

Keywords

Age of the air; Ventilation efficiency; Computational fluid dynamics (CFD); Indoor Air Quality; Air distribution; Breathing zone.

Practical application

The ventilation efficiency is an air quality indicator, which shows the sufficiency of a ventilation system and that has been assessed in several studies considering different room dimensions, location of the supply and the exhaust and variation of the indoor conditions of relative humidity and temperature. However, the position of diverse elements inside a room, such as furniture, has influence on the air movement and therefore, on the ventilation efficiency. Thus, it is important to assess the effect caused by the furniture located indoors, which is under concern of this study.

Introduction

Today, in industrialized countries, people spend between 80% and 90% of the time indoors [1] and, depending on the person, the presence at home varies between 60% and 90% of the day, 30% of that time is spent sleeping [2, 3]. For this reason, indoor air quality (IAQ), especially in residential buildings, greatly influences human health. Therefore, it is essential to design a suitable ventilation which guarantees a good IAQ and, in turn, meets the requirements of comfort and energy efficiency. Energy saving in ventilation has a great potential since, through a more efficient ventilation strategy, consumption can be reduced by 5-9% of the total primary energy consumption. In the E.U., 40% of the energy consumed is due to the air conditioning and lighting of buildings [4-8]; more precisely, the energy consumed in households represents 25.4%; the electricity consumption represents 25% of that percentage.

The most widespread strategies to improve IAQ are, in addition to the increase in fresh air supply, controlling the emission of pollutants, cleaning the air and/or improving ventilation efficiency; the latter is within the scope of this study. Ventilation efficiency is an air quality indicator which reflects the fresh air distribution within the space; thus, it shows a qualitative measure of the performance of the ventilation system. As shown in previous studies, ventilation efficiency depends on the flow pattern [9, 10], as it shows to what extent an occupied area is properly ventilated compared to the piston flow model (optimum theoretical model, with an efficiency of 100%). In order to characterize the flow patterns, it is necessary to carry out a previous age-of-the-air assessment, since it shows the location of the stagnant-air zones in a room considering that the age of the air at the inlet is equal to zero (100% fresh).

The way air flows inside a room follows multiple paths, for this reason the air must be studied from a statistical point of view. In this context, the room mean age of the air (RMA) and the local mean age of air (LMA), parameters directly related to the air path, must be evaluated. RMA is the average time it takes for the air particles in a room to leave since they enter through the inlet. LMA is the statistical value which shows the

mean value of the age of the air and it is defined as the average time taken by all the particles of the supplied air to move from the inlet to any point of interest [10].

Ventilation efficiency is determined by comparing the existing flow model in the case study with the piston flow model [10]. Therefore, the efficiency is the result of the relationship between LMA at the outlet and twice the RMA, since it is an arithmetic mean, according to equation 1.

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

Where ε^a is ventilation efficiency (%), τ_e is LMA at the outlet (s) and $\langle \bar{\tau} \rangle$ is RMA (s).

The perfect mixing flow model (ventilation efficiency of 50%) is adopted in all national regulations as the best possible. However, the most common flow model, especially in homes, is the short-circuiting model (ventilation efficiency below 50%) which indicates the existence of an insufficient level of ventilation and, therefore, the need to increase the fresh-air supply or to use architectonic design techniques in order to avoid the emergence of stagnant-air zones and thus improve the ventilation efficiency.

LMA and RMA are calculated by means of experimental analysis using tracer gas methods and numerical analysis using computational fluid dynamics (CFD) techniques. The experimental approach consists of injecting a tracer gas into a single space, marking the indoor air, and continuously recording the gas concentration at different points of study. Thus, it is possible to differentiate the air present in the room from the fresh air entering the space. Tracer gas techniques can be carried out according to tracer decay, constant tracer concentration and constant tracer injection methods [11].

LMA can be also assessed by numerical analysis, provided that it is validated by the experimental analysis. According to Chanteloup and Mirade (2009) [12], there are three strategies to be followed in order to calculate LMA: transient method, steady-state method and particle marker method. The first two are the most reliable for the calculation of LMA as stated by Li et al. (1992) [13]. Previous numerical studies [14-18] have developed an assessment of the ventilation efficiency using the steady-state method by solving a user-defined partial differential equation to describe the transport of the “age of the air” scalar. However, former research on ventilation efficiency optimization according to the arrangement of elements (furniture) within an enclosure is not found in the literature. The path followed by the ventilation airflow is affected by the presence of furniture, since RMA and LMA values are modified with regard to the empty room (ER) and, therefore, the efficiency is disrupted.

The objective of this study was to carry out a characterization of the ventilation efficiency in a 30 m³ room, under isothermal conditions, considering 47 different dispositions of furniture. A numerical study of the age of the air using both the steady-state method and a user-defined function (UDF) was developed. The numerical analysis was validated through the tracer gas decay technique.

