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Analysis of air quality by ventilation in house in the framework of the COVID-19 pandemic: the case of Spain

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Abstract: After the arrival of a new airborne virus to the world, science is aiming to develop solutions to withstand the spread and contagion of the SARS-CoV-2 coronavirus. The most severe among the adopted measures is to remain in home isolation for a significant number of hours per day, in order to avoid the spreading of the infection in an uncontrolled way through public spaces. Recent literature showed that the major route of transmission is via aerosols produced especially in poorly ventilated inner spaces. With regard to contagion rates, accumulated incidence or number of hospitalizations due to COVID-19, Spain has reached very high levels, therefore this article develops a quantitative and qualitative analysis of the requirements established in Spain with respect to the European framework in reference to ventilation parameters indoors. For this, a case study has been analyzed, representing a common residence in current Spanish residential developments. Results show that the criteria established in the applicable regulations are not sufficient to ensure health as well as to avoid contagion by aerosols indoors.

Keywords: ventilation; indoor air quality; COVID-19; aerosols; Spain

0. Nomenclature list

Abbreviation	Term
ACH	Air changes per hour
CO	Carbon Monoxide
CO ₂	Carbon dioxide
COVID-19	Corona virus disease 2019
CTE	Technical code of the building
EN	European Norm
HS	Basic document on salubrity
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IEQ _{cat}	Indoor Environmental Quality category for design
NOX	Oxides of nitrogen
ns	Crowding index per unit area
O ₃	Ozone
OMS (WHO)	World Health Organization

PM	Particulate Matter
ppm	parts per million
qB	ventilation rate for building materials
Qop	specific external air flow per person
qp	ventilation rate for people
qv	minimum flow for housing
R/h	Air renewal per hour
SIMA	Italian Society of Environmental Medicine
SO ₂	Sulfur dioxide
UNE	A Spanish standard
UNESCO	United Nations Educational, Scientific and Cultural Organization.
UNI	Italian national unification body

1. Introduction

At the end of 2019 a new airborne virus “COVID-19” was first identified in Wuhan, China. The quick spreading soon turned into a worldwide pandemic, seeing that people does not have immunity against it, along with a high level of contagion and a significant mortality rate [1]. The first cases were registered in Europe at the end of January [2]. The first 100 infections are counted as day zero, which in Spain were reached on March 5, 2020 [3, 4]. From that moment on, different governments have taken measures such as closure of airports [5], schools, commercial activities, restaurants, etc. [6-8].

With the arrival of the COVID-19 pandemic, people across the world have experienced remarkable changes to the way they live their lives at home. Suddenly, the society have had to face an involuntary confinement, from one day to the next, been obligated to stay indoors much longer than usual, sharing spaces no matter occupants are of the same nuclear family or not. Workers have had to start working remotely from buildings and both children and teenagers have had to follow and deal with online lessons [9-10].

Mankind is facing issues related to the ongoing pandemic that can definitely affect the quality of life, e.g. considering the importance of ventilation on the air distribution, determining comfort and health in indoor environments [11-12]. According to various studies, contagion is due to the exposure of aerosols that convey the virus through the environment, and this risk can be minimized with clean air derived from good indoor ventilation [13-18]. A well-ventilated home is beneficial to health. The air circulation allows it to be oxygenated, which facilitates the expulsion of dust particles and mites, regulates the humidity of the environment and eliminates bad odors. In addition, ultraviolet rays can act against some microorganisms, therefore, if possible, it is also beneficial for sunlight to flood the house. On the contrary, when the house is not well ventilated, in addition to favoring the spread of germs (especially in closed and humid environments), we can suffer energy dips, frequent headaches, sleep difficulties or respiratory symptoms may intensify, in addition to the increase in infections in times of pandemic like the one we are experiencing.

