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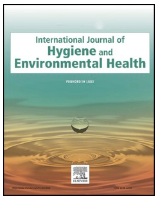

Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with Mediterranean climate

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ABSTRACT

Current evidence and recent publications have led to the recognition that aerosol-borne transmission of COVID-19 is possible in indoor areas such as educational centers. A crucial measure to reduce the risk of infection in high occupancy indoors is ventilation. In this global pandemic context of SARS-CoV-2 virus infection, a study has been carried out with the main objective of analyzing the effects of natural ventilation conditions through windows on indoor air quality and thermal comfort during on-site examinations in higher education centers during the winter season, as this implies situations of unusual occupation and the impossibility in many cases of taking breaks or leaving classrooms, as well as the existence of unfavorable outdoor weather conditions in terms of low temperatures. For this purpose, in situ measurements of the environmental variables were taken during different evaluation tests. As the main results of the study, ventilation conditions were generally adequate in all the tests carried out, regardless of the ventilation strategy used, with average CO_2 concentration levels of between 450 and 670 ppm. The maximum CO_2 concentration value recorded in one of the tests was 808 ppm. On this basis, the limit for category IDA 2 buildings, corresponding to educational establishments, was not exceeded in any case. However, these measures affected the thermal comfort of the occupants, especially when the outside temperature was below 6 °C, with a dissatisfaction rate of between 25 and 72%. Examinations carried out with outside temperatures above 12 °C were conducted in acceptable comfort conditions regardless of outside air supply and classroom occupancy. In these cases, the dissatisfaction rate was less than 10%. The results obtained have made it possible to establish strategies for ventilation in the implementation of future exams, depending on the climatic conditions outside.

1. Introduction

COVID-19 is the infectious disease caused by the SARS-CoV-2 coronavirus, unknown until the outbreak in the city of Wuhan (China) last December 2019, which has become a pandemic with a major global health, social and economic impact (INSST et al., 2021). The first two reported cases of COVID-19 in Spain were confirmed on 11th February of 2020. Both were considered as imported cases of infection (Instituto de Salud Carlos III et al., 2020a), whereas the first official COVID-19 death in Spain was reported two days later in a man who had travelled to Nepal (Instituto de Salud Carlos III et al., 2020b). Since then, numerous studies have been conducted on SARS-CoV-2 coronavirus behaviour, viability, survival, spread and transmission. In this regard, current evidence and research carried out by epidemiologists and engineers experts in this field (Allen and Marr, 2020; Miller et al., 2021) have led the World Health Organization (WHO) to recognize that it is coronavirus could be transmitted through small particles suspended in the air, known as aerosols (WHO, 2021).

An aerosol is a suspension of liquid or solid particles in a gaseous medium, usually air, which due to its small size and low weight, can remain in the air for a variable period. These particles may be inhaled, impact or deposit on mucous membranes or penetrate through the skin and cause adverse health effects to the population (Kulkarni et al., 2011).

Bioaerosols in educational environments come from outside air, entering directly through doors and windows, or through ventilation

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and air-conditioning systems, from construction materials and the furniture of buildings, favored by environmental conditions of high humidity, temperature and accumulation of dirt or organic material that allow the growth of fungi, bacteria, mites, etc., and from human presence and activity, which generates and expels droplets when talking, sneezing or coughing (INSHT, 2015; Kim et al., 2018). This way is the main source of SARS-CoV-2 infection (van Doremalen et al., 2020).

Transmission of the SARS-CoV-2 virus occurs mainly through direct and close contact with infected persons who, when talking, coughing or sneezing, expel respiratory droplets or saliva larger than 100 μm. These droplets can fall and land on objects from which they can be spread by touching them and then putting their hands to their nose, mouth or eyes, or they can be inhaled directly by others if they are close enough (Faridi et al., 2020). However, as mentioned above, there is evidence of transmission by aerosols of 100 μm or less in size, which can infect people at a distance of more than 2 m. These transmissions usually occur in enclosed spaces with inadequate ventilation, where people stay for a long time (CDC, 2020; WHO, 2020a).

A crucial preventive measure to reduce the risk of contagion in indoor spaces, in addition to the use of masks, interpersonal distance and hygiene measures, is ventilation, defined as the renewal of indoor air with outdoor air, either by natural or mechanical means or a combination of the two systems (Ministerio de Sanidad and Gobierno de España, 2020).

On the one hand, natural ventilation is achieved by non-mechanical means, normally by opening doors and windows, taking advantage of the pressure differences generated by a temperature gradient or by the action of the wind. The highest efficiency is achieved with natural cross ventilation, in other words, by opening two doors or windows in opposite walls of the room to promote air circulation and ensure an efficient sweep throughout the space. In situations of high COVID-19 transmission, the prioritisation of natural ventilation should be assessed against the thermo-hygrometric conditions necessary for thermal comfort or energy efficiency requirements (Atkinson, 2009).

