



Ventilation for Residential Buildings: Critical Assessment of Standard Requirements in the COVID-19 Pandemic Context

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After the arrival of a new airborne virus to the world, science is aiming to develop solutions to withstand the spread and contagion of SARS-CoV-2. The most severe among the adopted measures is to remain in home isolation for a significant number of hours per day, to avoid the spreading of the infection in an uncontrolled way through public spaces. Recent literature showed that the primary route of transmission is *via* aerosols, especially produced in poorly ventilated inner spaces. Spain has reached very high levels concerning contagion rates, accumulated incidence, or number of hospitalizations due to COVID-19. Therefore, this article aims to develop a quantitative and qualitative analysis of the requirements established in Spain, with respect to the European framework in reference to ventilation parameters indoors. The different parameters that serve as calculation for the ventilation flow in homes are analyzed to this aim. Results show that the criteria established in the applicable regulations are insufficient to ensure health and avoid contagion by aerosols indoors.

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

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, showing that people do not have immunity against it, along with a high level of contagion and a significant mortality rate (Li et al., 2020). The first cases were registered in Europe at the end of January (Spiteri et al., 2020). The first 100 infections are counted as day zero, which in Spain were reached on March 5, 2020 (Domínguez et al., 2020; Glass, 2020). From that moment on, different governments have taken measures such as the closure

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Abbreviation: ACH, air changes per hour; CO, carbon monoxide; CO₂, carbon dioxide; COVID-19, coronavirus disease 2019; CTE, technical code of the building; EN, European Norm; DB 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; O₃, 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; SO₂, sulfur dioxide; UNE, a Spanish standard; UNESCO, United Nations Educational, Scientific and Cultural Organization; UNI, Italian National Unification Body.

of airports (Borrelli, 2020), schools, commercial activities, restaurants, etc. (Ordinanza del Ministro della salute 30 gennaio 2020, 2020; Delibera del Consiglio dei Ministri 31 gennaio 2020, 2020; Ley 33/2011 de 4 de octubre, 2011).

With the arrival of the COVID-19 pandemic, people worldwide have experienced remarkable changes to the way they live their lives at home. Suddenly, the society has had to face involuntary confinement, from one day to the next, and 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 (Elnikova et al., 2020; Voss and Wittwer, 2020).

Humankind 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 (Gilani et al., 2016; Hamdy and Mauro, 2019). According to various studies, contagion is due to aerosols' exposure that conveys the virus through the environment, and this risk can be minimized with clean air derived from good indoor ventilation (Zoran et al., 2020; CCAES, 2020; Dati aggregati quotidiani Regioni / PPAA, 2021; Urrutia-Pereira et al., 2020; Filippini et al., 2020; Baldasano, 2020). 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 odours. 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, one can suffer energy dips, frequent headaches, sleep difficulties, and breathing issues, not to mention the risk of infection in times of pandemic like the one we are experiencing. In addition, poor ventilation fosters the spread of germs, especially in closed and humid environments.

Therefore, the need to improve indoor air quality arises, as it may contain atmospheric pollutants. The latter can be divided, according to their physical nature, into gaseous and particulate matter, and according to their formation, into primary pollutants: sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and secondary pollutants: ozone (O_3) and particulate matter (PM) (World Health Organization, 2005; Garcia-Chevesich et al., 2014; Madureira et al., 2016; Coleman and Meggers, 2018; Ogen, 2020). 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 the living environment (Vicciono et al., 2012; Sironi et al., 2014; Vicciono et al., 2014). However, in order to avoid high concentrations of the abovementioned 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 CO_2 (Giechaskiel, 2020; Rossi et al., 2020). Obviously, with the increase in time spent indoors, the time of use of appliances, lighting, heating, etc., increases, which can also increase the amount of CO_2 released (Heinonen et al., 2016; Aguilera et al., 2018).