Therefore, it is evident the need to improve the indoor air quality, as it may contain atmospheric pollutants which can be divided, according to their physical nature, into gaseous and particulate matter, and according to their formation, into primary pollutants: sulfur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO) and

secondary pollutants: ozone (O₃) and particulate matter (PM) [19-23]. Electronic noses, shortly e-noses consisting of a sensor array and a pattern recognition algorithm, may be conveniently used as smart devices to monitor indoor air quality in living environment [24-26]. However, in order to avoid high concentrations of the above mentioned substances, it is necessary to have good indoor ventilation. Furthermore, the presence of people in confined spaces for a higher number of hours per day may imply an increase in the concentration of CO₂ in our rooms [27, 28]. Obviously, with the increase of time spent indoors, increases the time of use of appliances, lighting, heating, etc., which can also increase the amount of CO₂ released into the indoors [29, 30].

Indoor heating and cooling yield the primary source of energy consumption while the use of appliances is the most important factor in terms of CO₂ emissions [31, 32]. Healthy environments may be, however, obtained through optimal systems that seek a balance between energy savings and optimal ventilation conditions [33-37]. According to the "Recommendations of the UNESCO Chair on Health Education and Sustainable Development & the Italian Society of Environmental Medicine (SIMA)", a strong accumulation of CO₂ can cause problems in people with lung conditions and can also decrease concentration and worker's and student's productivity [38-41].

An efficient living, work or study environment is therefore a fundamental requirement for building occupants to either live healthy or work productively. Thus, improving indoor air quality can be very important to increase productivity, and, moreover, to avoid the spread of the virus [42-45]. In order to reduce the likelihood of transmission via air, the WHO recommends a natural ventilation rate of at the least 60 liters per second and per person, and at least 6 air changes per hour [46-47]. In light of the carried literature review, some questions can be raised: what are the regulations in Spain and Europe in matter of ventilation parameters? Are indoor environments up to the task of adopting the imposed, yet hopefully transitory, "new way of life"? Can them be considered safe in terms of preventing contagion, safeguarding public health? And also, have them proper ventilation system, according new demands in times of pandemic? In the following we try to address the above posed questions.

2. Materials and Methods

The methodology used for the analysis of the air quality consists in the calculation of flow rates and R/h of ventilation adopted indoors in Europe and Spain, considering the amount CO₂ emitted per person in the framework of the new issued directives of COVID-19. To verify that the indoor ventilation is still adequate to the new requirements, the existing regulations at European level are analyzed in comparison to the Spanish regulations regarding the minimum measurements indoors, to finally choosing a standard home to make the comparison of both regulations.

2.1. Regulations regarding ventilation

The current legislation in Europe and Spain is analyzed to calculate the main parameters needed to maintain a healthy indoor air quality according to the applicable regulations. The factors that most influence the improvement of health are: air renewal per hour, the minimum ventilation flow, as well as the concentration of CO₂ indoors. They will be studied according to the different legislation.

2.1.1. Minimum flow rates per house

- For Europe:

For an additional comparison, we will also consider the European standard EN 16798: 2019 "Energy performance of buildings - Ventilation for buildings" will be considered, in which the quality of the indoor environment is taken into account by categories (Table 1), as well as the surface of the premises and the number of building residents who can be established.

Table 1. Description of the air quality categories in buildings. Source: EN 16798-2: 2019

Category	Level of expectation	Explanation
IEQ I	High	Should be selected for occupants with special needs (children, elderly, and people with disabilities).
IEQ II	Medium	The normal level used for design and operation.
IEQ III	Moderate	Will still provide an acceptable environment. Some risk of reduced performance of the occupants.
IEQ IV	Low	Should only be used for a short time of the year or in a space with very short time of occupancy.

The ventilation flow through residential buildings is calculated based on the criteria established for predefined supplied ventilation air flow rates: Total ventilation for case 1 and supplied air for cases 2 and 3 in residential buildings (Table 2). Finally, the result with the highest value obtained is chosen, this being the most restrictive.