Mechanical ventilation controls the air inlets and outlets, so it is not influenced by outdoor weather conditions and allows control of the flow rate introduced. It is recommended that, even if there is mechanical ventilation, natural ventilation is regularly carried out by opening doors and windows to achieve well combined ventilation (INSHT, 2006a).

Air ventilation rate per hour is used to check the air renewal in a given place (ACH) (Ministerio de Sanidad and Gobierno de España, 2020). On the other hand, to evaluate indoor air quality (IAQ) as well as ventilation conditions, the level of CO_2 concentration is used, as this is a good indicator of human bioeffluent emissions (INSST et al., 2021).

Educational establishments are environments vulnerable to the transmission of the SARS-CoV-2 virus regardless of their level, as they are enclosed spaces where the activities carried out to involve a large number of contacts in which a safe distance cannot be kept, so preventive measures such as the use of masks and ventilation are essential to curb possible infection.

There are studies that associate poor quality classroom environments with an increased risk of respiratory and allergic diseases, as well as compromised academic performance of students and working conditions of teachers (Baloch et al., 2020; Grineski et al., 2016).

Minguillón et al. have developed guidelines for ventilation in nursery and primary school classrooms, in which they set out different measures to reduce the risk of infection. This document set out recommendations for effective ventilation and air purification based on room volume, number and age of occupants and activity. In addition, it provided tools to determine whether the ventilation conditions achieved are adequate (Minguillón et al., 2020). In the same line, Allen et al. carried out a manual to measure the air renewal rate in classrooms (Allen et al., 2020). Villanueva et al. studied ventilation conditions and particulate matter in 19 childhood education, primary and secondary school classrooms located in the metropolitan area of Ciudad Real (Spain) during the reopening of schools after confinement. This study showed that preschool classrooms were the educational environments with the lowest average CO_2 levels (553 ppm), while secondary school classrooms had the highest average carbon dioxide concentration, with values close to 700 ppm (Villanueva et al., 2021). Similar work has been done by Zemitis et al. in secondary school in south-eastern Latvia. In this study, CO_2 concentration levels significantly exceeding 1000 ppm were obtained in all the classrooms studied. The average concentration was approximately 2380 ppm and even reached absolute maximum levels of 4424 ppm (Zemitis et al., 2021). Vassella et al. developed an intervention study to verify whether the recommended indoor air quality objectives can be achieved by following reasonable ventilation regimes that are also suitable for countries with cold winters. To this end, they first measured CO_2 levels in classrooms without any ventilation intervention and compared the effectiveness of natural ventilation during breaks only in 100 primary and secondary classrooms. It was found that the average CO_2 levels were reduced from 1600 ppm to 1097 ppm, demonstrating the effectiveness of ventilation in trying to control possible COVID-19 infection (Vassella et al., 2021). Finally, Asif and Zeeshan monitored and assessed indoor CO_2 levels in naturally ventilated classrooms in Pakistan, among other parameters. It was found that carbon dioxide concentrations exceeded those recommended by ASHRAE, even reaching values above 4000 ppm when the classrooms were occupied (Asif and Zeeshan, 2020).

Requirements for increased natural ventilation mean that thermal comfort conditions inside classrooms can be altered, especially when there are low temperatures outside, as is the case in the winter season. Environmental conditions assessment in schools has been addressed by different authors. A study by Alonso et al. analyzed the effects of the COVID-19 pandemic on thermal comfort and IAQ in winter. For this purpose, in situ measurements of environmental variables were carried out before and during the pandemic in two classrooms of a primary school located in southern Spain. The results showed a reduction of 400 ppm when the schools were naturally ventilated during all teaching hours. However, the analysis of standards shows that over 60% of hours are thermal discomfort conditions (Alonso et al., 2021). Heracleous and Michael evaluated the impact of natural ventilation on the indoor thermal environment through an extensive study conducted in both winter and summer in schools located in Mediterranean climate zones. For the winter period, students felt neutral or slightly cool, with mean wind chill values of −0.07 and a percentage of dissatisfied students of approximately 30% (Heracleous and Michael, 2020). In a study carried out in primary schools in the northern part of Sweden during the heating period, parameters related to thermal comfort were measured and the Predicted Mean Vote (PMV) was calculated (Yang et al., 2018). Finally, Jiang et al. developed a thermal comfort assessment model emulating different ventilation conditions in primary and secondary schools in rural China during winter. The result subsequently indicated that the comfortable temperature range for 90% of the pupils was 13–18 °C (Jiang et al., 2020). In terms of studies analyzing thermal comfort in settings other than educational establishments. For example, Pourshaghaghy and Omidvari evaluated the level of thermal comfort in several areas of a hospital in Iran. PPD values were higher than 10% in all areas of the building, with the worst thermal conditions in the surgery section (Pourshaghaghy and Omidvari, 2012). On the other hand, in hot climate zones, the use of techniques to cool the air is key to providing an acceptable level of comfort. Therefore, Yüksel et al. investigated how these measures affect a mosque in Turkey. The use of air conditioning improved the overall thermal sensation from a PPD of 40%–13% (Yüksel et al., 2020).

