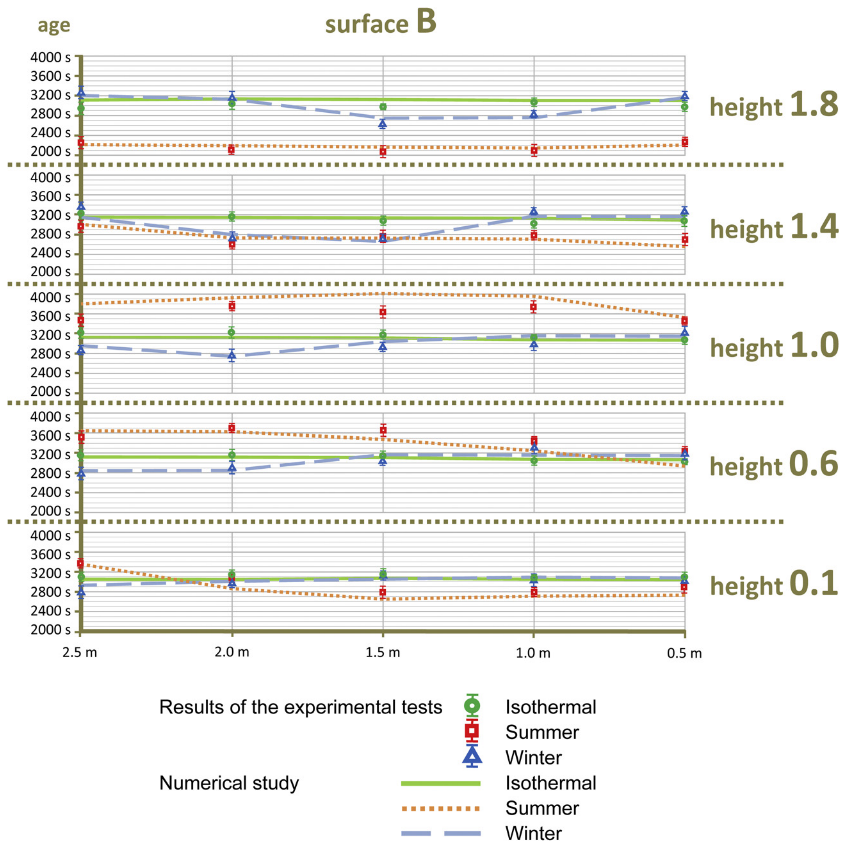

Fig. 3. Local mean age of the air and validation of the numerical study.

This tool is used in cases of fluid dynamics, when studying the three essential principles that determine the physical behaviour of any type of flow inside an enclosure: conservation of mass, conservation of linear momentum and conservation of energy. These principles are normally expressed through mathematical equations that, in general, are partial differential equations. The CFD software divides the enclosure in cells or controlled volumes, where these partial differential equations are replaced by algebraic approximations of pressure, velocity, temperature and other variables.

It has been used the CFD software package developed by Ansys, Inc. that is integrated by the tools Gambit 2.4, as pre-processor for geometry modelling and grid generation, and Fluent 6.3.26, for configuring the operating and boundary conditions, calculating the equations and post-processing the data. Regarding the hardware, due to the high computational cost, a cluster integrated by personal computers was used as the only calculation engine.

The three-dimensional model of the fluid domain geometry is prepared using a structured grid with volumetric hexahedral cells. This grid was designed under a non-uniform character, refining

Surface B					Height above floor level
3201s 3117s 2216s	3162s 3142s 2199s	2761s 3145s 2172s	2772s 3132s 2159s	3157s 3113s 2214s	1.80
3118s 3146s 2995s	2795s 3141s 2731s	2676s 3132s 2717s	3148s 3116s 2703s	3147s 3102s 2571s	1.40
2956s 3129s 3806s	2764s 3117s 3915s	3049s 3108s 4005s	3155s 3097s 3944s	3140s 3091s 3519s	1.00
2865s 3116s 3660s	2948s 3100s 3622s	3169s 3089s 3485s	3166s 3082s 3255s	3157s 3078s 2935s	0.60
2916s 3061s 3343s	3007s 3067s 2876s	3046s 3080s 2644s	3075s 3064s 2704s	3093s 3054s 2739s	0.10
2.50	2.00	1.50	1.00	0.50	
Horizontal distance from inlet					

Fig. 4. Age of the air at the check-points (winter-iso-summer).