Table 2. Ventilation air flow rates. 3 different calculation methods (1), (2) and (3)

Category	Total ventilation including infiltration air (1)		Airflow delivered per person (2)	Supplied air flow based on Indoor Air Quality (IAQ) perceived by adapted people (3)	
	$l/s \cdot m^2$	Ach	$l \cdot s^{-1} \cdot pax^{-1}$	q_p in $l \cdot s^{-1} \cdot pax^{-1}$	q_p in $l \cdot s^{-1} \cdot m^2$
	I	0.49	0.7	10	3.5
II	0.42	0.6	7	2.5	0.15
III	0.35	0.5	4	1.5	0.1
IV	0.23	0.4			

- For Spain:

In Spain, according to CTE HS 3 "Quality of indoor air", the amount of minimum flow in l/s depending on the number of dry and humid areas present in the housing is taken into consideration (Table 3) [48].

Table 3. Minimum flow rate for constant flow ventilation in rooms. Source: CTE HS 3 [48].

Housing type	Minimum flow q_v in $l\ s^{-1}$				
	Dry areas			Humid areas	
	Main bedroom	Rest of bedrooms	Living room and dining rooms	Minimum in total	Minimum per area
0 or 1 bedrooms	8	-	6	12	6
2 bedrooms	8	4	8	24	7
3 bedrooms	8	4	10	33	8

In order to calculate the value of the minimum flow q_v in $l\ s^{-1}$, the number of bedrooms present in the housing (admission calculation) and the number of toilets, bathrooms or kitchens must be considered (extraction calculation). In this way, the final result of the flow of the house will be determined by the highest resulting value, whether of admission or extraction, being the same for both cases so that there are no pressure differences inside the property.

2.1.2. CO₂ concentration per housing

- For Europe:

According to the EN-16798-2 standard, the maximum concentration of CO₂ for each of the categories is shown in Table 4 [49] referring to premises in a housing.

Table 4. Design CO₂ concentrations for living rooms and occupied rooms.

Category	Design Δ CO ₂ Concentrations for Living Rooms (ppm)	Design Δ CO ₂ concentrations for rooms (ppm)
I	550	380
II	800	550
III	1350	950
IV	1350	950

- For Spain:

In Spain, as established by CTE HS 3 "Indoor air quality", it is considered that a sufficient flow of outdoor air must be provided in the living areas of the houses to achieve that in each area the average annual concentration of CO₂ is less than 900 ppm and that the annual accumulated CO₂ that exceeds 1,600 ppm is less than 500,000 ppm · h, at the same time. [48].

2.2. Minimal measurements of surfaces and heights in housings and premises according to Spanish regulations.

For a comprehensive view of the calculation of renovations per hour, it has been necessary to verify the construction directives in Spain regarding the minimum surface area that makes up a home, also verifying the minimum net room height of housings in this country. In Spain, the dimensions of the houses are dictated by the Urban

Regulations and the General Urban Planning of each city. In this case, a comparison has been made of the regulations currently used in some cities.

According to the Urban Regulations and General Urban Planning, in most of the cities in Spain the following parameters are expected: a minimum net room height of 2.5 m in dry areas, and at least 2.2 m height in wet areas. On the other hand, a double room has a minimum size of 10 m² while the minimum for a single room is 6 m². The minimum size for a living room is 10 m², reaching 14 m² if the kitchen is included. For a kitchen the minimum area is 5 m², for a main bathroom 1.5 m² and for a secondary bathroom of 1.1 m². A studio for one person has a minimum floor area of 25 m², whereas a house for two people should be at least of 37 m².

The latest statistics data for the countries of the European Union shows that multi-family housing is the most common residence form in nine countries: Latvia (66.2%), Spain (64.9%), Estonia (61.5%), Greece (60.6%), Lithuania (59.5%), Germany (56.3%), Malta (53.8%), Italy (52.6%) and the Czech Republic (51.5%), in the rest, single-family homes with larger surfaces prevail [50]. Spain is the second country in the European Union with the smallest housings, according to the latest registered data. In the last century, residential developments have been declining in size, with Spain being one of the countries with the smallest useful area per housing, and a large number of individual housing developments or studios have also been developed [51].