Methodology

Steady-state numerical method

The numerical study was developed using Fluent 17 (CFD code) to solve the transport equation for a user defined scalar (UDS). This way, the calculation of LMA was implemented in the code, allowing the study of the age of the air distribution and the ventilation efficiency assessment. to calculate the transport of an arbitrary scalar Φ_i , it was necessary to solve an additional convection-diffusion equation [12, 19], according to equation 2:

$$\frac{\partial \rho \Phi_i}{\partial t} - \nabla \cdot (\Gamma_i \nabla \Phi_i) = S_{\Phi_i} \quad (2)$$

In this study, we considered steady-state conditions, where the age of the air is assumed as a passive quantity which does not affect flow patterns. Consequently, equation 2 acquires the following simplified form (equation 3):

$$S_{\Phi_i} = \nabla \cdot (\rho \vec{v} \Phi_i - \Gamma_i \nabla \Phi_i) \quad (3)$$

Where ρ is the density of the fluid ($\text{kg} \cdot \text{m}^3$); v is the velocity of the fluid ($\text{m} \cdot \text{s}^{-1}$); Φ_i is the age of the air (τ_i) or the scalar to be calculated; Γ_{Φ_i} is the diffusion coefficient of the scalar, which depends on the effective viscosity of the air (μ_{eff}) according to equation 4; and S_{Φ_i} is the source term of the scalar which is generally considered equal to 1 [15, 20, 21].

$$\Gamma_{\tau_i} = 2.88 \cdot 10^{-5} \rho + \frac{\mu_{\text{eff}}}{0.7} \quad (4)$$

Implementation and validation of the numerical analysis

The numerical method was included in the CFD code Fluent through UDF. This is a predefined function in programming language C which can be linked to the Fluent solver, thus the standard functions of the CFD code can be improved. The accuracy of the programming of the UDF, and therefore the validation of the numerical model, was verified through the tracer gas concentration decay technique.

The experimental tests were carried out in the test chamber of the Ventilation Laboratory of the School of Architecture of Valladolid [22, 23]. The chamber is 3.00 m x 4.00 m base and 2.50 m height; it has an inlet of 0.40 m x 0.01 m (40 cm^2) and an outlet, in the contiguous wall, of 0.70 m x 0.01143 m (80 cm^2), as shown in figure 1.

The characteristics of the test chamber (dimensions and inlet and outlet) are the same as those used to define the interior space of the single bedroom which has been assessed numerically. To develop the validation, the furniture (built with cardboard) considered in the numerical simulations was included in the chamber (figure 2).

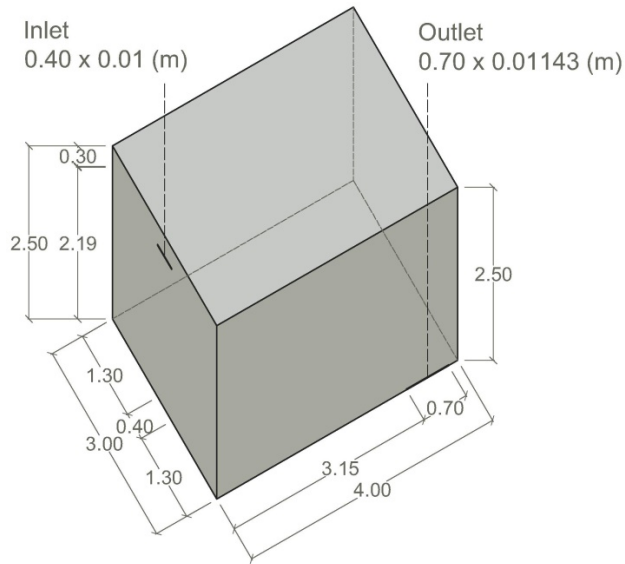


Figure 1. Test chamber dimensions (in meters)



Figure 2. Furniture included in the test chamber

The test consisted of the tracer gas injection, in this case sulfur hexafluoride (SF_6), to mark the air inside the enclosure until reaching a known concentration of tracer gas, then the injection is stopped and the rate at which the air exchange replaces the entire marked air is determined. 9 points were set in the chamber in order to develop the experimental analysis (EA) and to find an average value for LMA, each of the 9 points were sampled three times (A, B, C) at two different heights: 2.00 m (UP) and 0.75 m (DOWN). This average was compared with the corresponding result of LMA from the numerical analysis (NA). A difference of less than 10% was found between the numerical and the experimental analysis (table 1). It is, therefore, a correct correlation considering similar investigations [24-26] which reach a difference around 20%. It was also demonstrated that the validation process and the tracer gas technique employed were adequate.

Table 1. Age-of-the-air (s) from the experimental and the numerical analysis

	UP (2.00 m)				DOWN (0.75 m)			
CASE	NA (UP)	EA (UP)	% dif	%DIF	NA (DOWN)	EA (DOWN)	% dif	%DIF
1A	5864.48	5514.65	5.97	6.26	5764.99	5223.07	9.40	5.47
1B		5536.69	5.59			5584.22	3.14	
1C		5440.27	7.23			5541.93	3.87	
2A	5930.84	5254.43	11.40	9.02	5702.33	5715.64	-0.23	3.61
2B		5287.73	10.84			5355.90	6.08	
2C		5645.87	4.80			5418.57	4.98	
3A	5947.62	5254.10	11.66	9.85	5813.42	5362.74	7.75	8.55
3B		5423.05	8.82			5343.48	8.08	
3C		5408.97	9.06			5242.89	9.81	
4A	5497.48	5404.55	1.69	5.20	5630.81	5267.43	6.45	7.40
4B		5090.71	7.40			5131.62	8.87	
4C		5140.07	6.50			5243.68	6.88	
5A	5330.28	5228.25	1.91	4.05	5588.01	5206.34	6.83	6.05
5B		4871.88	8.60			5365.26	3.99	
5C		5243.53	1.63			5178.74	7.32	
6A	5693.93	5145.24	9.64	5.45	5891.19	5366.40	8.91	9.65
6B		5467.32	3.98			5387.68	8.55	
6C		5538.97	2.72			5213.16	11.51	
7A	5727.55	5409.21	5.56	7.54	5661.19	5412.50	4.39	6.08
7B		5379.60	6.07			5134.22	9.31	
7C		5098.55	10.98			5403.88	4.55	
8A	5942.93	5357.85	9.84	9.46	5656.96	5283.47	6.60	6.01