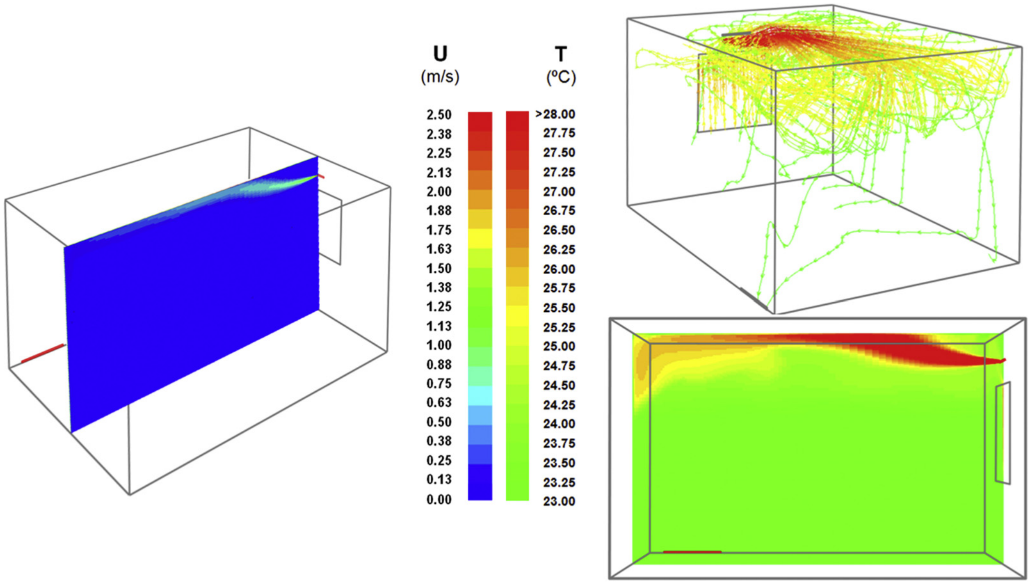

Fig. 5. Pathlines (temperature) in summer.

those areas where appeared high temperatures and air velocity gradients [26]. The overall number of cells in the final model is approximately 2.1×10^6.

The configuration of the operating conditions is adjusted to those existing in the full-scale test chamber, as well as the boundary conditions of the openings and all elements affecting the calculation: energy transport equation, Boussinesq model for natural convection, radiation models (Rosseland, P1), boundary surface temperatures, and intensity and length scale for the turbulence created by the inlet and outlet air.

The irregular, chaotic and unpredictable character of the turbulent flow justifies the utilisation of statistical methods for analysis of this turbulent flow. The Reynolds Average Navier–Stokes RANS model [27] is based on these concepts. Specifically two-equation models (Standard $\kappa-\varepsilon$, Re-normalisation Group Theory RNG $\kappa-\varepsilon$ and Realisable $\kappa-\varepsilon$) are adopted in a process of four successive equation approximations (up to 15,000 iterations) [28], and ensuring the basic principles of consistence, convergence and stability (Lax theorem) [29].

When calculated, during the postprocessing phase, the simulation allows the age of the air and temperature at the check points to be calculated and, through the comparison with the values obtained in the experimental procedure, the adopted solution can be validated (Fig. 3). In this way, large amount of complementary data (air velocity distribution, pressure, temperature, local mean age of the air and room average age of the air) can be obtained.

6. Results

The results obtained at the check points reveal an air flow pattern characteristic for each of the configurations of temperature (winter -blue-, isothermal -black-, and summer -red-) analysed (Fig. 4).