Most of the studies carried out so far in this field focus exclusively on the assessment of ventilation conditions when teaching in pre-school, primary and secondary schools. However, these studies do not take into account thermal comfort conditions for teachers and students, which could be significantly affected by an increase in the intake of colder air during ventilation in winter. Nor do they take into account special conditions such as exams, where, as a general rule, they take longer than theoretical and practical classes and, breaks and departure are not possible when necessary. On the other hand, university classrooms where teaching takes place are considerably more occupied and there are laboratory practices where measures to reduce the risk of infection may be more complicated to carry out. Also, depending on the age of the university students, specific CO_2 generation rates per person are required that have not been considered in other studies.

Based on the above, a study has been carried out to assess the indoor air quality and environmental conditions existing during on-site examinations in a higher education center located in the southwest of Spain during the January 2021 exams. For this purpose, ventilation conditions have been studied, establishing different strategies by measuring in situ the existing CO_2 concentration levels depending on the same and the number of occupants present in each classroom. Similarly, the ventilation rate and external airflow rate have been determined. It has also been examined how the measures adopted to try to avoid COVID-19 infections interfere with the thermal comfort of the occupants depending on their clothing and the type of activity carried out in the classrooms.

The results obtained have allowed us to discern the most effective ventilation strategies to maximize thermal comfort inside the classrooms.

2. Materials and methods

2.1. Description of the local context and sample design

The official closing date for university centers in Spain by COVID-19 took place on the 16th of March 2020. For the return to on-site university education scheduled for September of the same year, a contingency plan was established for educational places that included measures in strict compliance with existing WHO recommendations for infection control, mainly promoting frequent hand hygiene, ensuring regular cleaning of surfaces, maximising physical distance to maintain at least 1.5 m of interpersonal distance and increasing ventilation of indoor spaces. In addition, the use of face masks by students and teachers was obligatory throughout the entire period in all areas of educational centers (WHO, 2020b). It was also agreed that presential exams would be held at the universities during the 2020–2021 academic year.

For the assessment of IAQ and thermal comfort, a university center located in Extremadura, a region in the south-west of Spain, was selected (38°53′2.5″N, 7°00′11″), located in an area with a Mediterranean climate. Fig. 1 shows the location of the higher education institution understudy, while Fig. 2 shows the location of each of the classrooms studied. Additional elements such as photographs of some of the classrooms and the north facade of the building are also included in this figure. The January exam period, which ran from 11th to 29th January 2021, was chosen for the study because of the lowest outdoor temperatures during the winter season. Specifically, during the first half of the selected period, temperatures were notably colder due to the presence of the Filomena squall over the Iberian Peninsula (AEMET et al., 2021).

During this period, moreover, the 14-day cumulative incidence of COVID-19 in the area where the study was conducted was around 1500 cases, while in Spain it was approximately 890 cases per 100,000 inhabitants. This meant that all tests had to be carried out with the maximum possible ventilation as the situation was considered to be extremely risky (CCAES et al., 2021).

A total of 88 exams, some of them with several groups, were held in a total of 13 classrooms.

All classrooms in the selected sample had exclusively natural ventilation. Windows and doors remained open at all times in most examinations, except for those where a different ventilation protocol was established. In one case, windows were opened according to the CO_2 measurements that were recorded, and in other cases, windows were partially opened, specifical windows in front of the door.

Based on the above, the following criteria were taken into account for the selection of classrooms and examinations sampled. As the main criterion, classrooms, where ventilation strategies other than the total opening of doors and windows were carried out, were considered. Classrooms were also chosen where a higher number of exams were held and which were located on different floors of the building. On the other hand, examinations were considered for all the degrees taught at the university center under study and for all academic years, as these have a variable number of students.

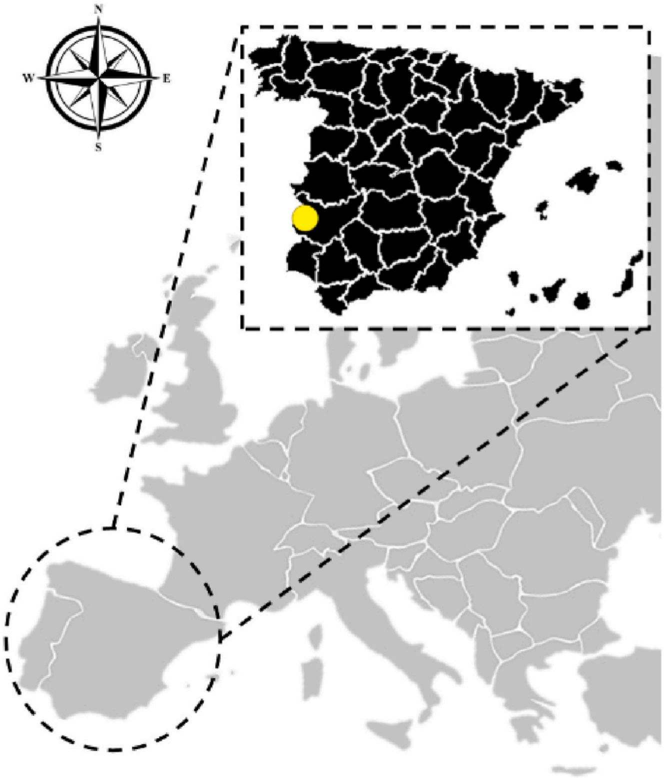

Fig. 1. University center location.