8B		5504.64	7.37			5319.19	5.97	
8C		5279.79	11.16			5348.75	5.45	
9A		5250.81	9.26			5281.90	6.97	
9B	5786.82	5280.23	8.75	8.87	5677.39	5256.43	7.41	6.85
9C		5289.11	8.60			5326.66	6.18	

CFD numerical analysis

Case studies description

The ventilation efficiency of 47 case studies was assessed considering different elements of furniture (A-F) and different dispositions of the same (1-8) in a single bedroom. The study was started by including a single bed (A) in the room and placing it, according to architecturally acceptable criteria, at different points in the room (1-8). Subsequently, a bedside table (B) was added and placed according to the previous arrangements considered for the bed (1-8) and so on with the closet (C), the shelf (D), the desk (E) and the chair (F). Figure 3 shows each of the dispositions studied. Additionally, the ventilation efficiency in the ER, without furniture elements, was calculated to compare the result with the previously assessed case studies.

The furniture considered in this research consisted of simple geometries and standard dimensions, as shown in figure 3. The shelf was modelled as a solid prism, with no gaps, since it usually contains books and additional objects that almost completely fill the empty spaces of the furniture. The same thing happens with the closet and the bedside table, also represented by solid prisms since, generally, the opening of its doors and drawers is sporadic, lacking of both interest and impact in the investigation.

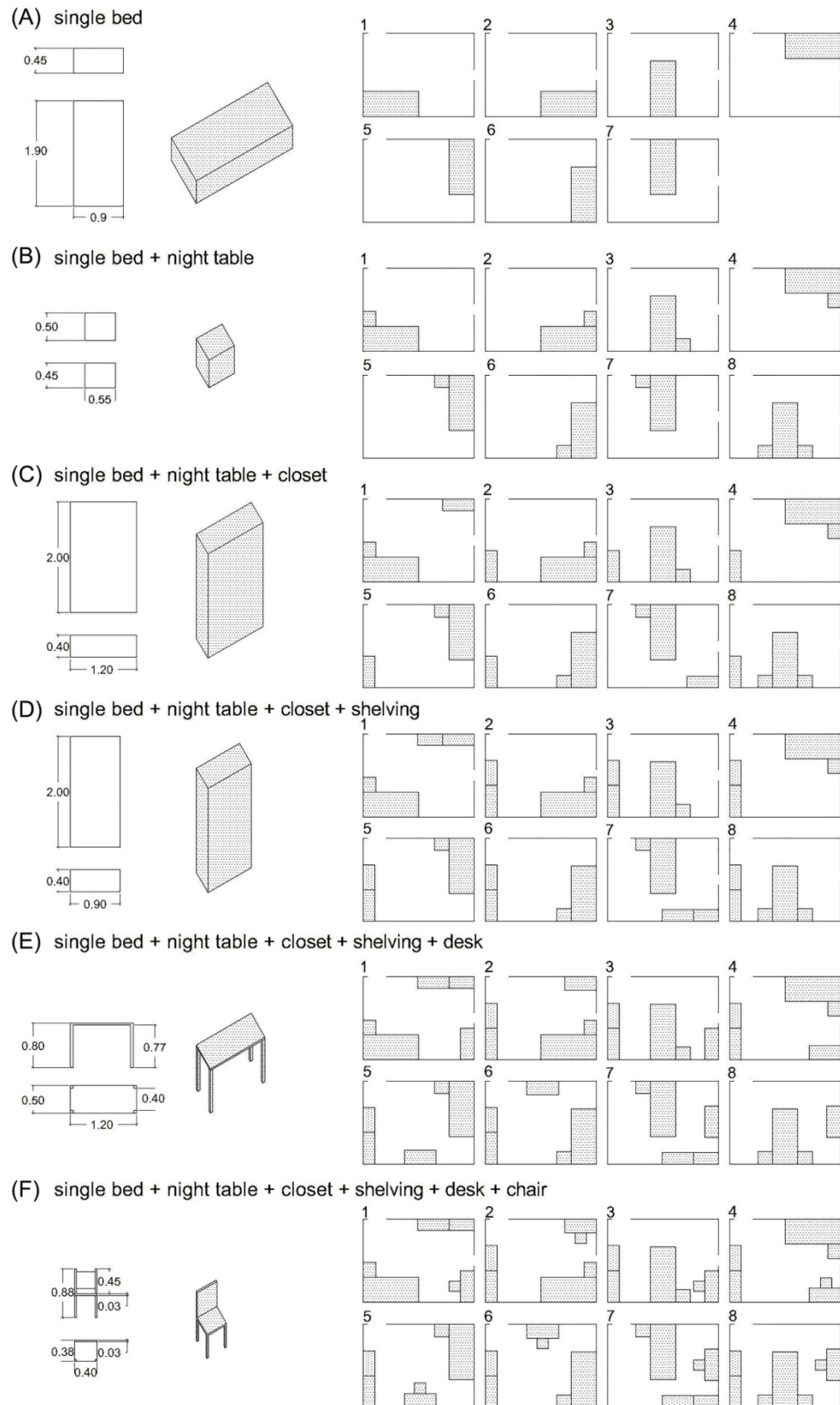


Figure 3. 47 case studies according to several elements and their arrangements

Mesh generation

The 3D geometric model was created in the ANSYS DesignModeler pre-processor and the mesh, in the ANSYS Meshing pre-processor. Figure 4 shows the grid used for the case A7.