Indoor heating and cooling yield the primary source of energy consumption, while the use of appliances is the most important factor in terms of CO_2 emissions (Jin et al., 2020; Yao et al., 2020). However, healthy environments may be obtained through optimal systems that seek a balance between energy savings and optimal ventilation conditions (Balocco and Leoncini, 2020; Darmanis et al., 2020; De Gaetani et al., 2020; Dudzik, 2020; Lee et al., 2020). According to the "Recommendations of the UNESCO Chair on Health Education and Sustainable Development and the Italian Society of Environmental Medicine (SIMA)," a substantial accumulation of CO_2 can cause problems in people with lung conditions. It can also decrease concentration and workers' and students' productivity (Espejo et al., 2020; Gautam, 2020; Pulimeno et al., 2020; Woodby et al., 2020).

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 (Abuhegazy et al., 2020; Fürhapper et al., 2020; Sun and Zhai, 2020; Aguilera-Benito et al., 2021). To reduce the likelihood of transmission *via* air, the WHO recommends a natural ventilation rate of at the least 60 L per second and per person and at least six air changes per hour (World Health Organization, 2020a; World Health Organization, 2020b). In light of the literature review carried out, 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 they be considered safe in terms of preventing contagion, safeguarding public health? Also, have them proper ventilation system, according to the new demands in times of pandemic? In the following, we try to address the aboveposed questions.

METHODS

Due to the importance of ventilation in times of pandemic, this research focuses on the effectiveness of air change in homes, checking whether the corresponding values agree with the new requirements and directives established by laws, to contain spreading contagion. The methodology used for the air quality analysis consists of calculating flow rates and R/h of ventilation adopted indoors in Europe and Spain, considering the amount CO_2 emitted per person in the framework of the newly issued directives of COVID-19. To verify that the indoor ventilation is still adequate to the new requirements, the existing regulations at the European level are analyzed in comparison to the Spanish regulations regarding the minimum measurements indoors. A regression analysis was carried out to estimate the relationships between the aboveobtained values and those derived with a one-way analysis of variance (ANOVA). This aspect is crucial because the increase of CO_2 concentration indoors, where people's breathing and related activities account for a greater share due to the confinement, would imply an insufficient air exchange, raising the risk of SARS-CoV-2 contagion.

TABLE 1 | Description of the air quality categories in buildings.

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

Source: EN 16798–2: 2019.

TABLE 2 | Ventilation air flow rates, three 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 m ²	Ach (air changes per hour)	l s ⁻¹ pax ⁻¹	q _p in l s ⁻¹ pax ⁻¹	q _p in l s ⁻¹ m ⁻²
I	0.49	0.7	10	3.5	0.25
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			

TABLE 3 | Minimum flow rate for constant flow ventilation in rooms. Source: CTE HS 3 (Gobierno de España, Ministerio de Fomento, 2019).

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

Regulations Regarding Ventilation

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

Minimum Required Airflow and Air Renovation per House

- For Europe:

In Europe, we consider the European standard EN 16798:2019 “Energy performance of buildings: Ventilation for buildings” where the quality of the indoor environment by category (Table 1) is taken into account, as well as the floor area and the people that can be set in case of nonresidential buildings.

The ventilation flow through residential buildings is calculated based on the criteria established for predefined supplied ventilation

TABLE 4 | Design CO₂ concentrations for living rooms and occupied rooms.

Category	Design ΔCO ₂ concentrations for living rooms (ppm)	Design ΔCO ₂ concentrations for rooms (ppm)
I	550	380
II	800	550
III	1,350	950
IV	1,350	950

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.

- 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) (Gobierno de España, Ministerio de Fomento, 2019).

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.

CO₂ Concentration per House

- For Europe:

According to the EN-16798-2 standard, the maximum concentration of CO₂ for each of the categories is shown in Table 4 (UNE-EN 15251, 2008), referring to premises in a house and the outdoor concentration.