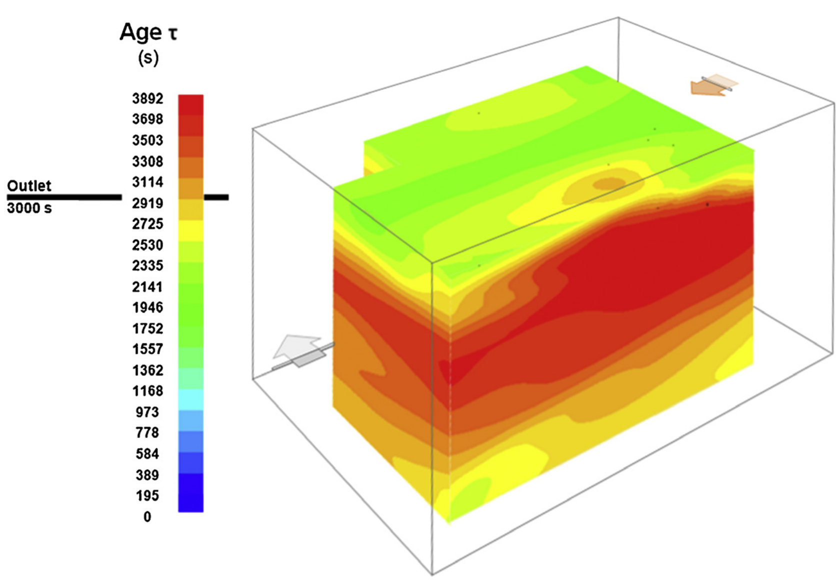

Fig. 6. Age of air in the occupied area (T_{out} = 43 °C).

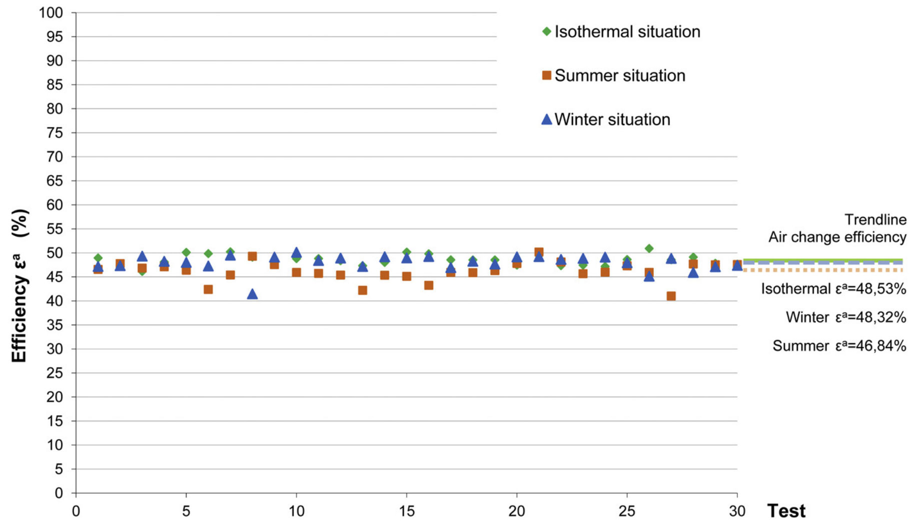

Fig. 7. Results of air change efficiency in the experimental test.

The distribution of temperatures of the incoming air stream differs from the distribution of temperatures in room air such that their interface could be used as an indicator of the depth of fresh air penetration. In the summer situation (inlet air temperature of 43 °C in a conditioned room at 23 °C), fresh air remains on the top side of the room until, being conditioned at ambient temperature, fresh air moves to the bottom side. Thus, the jet flows out horizontally, and at the corner, it is deflected downward, and the buoyancy forces start to oppose the flow. At the turning point, the jet has its maximum potential energy and when it ascends, the potential energy is turned into kinetic energy. This ascending flow meets the primary jet flow and is constrained to go towards the back wall. At the back wall, the ascending flow turns downwards again, and the process is repeated [7]. At the same time, the convective movement at the window favours this process.

The process can also be visualised using the fresh air penetration depth. The process can be characterised by the decrease in the velocity component for the fresh air stream along the inflow direction to a predetermined value of, for instance, close to zero (Fig. 5) [30].

In this environmental situation, the room average age of the air for the whole room volume is $\langle\bar{\tau}\rangle_{T_{out}=43^{\circ}C} = 2813$ s, which results in an air change efficiency of $\varepsilon^{a}_{T_{out}=43^{\circ}C} = 53.3\%$.