Thus, a total of 7 classrooms (53.8%) out of the 13 that were available for the exams held in January were analyzed (unselected classrooms have identical characteristics in terms of size and number of windows). Concerning the number of examinations, measurements were carried out in 18 of the 88 examinations planned (20.5%), of which 10 were in the morning and 8 in the afternoon. Different lengths of exams were also considered, some of them including a break.

It should be noted that, in morning exams, windows were opened 30 min before the exams started and remained open until the end of the afternoon exams.

2.2. Equipment for assessing ventilation and thermal comfort conditions

To evaluate the ventilation conditions in different classrooms during the tests, as well as to monitor the IAQ, the level of CO_2 concentration (in parts per million, ppm) was used as an indicator. In this study, a portable instrument was used to measure and record the existing CO_2 concentration (model PCE-AQD 20, PCE Instruments, PCE Deutschland GmbH, Meschede, Germany). The CO_2 measurement range was from 0 to 10,000 ppm, with a resolution of 1 ppm. Equipment accuracy is as follows: <1000 ppm: ±40 ppm, <3000 ppm: ± (50 ppm + 3% of the value), >3000 ppm: ± (50 ppm + 5% of the value). CO_2 concentration levels were measured and recorded at an interval of 2 s.

At the same time, a thermal environment meter (model HD32.1, DeltaOHM, GHM Group, Remscheid, Germany) was used to assess the microclimate in the classrooms during the exams. In this case, a combined probe for measuring air temperature and relative humidity, with a

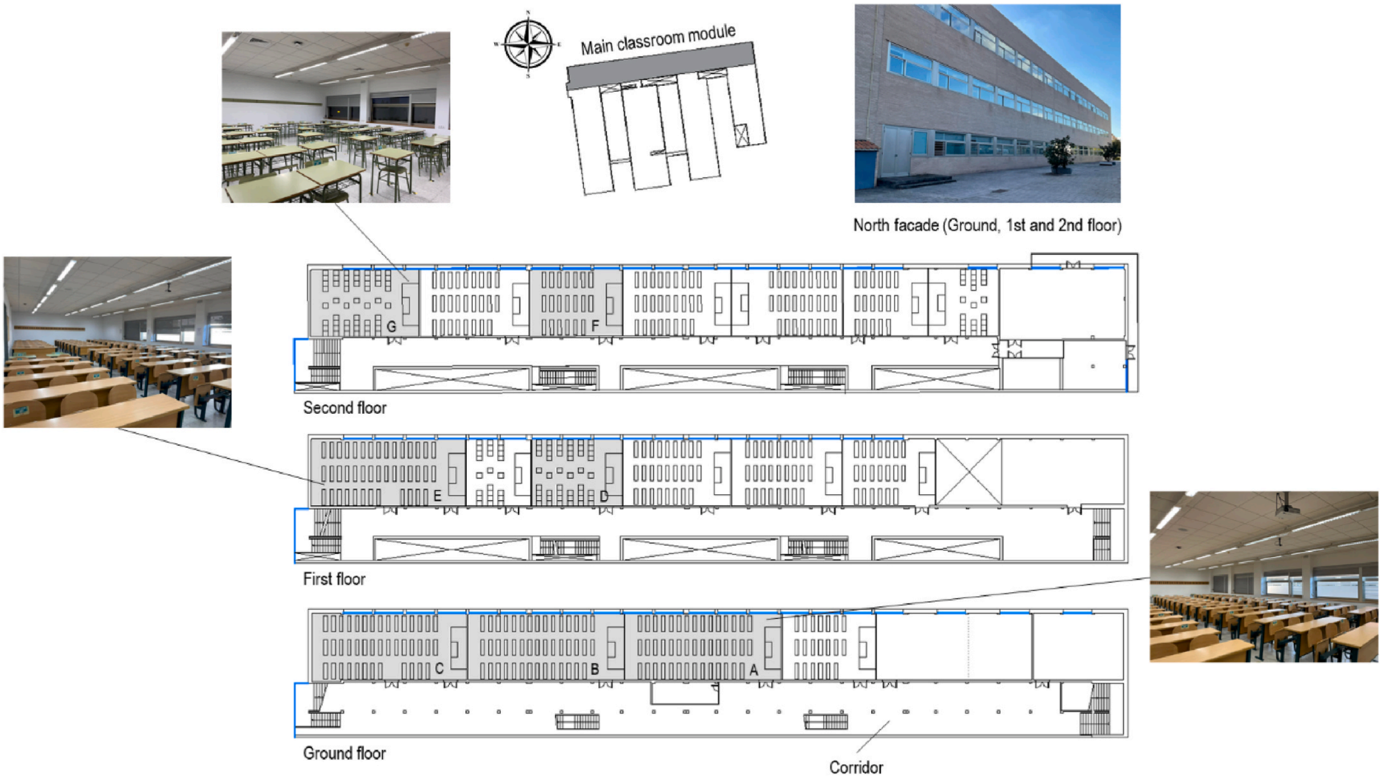

Fig. 2. Location of the classrooms studied in the university building.