The overcrowding of cities, the increase of the land price in the larger ones, together with the economic crisis we are undergoing in recent years, has motivated urban developments to conceive a type of housing that is increasingly smaller and with a higher degree of overcrowding [52].

2.3. Requirements recommended by governments due to the pandemic

Due to the importance of reducing the concentration of different pathogens in the air to minimize the risk of COVID-19 infections, different governments have published implementation guides with restrictions regarding ventilation flow, air renewals per hour and the maximum concentration of CO₂ [53-56].

In Spain, the government published different manuals on recommendations for ventilation systems based on the prevention of the spread of COVID-19. With regard to the minimum flow rate of ventilation it is recommended at least a value of 12.5 l/s per occupant [57]. Regarding the CO₂ concentration, an optimum value of 500 ppm is indicated [58]. It should also be considered that the WHO recommends 6 air changes per hour for a room [46-47].

2.4. Analysis of the proposals applied to a case study

To evaluate all the aforementioned aspects, a residential building is taken as case study, to carry out the analysis of the ventilation parameters. The chosen solution is sufficiently representative of most of the Spanish residential developments currently being carried out in urban development areas. The apartment (Figure 1) is conceived with the following formal and constructive characteristics:

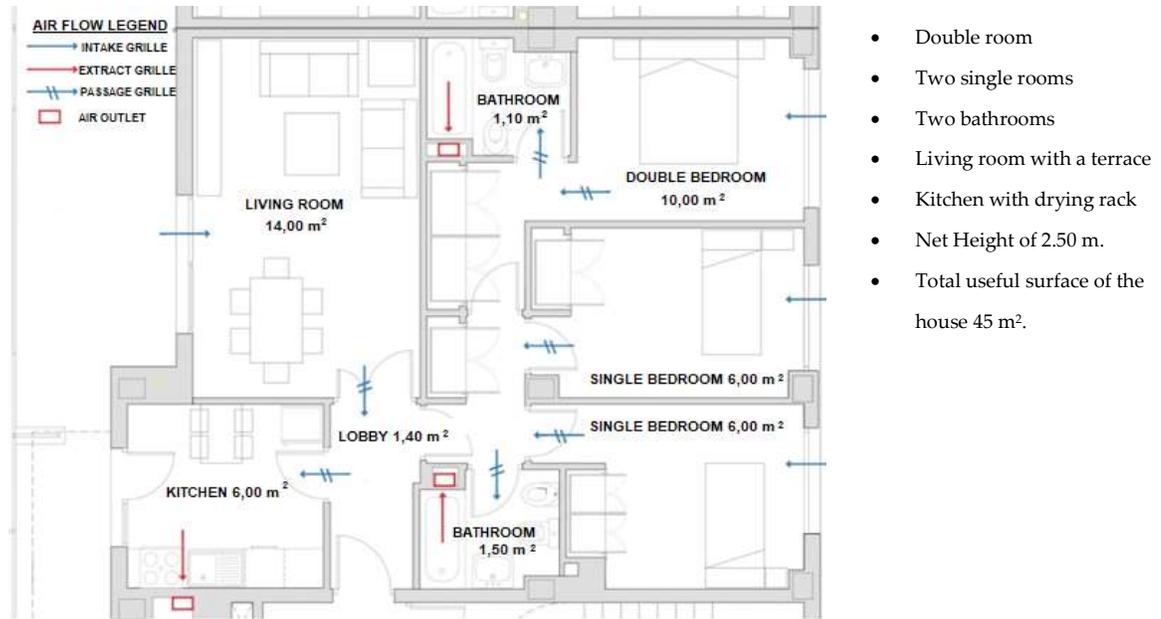


Figure 1. Apartment taken as case study

3. Results

The results, next discussed, indicate the influence of the chosen ventilation parameters on the apartment shown in Figure 1. In the following sections it is shown whether the current regulations meet the new criteria established during the COVID-19 pandemic.