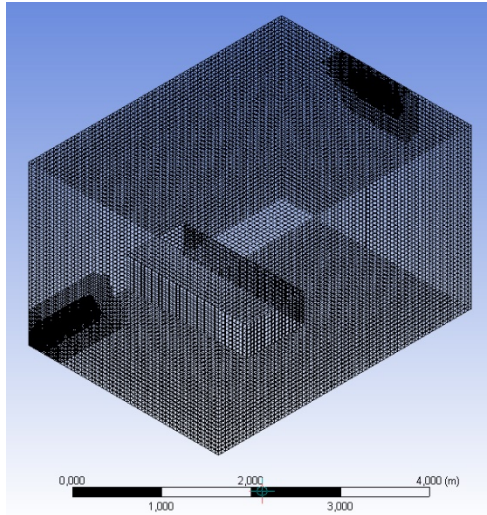


Figure 4. Mesh used for the case A7

A computational saving criterion for mesh construction was followed, so that 500000 elements and 600000 nodes were not exceeded in any model, assigning a higher mesh density at the inlet, outlet and singular elements of the geometry.

A hexahedral mesh was created in all the case studies, since they contain a simple geometry, through the Cartesian meshing method Cutcell. The Orthogonal Quality (OQ) criterion was used to check the quality of the mesh. In all cases, as shown in figure 5, the mean is above 0.95, so the meshing is optimal [27].

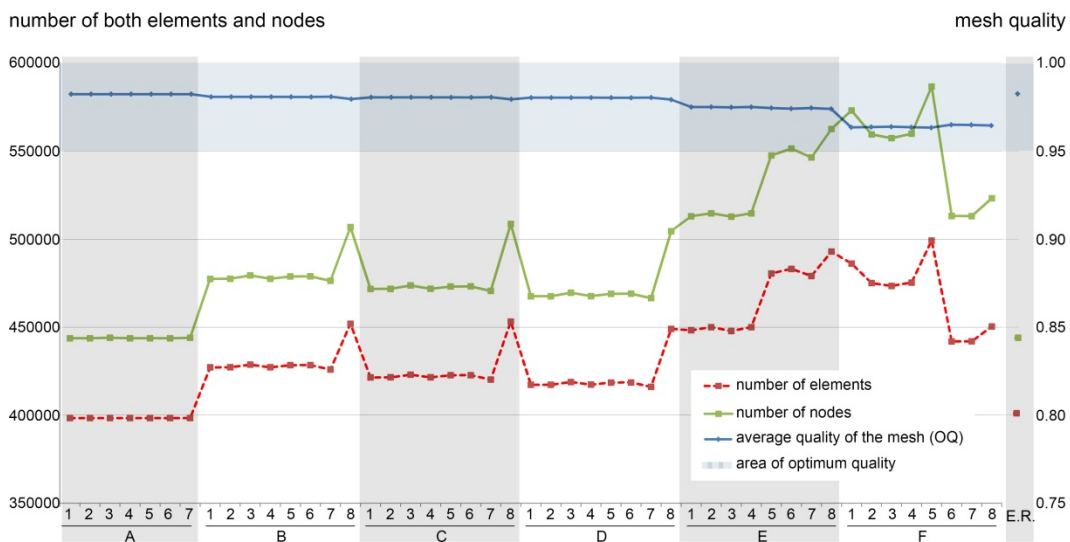


Figure 5. Number of nodes, elements and mesh quality of the case studies and the E.R

Model set-up and input data

The flows in ventilation systems, in particular in the interior of a bedroom, are highly turbulent. To simulate these flows, Reynolds Average Navier-Stokes (RANS) [27] and specifically the two-equations models (k - ϵ) were used, since they have a high level of adaptation to different types of problems and a high accuracy in the results. In order to achieve a convergence solution and a high precision in the solution, a continuous simulation process was followed, carrying out the calculation by means of the three turbulence models in succession: Standard k - ϵ , RNG k - ϵ and RKE [18, 28], setting 10000 iterations per model. This approach has been extensively justified in previous work [18].

In this investigation it was assumed that the air was in thermal equilibrium with the walls, floor, ceiling and furniture of the room (isothermal conditions). The air density was established at 1.225 kg/m^3 and its dynamic viscosity at $1.7894 \cdot 10^{-5} \text{ kg/(m}\cdot\text{s)}$. With respect to the boundary conditions, a constant exhaust-air velocity at the outlet (door) of 0.625 m/s , which corresponds to a ventilation flow of 5 l/s (according to the Spanish regulation for a single bedroom [29]), was set. The default value of 5% was chosen for the turbulence intensity, since it is considered sufficient for the nominal turbulence, and a turbulence scale length of 0.01 (normalized).

In short, and according to the established methodology, this study aimed to show an optimization of the ventilation efficiency in a given room according to the arrangement of the furniture. To this end, a CFD numerical analysis, validated by means of the tracer gas concentration method, was used in order to assess the distribution of the age of the air within the space.