measuring range of −40 °C to +100 °C; a probe for measurement of balloon temperature, with a measuring range of −10 °C to +100 °C; a sonde for radiant temperature recording, with a measuring range of 0 °C to +60 °C; and an omnidirectional hot wire probe for air velocity recording, with a measuring range of 0 °C to +80 °C. The atmospheric pressure measurement accuracy is ±0.5 Pa, with a response time of 1 Hz. The temperature measurement range of the instrument is −200 °C to +650 °C, with a resolution of 0.01 °C in the range ±199.99 °C and 0.1 °C and accuracy of ±0.01 °C in the range ±199.99 °C and ±0.1 °C in the remaining field. Finally, the relative humidity measuring range (capacitive sensor) is 0–100% RH, with a resolution of 0.1% RH and an accuracy of ±0.1% RH. DeltaLog 10 software associated with the device was used for data reading and processing.

Continuous monitoring of environmental parameters and CO_2 concentration of the classrooms was carried out throughout the duration of the selected exams. CO_2 measuring equipment was placed at the end of the classrooms, in order to avoid direct exhalation by the occupants (Heracleous and Michael, 2020), at a height that coincided with the breathing zones of the occupants, keeping a distance of at least 1.5 m from walls and at least 1 m from people (Griffiths and Eftekhari, 2008; WHO, 2020a). Thermal environment measuring equipment was placed in the central part of the rooms in order to representatively assess the microclimate present during tests (AENOR, 2002; Yang et al., 2018). Both types of equipment were set up and activated 15 min before the students entered the classroom for exams to ensure the steady-state of the measurements. Air temperature, relative humidity and outdoor CO_2 concentration were measured before and after each test. Data on outdoor airspeed were obtained from the Spanish State Meteorological Agency (Agencia Estatal de Meteorología, AEMET) (AEMET, 2021).

2.3. *Building's general characteristics and indoor spaces under study*

The university center understudy has a built surface area of 13,055 m^2 and a useable surface area of 11,418 m^2, distributed over 4 floors. All classrooms in this building only had natural ventilation. Interior partitions between classrooms are made of concrete blocks with a direct plasterboard backing. The building has a hot water radiator heating system, which was kept on during the sampling.

Fig. 3 shows the geometry of each of the classrooms studied, as well as the location of the measuring equipment used. All the windows are shown in blue. All classrooms are rectangular and have openings for cross ventilation, described as the best approach to natural ventilation. Slight differences in the dimensions, shape and configuration of openings may influence the ventilation efficiency (Chenvidyakarn and Woods, 2005; Lee and Choi, 2002), but since all classrooms are cross-ventilated and similar in shape, this aspect was not considered in the work. Windows face north, opening to the outside where there is a one-storey building in the immediate vicinity. They have two leaves of 1.10 m and 2.05 m, respectively. Exit doors from classrooms are double doors, each 90 cm wide, leading to the school's interior corridors.

For each classroom, the following information was collected: starting time of the test, the classroom type (A, B, C, D, E, F and G), the floor on which it is located (0-ground floor, I-first floor, II-second floor), classroom area and volume, test duration, number of students and teachers, percentage of occupancy over the COVID-19 capacity (already reduced to 60% of the maximum occupancy of the classrooms), occupancy/volume ratio (O/V), number of windows and doors, ventilation strategy adopted (1-door/s open and windows open, 2-door/s open and windows open according to CO_2 measurements, 3-door/s open and only one window open) and open area of windows and doors. According to the measured surfaces and ceiling heights, the assessed classrooms had volumes ranging between 250 and 410 m^3. Classroom occupancy ranged from 5 to 40 people (teachers + students). Therefore, the occupancy/volume ratio was between 0.01 and 0.10 persons/m^3.

In other studies, such as the one carried out in Ciudad Real (Spain), the average occupancy was 24 people in classrooms of approximately 60 m^2 (Villanueva et al., 2021), values significantly higher than in this study (with minimum ratios of 3.4 m^2/person and maximum of 22.5 m^2/person). Classrooms studied in Switzerland had a volume of 200 m^3, also smaller than almost all the classrooms analyzed, and the window