In addition, UNE 171330-2 shows the inspection procedures for indoor environmental quality. In this sense, the standard indicates a maximum comfort criterion of 500 ppm and a maximum permissible indoor limit value of 2,500 ppm.

- 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 ppmh, at the same time (Gobierno de España, Ministerio de Fomento, 2019).

Prescriptions Indicated By the Competent Authorities Due to the Pandemic

Due to the importance of eliminating the concentration of different pathogens in the air to minimize SARS-CoV-2 infections, different governments have published application guides with restrictions regarding the ventilation flow, air changes per hour, and the maximum concentration of CO₂ (ASHRAE Board of Directors, 2020; Bonadonna et al., 2020; Instituto para la diversificación y ahorro de energía, 2020; Rapporto Istituto Superiore della Sanità (ISS), 2020).

In Spain, the government published different manuals on recommendations for ventilation systems based on preventing 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, a condition that can be achieved by increasing ventilation or reducing occupation (Gobierno de España, 2020). Regarding the CO₂ concentration, an optimum value of 500 ppm is indicated (Allen et al., 2020).

It is also essential to consider that the WHO advises controlling airborne transmission adequately, recommending a natural ventilation rate of at least 60 L/s per person and six air changes per hour (World Health Organization, 2020a; World Health Organization, 2020b).

TABLE 5 | Minimum surfaces and heights in residential rooms in Spain.

Area	Measurements	
	Minimum height (h)	Minimum surface (m ²)
Main room (2 pers.)	2.5	10.0
Secondary room (1 pers.)	2.5	6.0
Secondary room (2 pers.)	2.5	10.0
Living room (plus kitchen)	2.5	10.0 (14.0)
Kitchen	2.2	5.0
Main bathroom	2.2	1.5
Secondary bathroom	2.2	1.1
Premises accessories	2.2	-
Studio (1 pers.)	-	25.0
House 1 room (up to 2 pers.)	-	37.0

Analysis of Proposals Applied to Case Studies

For a comprehensive view of the calculation of air changes 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 ruled by the Urban Regulations and the General Urban Planning, for 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 (Table 5).

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 decreasing 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 (Eurostat, 2020; Trilla Bellart, 2003).

The overcrowding of cities and the increase of the land price in the larger ones, together with the economic crisis we are undergoing in recent years, have motivated urban developments to conceive a type of housing that is increasingly smaller and with a higher degree of overcrowding (Manville and Greatbanks, 2020).

In order to evaluate all the aspects mentioned above, two dwellings are taken as case studies, in which two real situations are presented, complying with the regulations established in the Urban Regulations and the General Urban Planning.

In the first case of study, the dwelling has the minimum surfaces per room, with a total area of 45 m² and a clear height of 2.20 m. It has three bedrooms and an estimated occupancy of three persons.

In the second case study, the dwelling has larger surfaces in each room, with a total area of 170 m² and a clear height of 3.00 m. It has five bedrooms and an estimated occupancy of 10 persons.

In this way, we can analyze the ventilation parameters with two dwellings that represent extreme cases in terms of surface