Nevertheless, a case study must be developed in the "occupied area", as that area is defined in the norm EN 13779 [31]. Considering this premise, the previous values change to $\langle\bar{\tau}\rangle_{ocT_{out}=43^{\circ}C} = 3250$ s and $\varepsilon^{a}_{ocT_{out}=43^{\circ}C} = 46.1\%$. This result indicates that there is an air blockage in the usable area (Fig. 6), and the predicted ventilation flow rate is not sufficient, so the system should increase the supply air flow to ensure the IAQ levels established in the regulations. This analysis can mean a new chance to validate and compare the performance of each environmental situation with regard to the efficiency: this is possible because all the check points are located within the occupied area, and each experimental test calculates the average age of air $\langle\bar{\tau}\rangle$ and the air change efficiency ε^{a} (Fig. 7).

In the winter situation (cold inlet air at 3 °C in a conditioned room at 23 °C), fresh air descends quickly by buoyancy, generating,

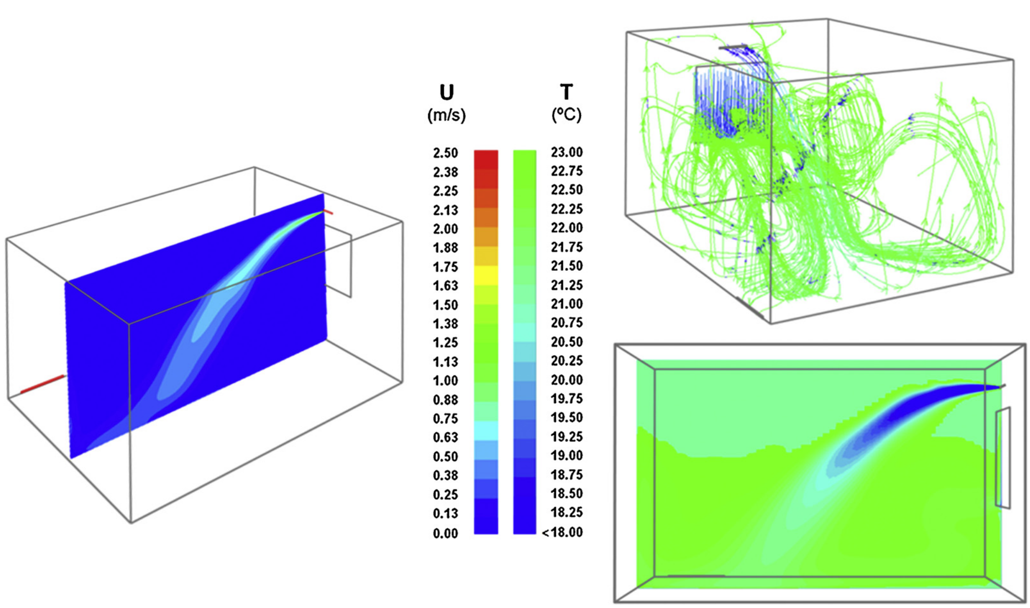

Fig. 8. Pathlines (velocity and temperature) in Winter.

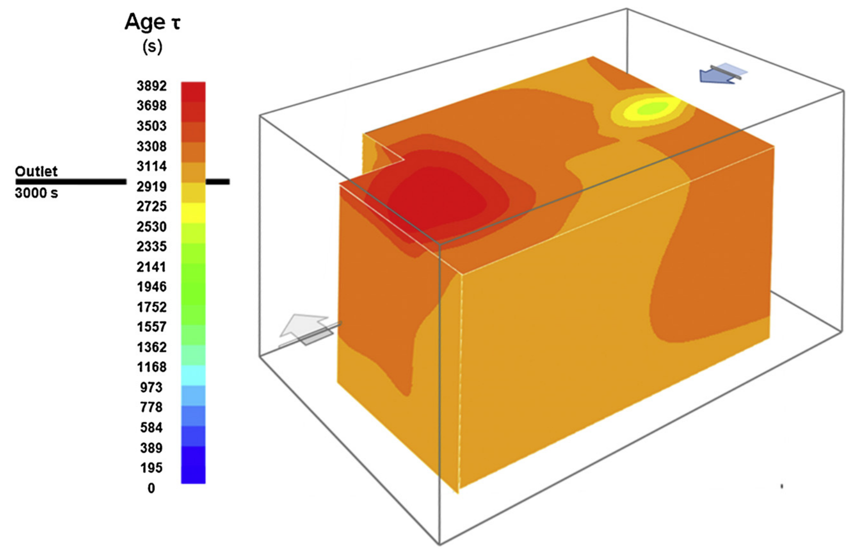

Fig. 9. Age of air in the occupied area (T_{out} = 3 °C).