3.1. Comparative analysis of the regulations on the ventilation flow rate

In order to make a comparison between the aforementioned regulations, a calculating procedure has been conceived for the apartment (Figure 1), subject to each of the considered legislations. The data related to category I (according to EN 16798-2) has been set as the optimal.

The ventilation flow rate according to CTE HS 3 standard has been calculated considering 3 bedrooms, a living room - dining, moreover it has been considered that the housing can be occupied by 4 people. As for Europe, the EN 16798-2 standard has been taken into account, where in its highest category we would have 10 l/s person.

The results of the total ventilation flow rate have been obtained from European regulations and have been compared to the recommendation provided today by the government of Spain due to the COVID-19. As shown in Table 5, the higher flow rate is obtained according to the requirements set out in the directives of Spain.

Table 5. Comparison of the Ventilation Flow results by regulations

Surface Total	Total ventilation flow		
	CTE HS 3	Spanish recommendation for Covid-19	EN 16798-2
	Spain	Italy	Europe
m ²	1 / s	1 / s	1 / s
45	33	50	40

3.2. Comparative analysis between the regulations on renewals per hour

Table 6 resumes the results of calculations, made by considering the flow rates calculated above and the volume of the apartment under study.

Table 6. Comparison of the results of renovations per hour by regulations

Volume Total	Renewals per hour		
	CTE HS 3	Spanish recommendation for Covid-19	EN 16798-2
	Spain	Italy	Europe
m ³	R/h	R/h	R/h
112.50	1.06	1.60	1.28

As expected, the data that provides the greatest number of renewals per hour, for the same volume of housing, is the one with the highest flow rate. In this case, the recommendations of the Government of Spain with 1.60 R/h represents a higher value with respect to European regulations.

In addition, it must be taken into account that the WHO provides in its guide, to establish 6 R/h which imply for the case at hand a flow rate of 334 l/s.

3.3. Comparative analysis between the regulations on the concentration of CO₂

This analysis is carried out with the criteria established by the European and Spanish regulations and in the recommendation guides against COVID-19.

Table 7. Comparison of CO₂ concentration results by the different regulations

CO ₂ concentration			
CTE HS 3	Spanish recommendation for Covid-19	EN 16798-2 (Rooms)	EN-16798-2 (Living rooms)
Spain	Spain	Europe	Europe
ppm	Ppm	ppm	ppm
900	500	380	550

The European standard EN-16798-2 is the one with the most restrictive values, reaching a maximum concentration of 380 ppm. As for living rooms, it establishes a maximum level of CO₂ concentration of 550 ppm, very similar to the recommendations in times of COVID in Spain.

4. Conclusions

From the results previously analyzed it can be concluded that the ventilation flow rates indicated by the considered regulations and guides of application in times of pandemic are insufficient to meet the renewal time advised by the WHO, and consequently the decreasing of levels of CO₂ levels indoors. However, in detail it is worth highlighting:

The ventilation flow established by the Spanish regulations presents better results than the European one, since it establishes a flow of 12.5 l/s per person due to ventilation requirements in the COVID-19 period. Therefore, it is verified that home confinement in this country has been able to work to mitigate the spread of the pandemic thanks to this reason [59-62].

As for the number of renewals per hour, the values are low for both Europe and Spain, in the case of a studio apartment lower than 2 R/h which means that it would be necessary to increase the criteria actually established by the various regulations to get closer to the 6 R/h, recommended by the WHO.

Regarding the concentration of CO₂, the values that are recommended not to exceed are set around 500 ppm. Spain may present a higher risk of pollutant concentration due to smaller volumes in the different areas of the houses compared to the minimum dimensions of houses established by other countries. Therefore, in Spain, an increase of the minimum measures of health concerning house ventilation is the preferred option, seen that it is a space where people spend more hours, in light of the fact there is no available legislation that establishes optimal measures that guarantee to avoid contagion through aerosols.

Acknowledgments: The authors gratefully acknowledge the support of the ERASMUS + Traineeship and Grupo de Investigación de Tecnología y Medio Ambiente (TEMA) at the School of Building Engineering at the Technical University of Madrid.

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