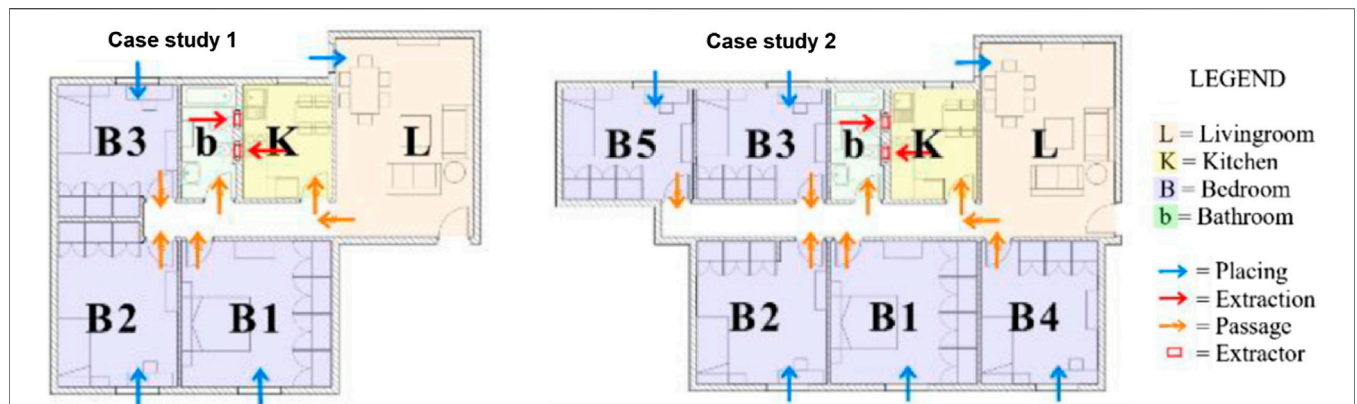


FIGURE 1 | Case study 1 and 2: housing with minimum and maximum floor areas.

TABLE 6 | Comparison of the ventilation flow results by regulations.

Case study	Total ventilation flow					
	EN 16798-2 method 1	EN 16798-2 method 1	EN 16798-2 method 2	CTE HS 3	Spanish recommendation for COVID-19	Spanish recommendation for COVID-19
	Europe		Spain		World	
	0.49	0.70	10.00	(*) (see Table 3)	12.50	60.00
	l / s m ²	ACH	l / s person	l / s (*)	l / s person	ACH
1	22.05	19.25	30.00	33.00	37.50	180.00
2	83.30	99.17	100.00	34.00	125.00	600.00

areas and heights. The dwellings of cases 1 and 2 (Figure 1) are designed with the following formal and constructive characteristics:

In addition to these two case studies, we will analyze how surface area, volume, and number of occupants affect the flow rates established by the different regulations.

RESULTS AND DISCUSSION

The results, next discussed, indicate the influence of the chosen ventilation parameters. They are analyzed in the two case studies, as well as in a general way by the calculation parameter established by the regulations. The following sections show whether current regulations meet the new criteria established during the COVID-19 pandemic.

Analysis of the Regulations on the Ventilation Flow Rate

Case Study Analysis

The data relating to category I (according to EN 16798-2) have been set as optimal. In the calculation with the European standard, a floor area of 45 m² and an occupancy of three persons were taken in case 1, and in case 2, a floor area of 170 m² and an occupancy of 10 persons were taken.

The ventilation flow according to CTE HS 3 has been calculated considering three bedrooms and a living/dining room in case study 1 and five bedrooms and a living/dining room in case study 2.

The results of the total ventilation flow rate have been obtained from the European standard and compared with the recommendation given today by the Spanish Government due to COVID-19 (Table 6).