Results

Age of the air distribution

Empty room (ER)

A ventilation flow of 5 l/s of fresh air was supplied through the inlet and, therefore, with an age of the air equal to zero at the entry point to the bedroom. Due to both the Coanda effect [24, 30, 31] and the finding of no obstacles (such as, for example, furniture elements), the air flow adhered to the contour surfaces of the room; first to the ceiling and later it was spread by the wall opposite to the one of the inlet. Therefore, the air volumes close to these surfaces had a lower age of the air than the rest of the space, as shown in figure 6. Finally, the air exchange flow was distributed in the space, obtaining a RMA of 6097.98 s and a LMA at the outlet of 5992.27 s .

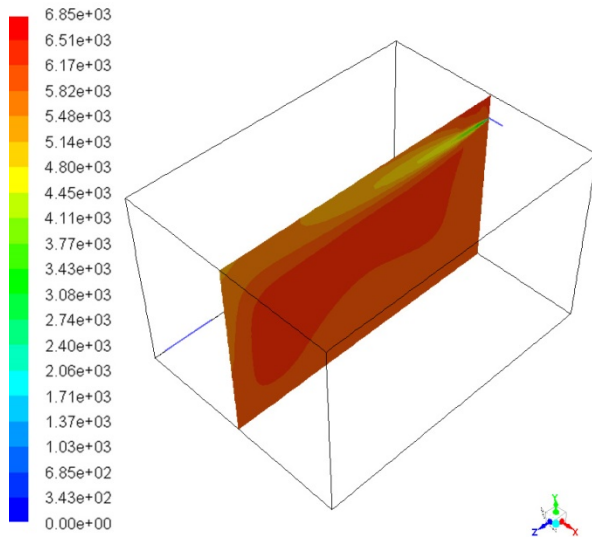


Figure 6. Age-of-the-air distribution (seconds) within the ER

Case studies with different furniture arrangements

The form of air circulation in ER was repeated in the other case studies, although with the influence (positive or negative) of the furniture on the age of the air of the enclosure. Figures 7.a. and 7.b. show the age of the air distribution (seconds) of the case studies arranged by elements considered (A-F) and by configurations (1-8). To display the age of the air inside the room, the most representative transverse (xy) and longitudinal (zy) planes were chosen in each case, taking into account the influence of the furniture present in the room on the efficiency of ventilation. Figures 7.a. and 7.b. therefore represent the areas of higher and lower air stagnation which arise as a consequence of the addition of furniture elements within the space.

There is a clear and logical tendency towards a lower age of the air, as the volume of the fluid decreased, through the addition of furniture. Thus, from configuration A to configuration F, there was a reduction in the age of the air values, as shown in figure 7. However, there were cases such as B-8 that did not follow that tendency, having stagnant zones which caused a high age of the air.

The cases A (bed) and B (bed and bedside table) presented a similar air flow between them. This was because, in B, the furniture was represented as a single volume, since both objects are usually placed contiguously in a bedroom. Therefore, in such cases and as shown in table 2, it can be seen that configuration 2 was the one with a lower age of the air in areas of stagnation: 6160 s in configuration A and 6110 s in B. However, the cases that presented the highest age of the air in stagnant zones were A-7 (6570 s) and B-4 (6530 s), but very close to B-7 (6510 s); this was due to the fact that, being the bedside table higher than the bed, it generated in B-4 a zone of flow restriction which increased the age of the air. In case C, the closet was added, isolated from the other volumes, being C-8 the case of lower age of the air (6080 s) and C-7 the one of greater age of the air (7050 s), where there was a zone of stagnation on the closet.