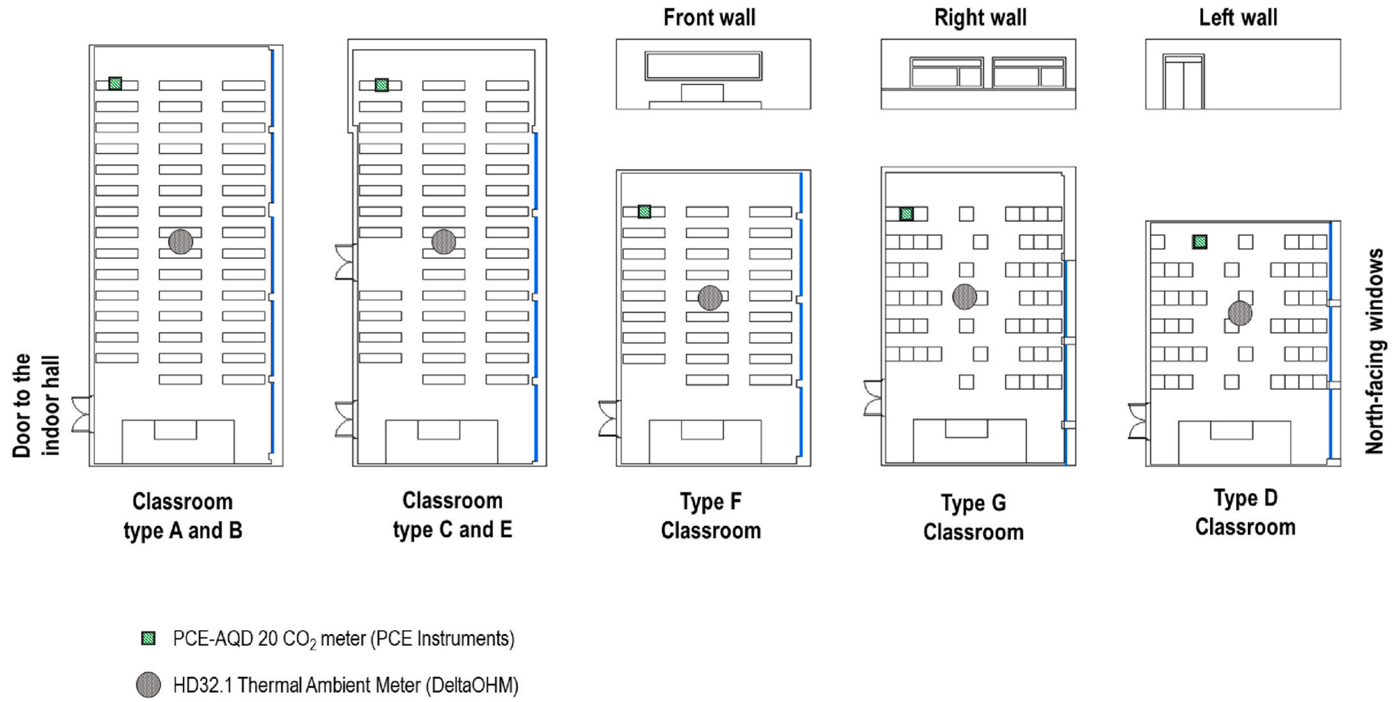

Fig. 3. Classrooms' geometry surveyed and location of measuring equipment.

area was 5 m^2, a higher value than the one available in this study (Vassella et al., 2021). In the work by Asif and Zeeshan, the classrooms' areas studied were significantly smaller (from 20.3 to 33.9 m^2) than those analyzed in this paper, and the open area of windows was also smaller. However, the average occupancy was around 20 people, so the stocking density was 1 m^2/person, slightly more than three times lower than the minimum in this work (Asif and Zeeshan, 2020).

Table 1 presents the data corresponding to various measurements made, including specific data to characterise the different tests that were carried out.

2.4. Reference values

In Spain, the UNE-EN 13779:2008 standard defined the requirements for ventilation and air-conditioning systems in non-residential buildings. This standard was the document on which the Regulation on Thermal Installations in Buildings (RITE) was based for this type of installation (AENOR, 2008). RITE classifies indoor air quality (IAQ) in four categories (IDA, Indoor Air), depending on the use of buildings, proposing in each case an outdoor airflow rate per person. Classrooms in educational establishments belong to IDA category 2, therefore an outdoor airflow of 12.5 l/s per person is recommended (European Parliament, 2002; RITE, 2007). This value reflects good air quality. However, to reduce the risk of COVID-19 infection, an outdoor airflow of 14 l/s per person per second is recommended (Ministerio de Sanidad and Gobierno de España, 2020). Both ASHRAE in ASI/ASHRAE 62.1–2019 and the Harvard Guide recommend a rate of 5–6 ACH for classrooms between 80 and 100 m^2 and 25 students (Allen et al., 2020; ASHRAE, 2019).

As mentioned above, one measure used as an indicator of IAQ is to use the CO_2 concentration level. For each indoor air quality category, the RITE sets permissible limit values for carbon dioxide concentration (in ppm) above the CO_2 concentration in outdoor air. For category IDA 2 it is recommended not to exceed a carbon dioxide concentration of 500 ppm above the CO_2 levels in the outdoor air (AENOR, 2008). A carbon dioxide concentration corresponding to an IDA 1 category establishes an optimal indoor air quality that is obtained with CO_2 concentration values below 350 ppm (measured over the outdoor CO_2 concentration). On the other hand, CO_2 levels above 800–1000 ppm (measured over the outdoor CO_2 concentration) could be an indicator of poor indoor ventilation. However, this CO_2 concentration is far from being harmful to human health and should only be interpreted as an indicator of the need for ventilation (Ministerio de Sanidad and Gobierno de España, 2020).