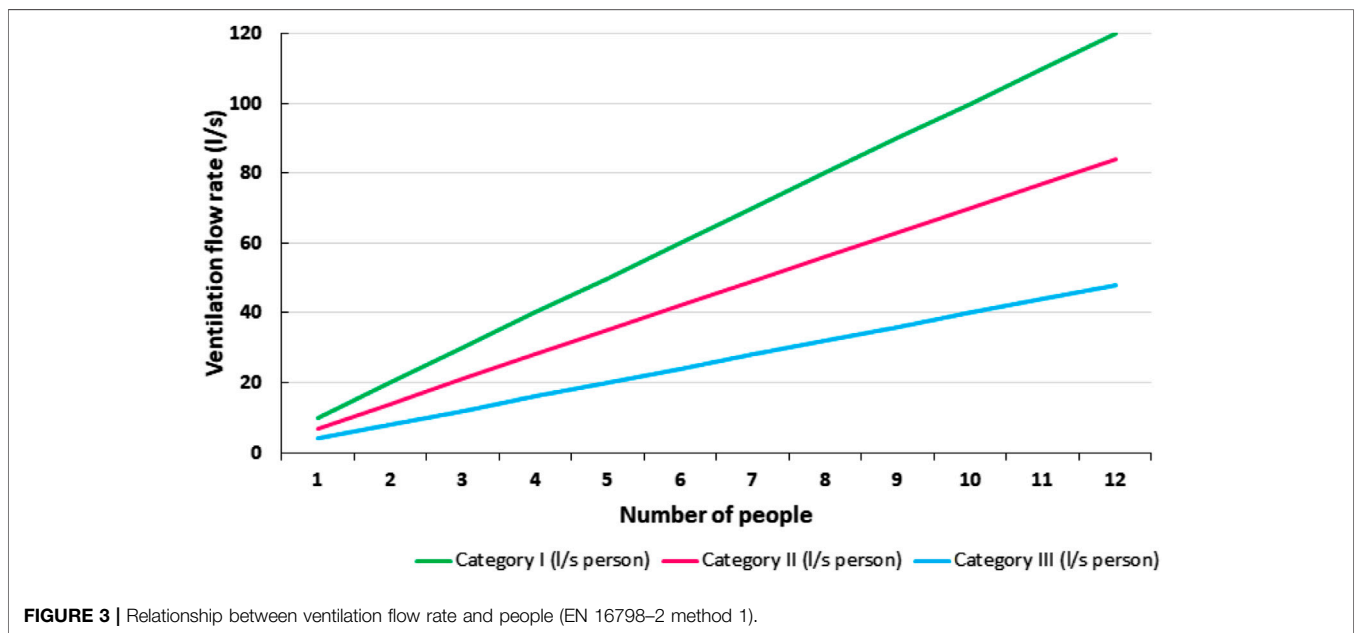
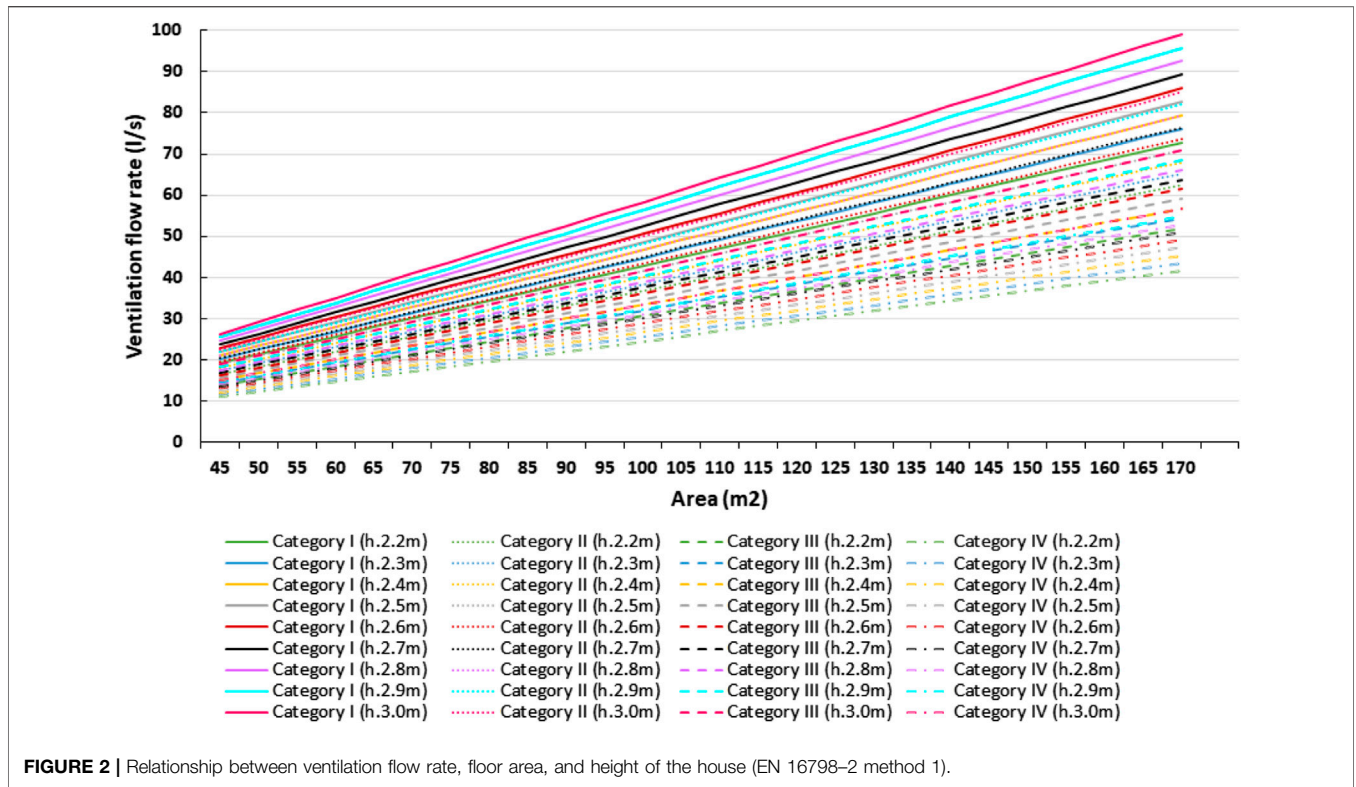
In the case of the European standard, the method that provides the highest ventilation flow rate is the one based on the number of persons. In addition to case study 2, the calculated air flow rates are increased by 60–70% compared to case study 1.