in some cases, upset draughts ($U > 0.2$ m/s) in the occupied area. In spite of the jet flows along the ceiling, the buoyancy is sufficiently strong that the jet will, after some distance, separate from the ceiling and start to drop. The location of the point of separation is not static. The point of separation fluctuates by tens of centimetres owing to interactions between turbulent eddies in the jet and the surroundings. In the same way as in the previous case, convective movement at the window reinforces this process. With these processes, the velocities and temperatures in the region where the jet descends are usually unacceptable from the point of view of comfort [7] (Fig. 8).

With respect to the IAQ, the room average age of air in the whole room volume is $\langle\bar{\tau}\rangle_{T_{out}=3^{\circ}\mathrm{C}} = 3126$ s, which means an air change efficiency of $\varepsilon^{a}_{T_{out}=3^{\circ}\mathrm{C}} = 48.0\%$.

The characteristics of the flow pattern affect only one part of the occupied area (Fig. 9) if there is a quick energy transfer: thus, the values obtained for the occupied area are $\langle\bar{\tau}\rangle_{ocT_{out}=3^{\circ}\mathrm{C}} = 3111$ s and $\varepsilon^{a}_{ocT_{out}=3^{\circ}\mathrm{C}} = 48.2\%$, implying the need to increase the supply air flow to fulfil the minimum IAQ levels.

Last, in the isothermal situation (where inlet air temperature is 23 °C, the same as the temperature in the conditioned room), the absence of the buoyancy and convective draughts allows air to move in a simply turbulent regime (Fig. 10).

For this situation, the room average age of air in the whole room volume is $\langle\bar{\tau}\rangle_{iso} = 3077$ s, which means an air change efficiency of $\varepsilon^{a}_{iso} = 48.7\%$. The air flow is modelled by the boundary walls, coming to the occupied area after turning into turbulent flow (Fig. 11), where values are $\langle\bar{\tau}\rangle_{ociso} = 3103$ s and $\varepsilon^{a}_{ociso} = 48.3\%$, showing the

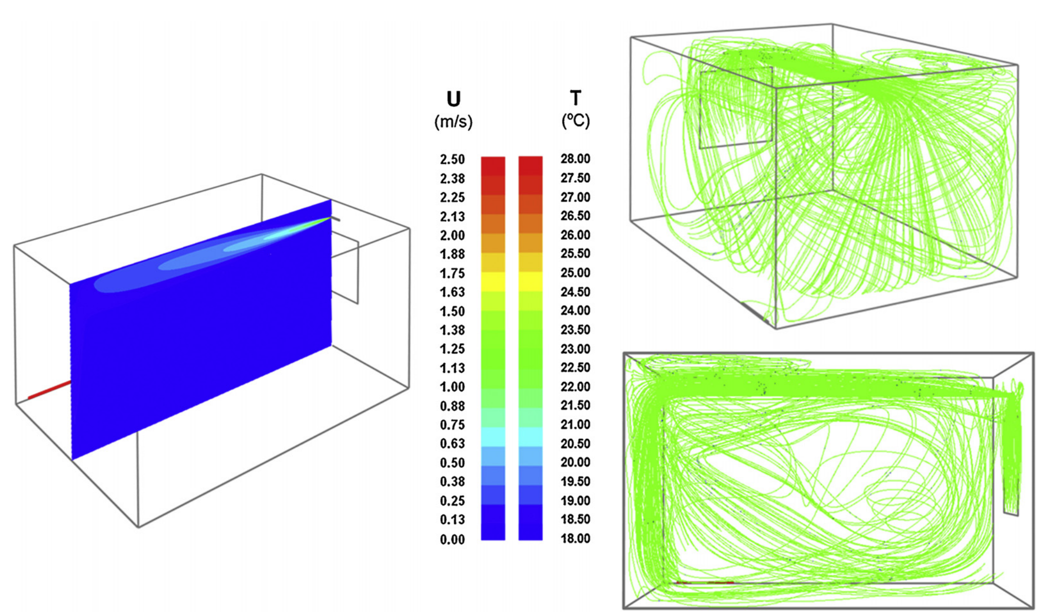

Fig. 10. Pathlines (velocity and temperature) in isothermal.