Table 2 shows recommended values for the two measures used in the ventilation analysis in terms of indoor air classification (IDA), that is, outdoor airflow per person, and CO_2 concentration.

The average outdoor carbon dioxide concentration during the evaluated period was calculated according to Expression (1), which used outdoor CO_2 values obtained before and after each of the tests carried out and obtained a value of 450 ppm. Thus, the indoor CO_2 concentration of 450 ppm + 350 ppm was considered as an ideal level and 450 ppm + 500 ppm as an acceptable level, these values correspond to ventilation conditions for indoor spaces of category IDA 1 and IDA 2 (AENOR, 2008).

$$\overline{Outdoor\ CO_2} = \frac{\left(\sum CO_{2before} + \sum CO_{2after}\right)/2}{No.\ exam} \qquad (1)$$

RITE also establishes a recommended operating temperature in buildings of 21–23 °C in winter and 23 to 25 °C in summer, a relative humidity between 30 and 70% and an air velocity not exceeding 0.2 m/s (European Parliament, 2002; RITE, 2007).

Finally, and regarding thermal comfort, the UNE-EN 16798-1:2020 and UNE-EN 7730:2006 standards define four types of categories that relate Predicted Percentage of Dissatisfied (PPD) to Predicted Mean Vote (PMV) according to the level of expectation associated with different indoor environment classes (I-High, II-Medium, III-Moderate and IV-Low) (AENOR, 2020, 2006). Percentage values of dissatisfied people up to 10% reflect a satisfactory situation for the majority of people (90% satisfied), whereas higher values indicate a situation of thermal discomfort. This PPD value corresponds to the range between −0.5 and 0.5 indicated for the PMV (Fanger, 1970).

Table 3 shows the comfort limits for each of the categories.

Table 1
General characteristics of classrooms studied.

No.	Time (h)	Classroom type	Floor	Area (m^2)	Volume (m^3)	Test duration (h)	No. students	No. teachers	Occupation COVID-19 (%)	O/V Ratio (persons/m^3)	No. windows	No. doors	Ventilation strategy	Open window area (m^2)	Open door area (m^2)
1	16:30	B	0	135.50	406.50	1	23	1	17.35	0.06	5	1	1	2.51	1.80
2	9:00	F	II	95.56	286.68	2	13	1	16.47	0.05	4	1	1	1.95	1.80
3	16:30	E	I	135.50	406.50	2	39	1	32.74	0.10	4	2	1	3.80	3.60
4	9:00	A	0	135.50	406.50	3	20	1	16.48	0.05	5	1	1	3.80	1.80
5	9:00	E	I	135.50	406.50	2.40	31	2	29.64	0.08	4	2	2	Variable	3.60
6	9:00	E	I	135.50	406.50	3.25 (Break)	22	2	19.20	0.06	4	2	1	3.12	3.60
7	16:30	A	0	135.50	406.50	2 (Break)	9	1	7.14	0.02	5	1	1	1.90	1.80
8	9:00	F	II	95.56	286.68	2	5	2	8.24	0.02	4	1	3	0.68	1.80
9	9:00	C	0	135.50	406.50	1.5	28	1	26.20	0.07	4	2	1	3.22	3.60
10	9:00	F	II	95.56	286.68	2.25	14	1	17.65	0.05	4	1	1	1.80	1.80
11	16:30	A	0	135.50	406.50	1.15	5	1	4.05	0.01	5	1	1	3.31	1.80
12	9:00	G	I	83.50	250.50	1	4	1	10.34	0.02	3	1	1	2.27	1.80
13	16:30	B	0	135.50	406.50	2	21	1	15.90	0.05	5	1	1	3.81	1.80
14	9:00	B	0	135.50	406.50	2.25	10	3	9.40	0.03	5	1	1	3.82	1.80
15	16:30	D	II	65.50	196.50	2	4	1	7.89	0.03	3	1	1	1.63	1.80
16	16:30	B	0	135.50	406.50	1	5	1	4.34	0.01	5	1	1	3.71	1.80
17	9:00	C	0	135.50	406.50	3	33	1	33.88	0.08	4	2	3	1.61	3.60
18	16:30	A	0	135.50	406.50	2.2	11	1	8.57	0.03	5	1	1	3.85	1.80

Ventilation strategy: 1-door/s open and windows open, 2-door/s open and windows open according to CO_2 measurements, 3-door/s open and only one window open.

Table 2
Outdoor air flow rate and CO_2 concentration above external levels according to category IDA (AENOR, 2008).