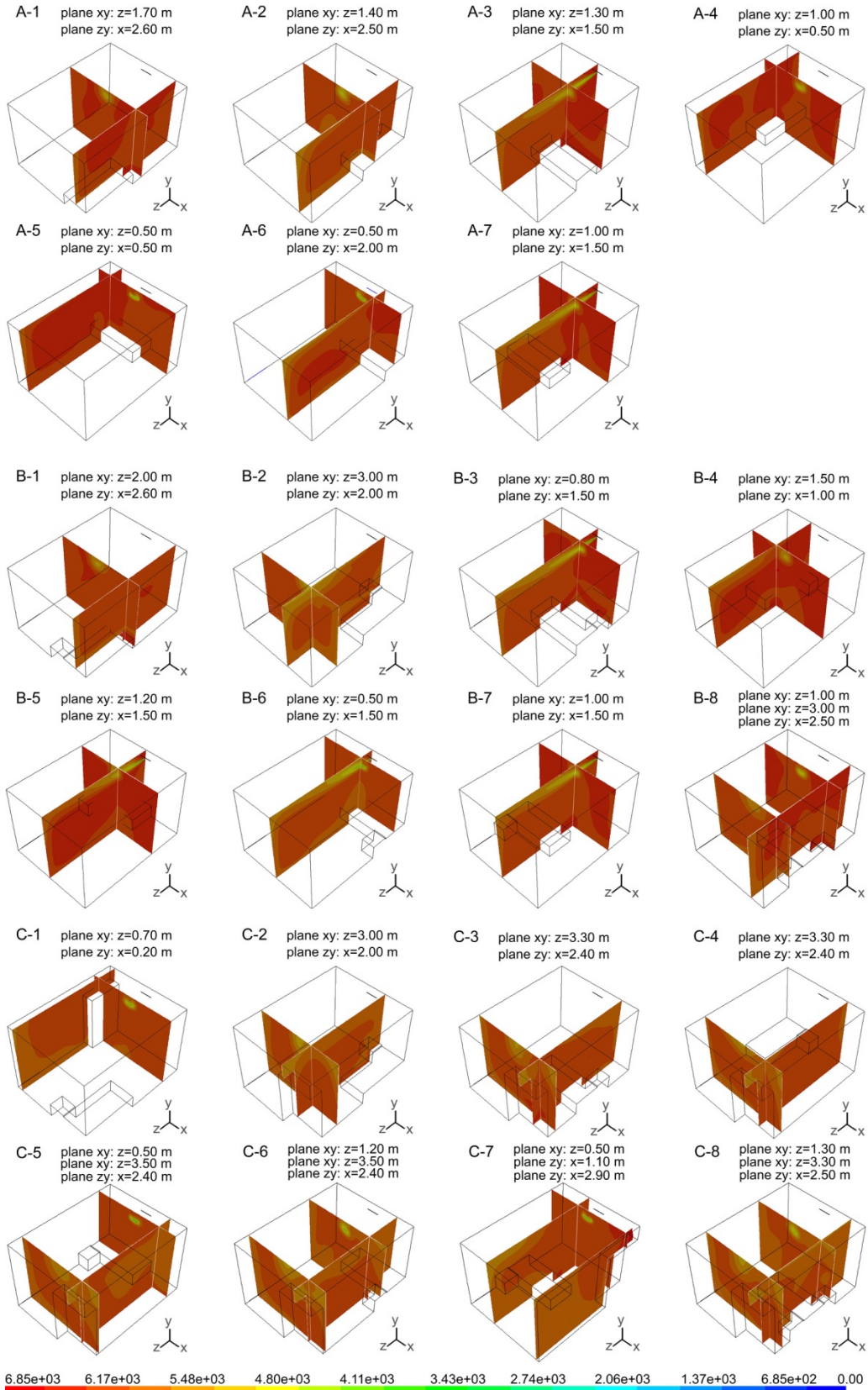


Figure 7.a) Age-of-the-air distribution (seconds). A, B and C arrangements

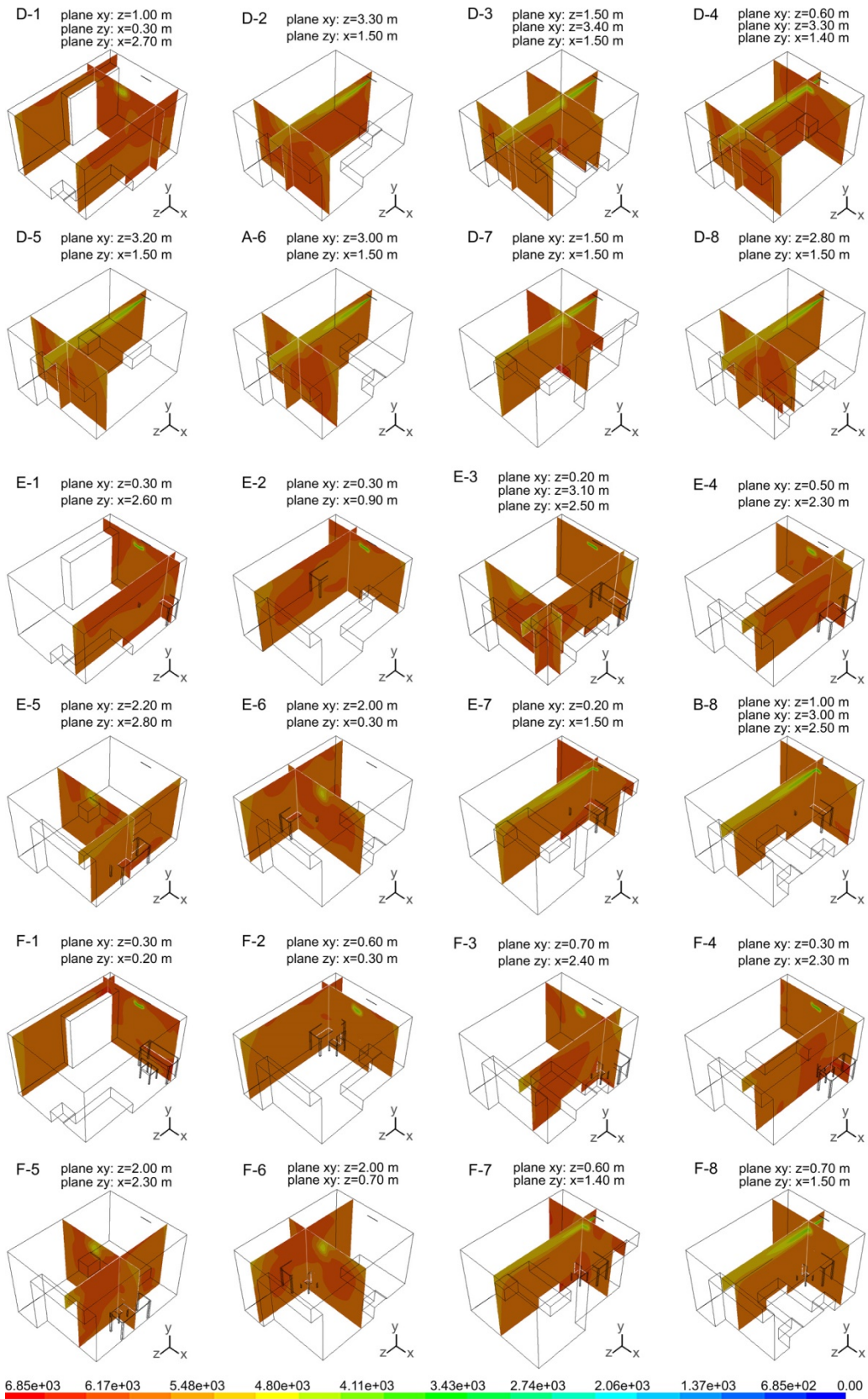


Figure 7.b) Age-of-the-air distribution (seconds). D, E and F arrangements

In short, whenever the arrangement of the furniture benefits the movement of the fluid, the age of the air will be lower; on the contrary, the opposite will happen when the furniture obstructs the air flow. Thus, as shown in table 2, the cases with lower age of the air in stagnant areas were D-5 (5960 s), E-8 (5940 s) and F-8 (5900 s) and the ones with higher age of the air were D-7 (6290 s), E-4 (6170 s) and F-1 (6430 s).

Table 2. Age of the air (s) in the stagnant-air areas of the different case studies

	Furniture					
	A	B	C	D	E	F
1	6300	6310	6100	6090	6160	6430
2	6160	6110	6150	6020	6010	6120
3	6490	6510	6220	6000	5980	6020
4	6340	6530	6200	6000	6170	6110
5	6410	6440	6180	5960	5980	6070
6	6350	6140	6120	6050	6050	6130
7	6570	6510	7050	6290	6060	6310
8	-	6480	6080	6010	5940	5900

Figure 7 confirms that, when discounting the volume of the air corresponding to the furniture of the room, RMA and LMA values were reduced. For each configuration according to the furniture considered (A-F), LMA values at the outlet were practically constant, while RMA had a higher fluctuation. The existing relationship between these values (RMA and LMA) determines the efficiency of ventilation, since the closer they are to each other, the greater the ventilation efficiency is and vice versa (figures 8 and 9). Figure 9 shows the ventilation efficiency of all the case studies; the ones having the highest efficiency (above 49.5%) were A-2, B-2 and B-6; while the ones with the lowest efficiency (less than 47.5%) were B-4, B-5 and D-2.