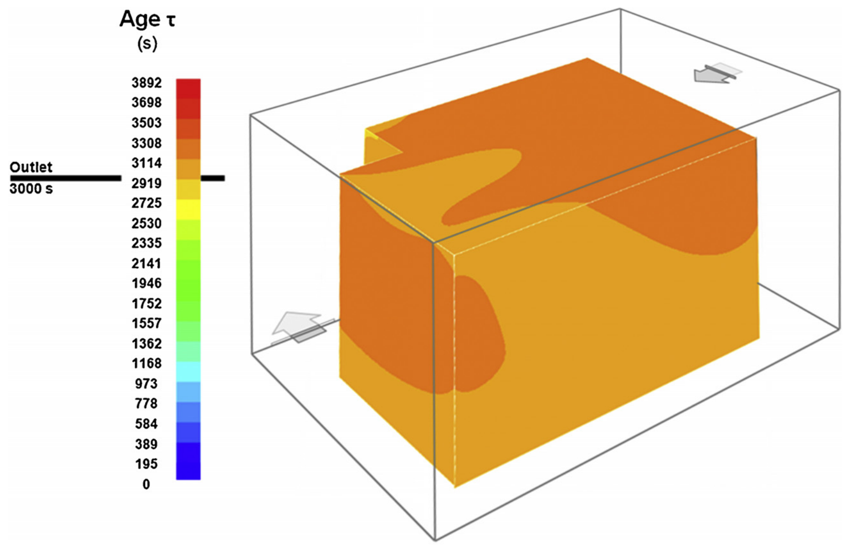

Fig. 11. Age of air in the occupied area (T_{out} = isothermal).

need to increase the supply air flow for fulfilling the IAQ values established in the regulations.

7. Conclusions

The experimental and numerical study of environmental temperature gradients reveals that, significantly, convective strengths are predominant and fully modify the characteristics of the air inlet in the room. For this reason, the study shows that local mean age of the air changes clearly depends on the pattern that the air flow acquires, which depends on the temperature. Thus, the study of all local conditions (e.g., age of the air, temperature, draughts) in the most significant areas of the room (i.e., length occupied) can be considered necessary.

Nevertheless, the process of energy transfer blurs this effect in the whole room average age of air and therefore in the air change efficiency. For this reason, the results obtained do not change significantly for the three situations evaluated, so it follows that the gradient of temperatures involves obtaining efficiency values ε^a similar to the values calculated for an isothermal situation. This reasoning simplifies the calculations on average age of air, and therefore the air change efficiency, on any room.

This conclusion makes an important difference if these ε^a values are compared with the values obtained by changing the geometry of the room and the relative positions of the inlet and outlet openings because these variables have a substantial effect and will have to be calculated in detail when modelling the ventilation air flow pattern [9].

The latter conclusion obtained through the process is that the CFD tools are useful to analyse the ventilation air flows. The ability to modify some parameters involved in the process of ventilation (volumetric flow rate, velocity and direction of the air flow, or temperatures) easily allows the study of extreme situations that are difficult to reproduce in the laboratory. The posterior post processing of results makes it possible to obtain a large amount of important data. The calculation of these important data is a slow and complex task if performed experimentally.

The main problem due to the use of these tools is the complexity of the correct configuration of the variables (what turns essential the validation of the adopted model using comparable experimental testing) and the requirement of high computational costs.

This point becomes critical when it is necessary to study the local mean ages of the air in the room (by the superimposed effects of buoyancy, energy exchange and radiant surfaces). However, the study of the room average age of air is simpler because the inlet air flow can be simulated as isothermal relative to the volume of air contained in the room, as the temperature conditions do not significantly alter the overall ε^a results.

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