In the case of the Spanish regulation, it is worth noting that the flow rates are practically the same, despite the significant differences between the two dwellings. The recommendations of the Spanish Government in times of pandemic reflect much higher and realistic ventilation flows in the current situation.

Finally, the WHO establishes very high flow rates, on the understanding that these are parameters established for high risks of contagion. In this case, the comfort of the occupants should be taken into account because these air flow rates may cause discomfort due to high air flows.

General Analysis of Ventilation Flows

Analyzing the parameters that affect the amount of flow calculated in each case, four variables need to be developed and analyzed in detail. These variables are the surface area, the



height of the dwelling, the number of occupants, and finally, the number of bedrooms in the dwelling.

Firstly, the floor area and height are parameters that are analyzed together, according to EN 16798–2 and method 1. As shown in **Figure 2**, for small surfaces—around 45 m²—and heights between 2.20 and 3.00 m, the ventilation flow rates

are between 11 L/s and 28 L/s. Conversely, when the dwelling has a larger surface area (170 m²), the ventilation range increases in the range between 41 L/s and 99 L/s.

It can be seen that the height is a parameter to be taken into account, but it is not as effective as the surface area of the dwelling. In terms of air quality improvement (category I) the

TABLE 7 | Calculation of ventilation according to Spanish regulations (CTE DB HS).

Number of bedrooms	Minimum flow q_v in $l\ s^{-1}$					Final calculations
	Main bedroom	Rest of the bedrooms	Living room and dining rooms	Calculated flow	Minimum in total	
1	8	-	6	14	12	14
2	8	4	8	20	24	24
3	8	4 + 4	10	26	33	33
4	8	4 + 4+4	10	30	33	33
5	8	4 + 4+4 + 4	10	34	33	34
6	8	4 + 4+4 + 4+4	10	38	33	38

TABLE 8 | Comparison of CO₂ concentration results by the different regulations.

CTE DB HS 3	Spanish recommendation for COVID-19	CO ₂ concentration		
		EN 16798-2 (rooms) Δ CO ₂ in-out	EN-16798-2 (living rooms) Δ CO ₂ in-out	UNE EN-171330-2 Δ CO ₂ in-out
Spain		Europe		
ppm	ppm	ppm	ppm	ppm
900	500	380	550	500

height affects more than in lower categories. In category I, between the heights of 2.20 and 3.00 m, the increase in flow rate is 15 L/s; however, in category IV, between the selected height range, the flow rate varies by only 5 L/s.