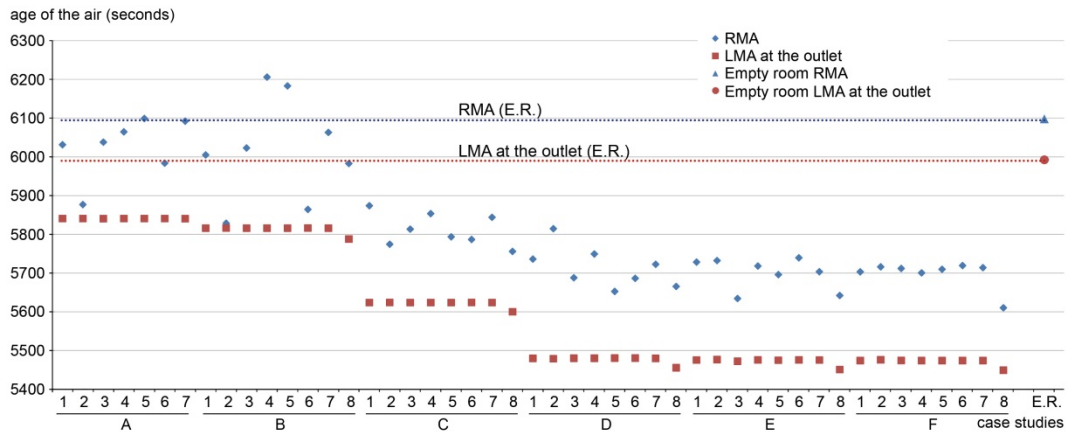


Figure 8. RMA and LMA at the outlet in both the 47 case studies and the ER

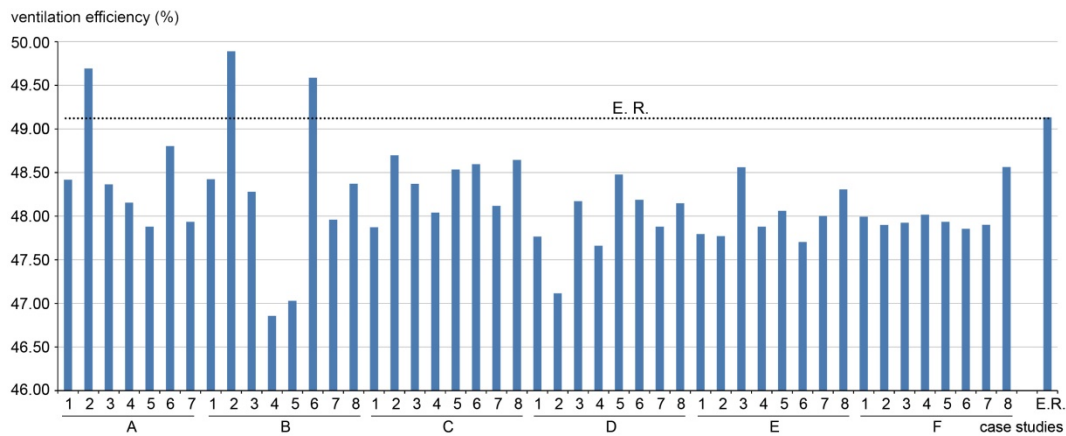


Figure 9. RMA and LMA at the outlet in both the 47 case studies and the ER

Discussion

In configurations A and B, the efficiency of all its cases has a greater fluctuation, with a difference, in A, of 3.65% between the cases with the highest and the lowest ventilation efficiency; and another of 6.08% in configuration B. From the configurations in C onwards, after introducing the closet and, therefore, reducing the air volume of the space, the difference between the cases with the highest and the lowest efficiency is smaller. In C, this difference is of 1.35%; in D, of 1.68%; in E, of 1.76%; in F, of 1.46%. Thus, the variation of the ventilation efficiency for each category (A-F) is reduced when the closet (C) is introduced.

Three of the case studies have a higher efficiency than the one of ER (of 49.13%): A-2 (49.69% of efficiency), B-2 (49.89% of efficiency) and B-6 (49.57% of efficiency); thus, it is demonstrated that there are furniture arrangements which facilitate the air flow and even improve it with respect to empty spaces. Cases B-4, B-5 and D-2 differ by more than 4% from ER; B-4 has the highest difference, with 4.63%; all other cases have an efficiency which keeps a difference of less than 3% with regard to ER.

The cases of better efficiency (A-2, B-2 and B-6) have as a common characteristic that the furniture included in them occupies the corner shared by the wall where the inlet is located and the wall contrary to the outlet, which facilitates the movement of the air towards the exhaust reducing, in turn, the ability to form stagnant air masses. In addition, the elements introduced have low height, since they do not exceed 0.50 m.

In cases of poorer efficiency (B-4 and B-5), the corner that is shared by the wall of the inlet with the one of the outlet is occupied (Fig. 3), hindering the movement of the air and creating areas of stagnation (Fig. 7.a.). Finally, in the case D-2, which shares the same configuration with B-2 (case of highest efficiency) but includes the closet and the shelf in the corner shared by the contiguous wall to the inlet and the contiguous wall to the outlet (Fig. 3); when adding these elements, the air flow is hampered, characterizing this case as one with the worst ventilation efficiency (47.11%) among those studied in this research (Fig. 9).

The literature on ventilation efficiency and air distribution in an enclosure is extensive [32-34], especially focused on the use of CFD techniques to assess ventilation systems and air flow distribution [35-40], type of space [30, 40, 41], position and size of both inlet and outlet [18, 20, 42, 43] and influence of the occupants [37, 44]. However, unlike such previous research, this study focuses on evaluating the ventilation efficiency according to the arrangement of furniture elements in a single space fixing the size and location of both the supply and the exhaust opening; in this particular field there are no examples in the literature. Additionally, it should be noted that the influence of the presence of furniture and its disposition on the ventilation efficiency is an important parameter to be considered, as shown in the outcomes of this study.

Conclusions

In this research, CFD techniques, validated by the tracer gas decay technique, were used to assess the ventilation efficiency in 47 isothermal cases. These cases differ according to the variation, in the same space (single bedroom), of the dispositions of furniture, in order to study the influence of the same on the air distribution within the enclosure. The process carried out in this study and the results obtained are useful to understand which the best arrangement of elements inside the bedroom is, in the sense that it can facilitate the air exchange.

According to the values of ventilation efficiency achieved, although it is not statistically significant, an improvement up to 1.65% in the ventilation efficiency concerning an empty room is achieved when the elements are introduced in a way that facilitates the air movement towards the exhaust, including them in the opposite wall to the outlet and close to the inlet. However, there are exceptions which require the development of an exhaustive study of the space, using CFD techniques in this case, to detect areas of stagnation.

It is concluded that there are certain furniture arrangements which are advisable to be avoided, in this study those dispositions would especially be the configurations where there is low-height furniture (bed and bedside table) in the corner that is shared by the

wall where the inlet is located and the wall where the outlet is placed. According to this study, these arrangements suppose a difference up to than 4.6% with regard to the empty room; however, it is not statistically significant.

In future research, a comprehensive study of the influence of temperature and velocity parameters on the distribution of the age of the air within an enclosure is planned. In addition, it is intended to assess the air distribution considering not only criteria related to energy efficiency but also the quality of the indoor air, carrying out the evaluation of the behavior of occupants and their breathing zone. Since the results achieved in this research are not statistically significant, a study of the area around to the bed pillow, as a point of inhalation during 8 hours of sleep, will be developed; so that, if there is no sufficient air exchange in that area, it is more harmful to health than if it occurs at another point; in addition, the absence of movement of the sleeper makes the air to be basically exchanged by the indoor air flow pattern

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Figure 1. Test chamber dimensions (in meters)

Figure 2. Furniture included in the test chamber

Figure 3. 47 case studies according to several elements and their arrangements

Figure 4. Mesh used for the case A7

Figure 5. Number of nodes, elements and mesh quality of the case studies and the E.R

Figure 6. Age-of-the-air distribution (seconds) within the ER

Figure 7.a) Age-of-the-air distribution (seconds). A, B and C arrangements

Figure 7.b) Age-of-the-air distribution (seconds). D, E and F arrangements

Figure 8. RMA and LMA at the outlet in both the 47 case studies and the ER

Figure 9. RMA and LMA at the outlet in both the 47 case studies and the ER