The analysis by one-way analysis of variance (ANOVA) showed that the surface area and the height of the dwelling present significant differences in the ventilation flow rate data, obtaining $F(2.695) = 10.87$, for $p < 0.005$, the null hypothesis being that surface area does not significantly affect the calculation of air ventilation and rejecting this hypothesis because the value of F is greater than the critical value.

The occupancy within the dwelling is also important when calculating ventilation flow rates, especially in high-quality cases. In category I, from 1 person to 12 persons, the flow rate increases by 110 L/s, in category II, by 77 L/s, and in category III, by 44 L/s (**Figure 3**).

In this case, ANOVA showed that the number of occupants of the dwelling presents significant differences in the ventilation flow rate data, obtaining $F(3.284) = 6.38$, for $p < 0.005$, the null hypothesis being that the number of people does not significantly affect the calculation of air ventilation and rejecting this hypothesis because the value of F is greater than the critical value.

According to the Spanish regulations in the CTE DB HS document, the calculation carried out based on the number of bedrooms is the most deficient because it sets very low air flow rate levels (**Table 7**). It would be necessary to know the square metres of each room or the number of occupants to set a value more in line with real needs. For this reason, European standards are closer to air flow rates that

may be more satisfactory in terms of achieving good indoor air quality.

Analysis Between the Regulations on the Concentration of CO₂

This analysis is conducted with the criteria established by European regulations, Spanish guidelines, and recommendations against COVID-19 regarding CO₂ concentration (**Table 8**).

The Spanish regulations present very restrictive values of CO₂ concentrations intramoenia, this being of 900 ppm, provided that the annual accumulated CO₂ that exceeds 1,600 ppm is less than 500,000 ppmh (Lepore et al., 2021). On the other hand, according to the recommendation guide in times of COVID-19, it is suggested that the concentration is not greater than 500 ppm. However, the European regulations EN-16798-2 and EN-171330-2 present limit values depending on the internal concentration compared to the external one, having a maximum difference of approximately 550 ppm (depending on the category). It can be seen that they are very different criteria that should be unified for the dimensioning of ventilation in homes and the improvement of people's well-being.

CONCLUSION

The ventilation flows indicated by the examined regulations and application guidelines are proven to be insufficient in times of pandemic. Therefore, the need to update them arises, due to the related risk of contagion.

The available calculating procedures disconcert the project technician because the ventilation air flow can be calculated based on different parameters such as the surface of the house, the volume of the house, the occupation, or even the number of bedrooms. It would be necessary to establish a unique criterion to establish the parameter that best suits the results we want to obtain to have good air quality. According to the study carried out, the surface is the leading and most objective parameter, followed by the volume of the house. Occupancy is a parameter that possibly makes more sense for other activities such as public use, but not for residential use. Also, the calculation by bedroom number is not effective and adapts to reality.

Despite the low ventilation flow prescribed in Spanish regulations, the Government during the pandemic has set a more restrictive criterion of 12.5 L/s per person due to ventilation requirements in the COVID-19 period.

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.

As a result of this study, the need has arisen to update the legislation on ventilation, since the criteria established long ago are not currently adequate to avoid contagion by aerosols indoors. Under the proposed new paradigm, future efforts are necessary to expand this research and analyze these values with different natural and forced ventilation systems. Considering

other factors such as occupation, activity, weather conditions, and energy efficiency, it should be noted that the abovementioned results are based on simplified and ideal scenarios without taking into account many influencing factors, such as temperature, humidity, evaporation of droplets, and particles. Therefore, the results should be used with care. However, this research can be seen as an initial analysis to understand the criteria required for ventilation in residential buildings in order to address the prevention of the transmission of infectious diseases.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

PB: methodology and writing. CR: drafting and formal review. GV: supervision and resources. EL: research and bibliographic search.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fbuil.2021.656718/full#supplementary-material>

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