Category	IAQ depending on the use of buildings	Measure 1: Outdoor airflow (l/s per person)	Measure 2: CO_2 concentration (ppm)
IDA 1	**Optimal air quality:** hospitals, clinics, laboratories and nurseries.	20	350
IDA 2	**Good air quality:** offices, residences, classrooms, etc..	12.5	500
IDA 3	**Medium air quality:** commercial buildings, cinemas, theatres, restaurants, gyms, computer rooms, etc.	8	800
IDA 4	**Low air quality**	5	1,200

Table 3
Discomfort limits by level of expectation (AENOR, 2020).

Category	Body thermal state	
	PPD (%)	PMV
I	<6	$-0.2 < PMV < +0.2$
II	<10	$-0.5 < PMV < +0.5$
III	<15	$-0.7 < PMV < +0.7$
IV	>15	PMV <0.7 or 0.7 < PMV

2.5. Calculation protocols

2.5.1. Determination of ventilation rate and real outdoor airflow rate

Ventilation rate was estimated by the tracer gas method using CO_2 generated by the occupants themselves as tracer gas (Batterman, 2017; Remion et al., 2019; Schibuola et al., 2016).

This method is based on the mass balance equation according to which the change in the amount of tracer gas present is obtained by the difference between that generated plus that introduced and that eliminated, as shown in the following differential equation (Almeida and De Freitas, 2014; Griffiths and Eftekhari, 2008; Krawczyk et al., 2016).

$$V \cdot \frac{dC(t)}{dt} = G + Q \cdot C_{ex} - Q \cdot C(t) \tag{2}$$

Where V is classroom volume (m^3), C(t) is the concentration of the tracer gas at time t (ppm), t is time (s), G is the tracer gas generation rate (l/s), Q is the exchange rate between inside and outside, that is, the actual renewals occurring (m^3/s), and C_{ex} is the outside concentration of the tracer gas (ppm).

Carbon dioxide density to air is 1.53 and the reference value is 5000 ppm (AENOR, 2008, INSHT, 2006b).

CO_2 generation rate per person (in l/s) was calculated by considering the volume of carbon dioxide from human respiration, which was calculated from the following expression (Luo et al., 2016; Sarbu and Sebarchievici, 2013).

$$V_{CO_2} = 0.83 \cdot \frac{0.00276 \cdot A_D \cdot M}{0.23r + 0.77} \tag{3}$$

Where M is the metabolic rate, also defined as the level of physical activity (met); r is the respiration coefficient (dimensionless) and is defined as the ratio between the volumetric rate at which CO_2 is produced and the rate at which oxygen is consumed, its value depends mainly on the diet (0.83–1.0) (Black et al., 1986; Wright and Wang, 2010) and A_D is the DuBois surface area (m^2) calculated from the height (H) in meters and body mass (W) in kg as follows:

$$A_D = 0.202 \cdot H^{0.725} \cdot W^{0.425} \tag{4}$$

CO_2 generation rate per person depends on age, gender, weight and metabolic activity. For teachers with a light and low activity level and an age range of 40–60 years, a value of 0.0062 l/s was selected, while for students with light activity level and an age range of 16–30 years, a value of 0.0057 l/s was selected (Persily and de Jonge, 2017).

The analytical solution of equation (2) is shown below, where C_{in} is the initial concentration of the tracer gas.

$$C(t) = C_{ex} + \frac{G}{Q} + \left(C_{in} - C_{ex} - \frac{G}{Q}\right) \cdot e^{-\left(\frac{Q}{V}\right)t} \tag{5}$$

To solve equation (5), the steady-state method was chosen to be used (Batterman et al., 2017; Haverinen-Shaughnessy et al., 2011; Zhong et al., 2019). This method is based on the assumption that steady-state and well-mixed conditions are achieved. Furthermore, it assumes that the CO_2 generation rate (that is, the occupants' number and activity) is constant over a sufficiently long time to reach the indoor equilibrium concentration. It also assumes that outdoor CO_2 concentration and ventilation rate remain constant during the measurement period (Batterman, 2017; Bekö et al., 2016).

ASTM (ASTM, 2018) suggests that the measured indoor equilibrium concentration C_{ss} should reflect at least 95% of the equilibrium value (that is, it is reached after 3 air changes). Using the mass balance equation, the steady-state concentration can be expressed as (Luther et al., 2018):

$$C_{ss} = C_{ex} + \frac{N \cdot G_p}{Q} \tag{6}$$

Where C_{ss} is the steady-state concentration (ppm), N is the number of persons present and G_p is the average CO_2 generation rate of a person (ml/s).

Considering that all the tests performed lasted longer than 45 min and that during at least that time the number of students in the tests remained constant, the conditions for reaching steady-state are fulfilled. In addition, in all cases the number of air renewals, as will be calculated later, was well above 3 (Hänninen et al., 2017; Persily, 2018).

C_{ss} was determined as the maximum average concentration over 5 min within the study window (Batterman, 2017). C_{ex} was calculated as the mean value of the outdoor CO_2 concentration measurements taken for 5 min before and after each of the tests analyzed. As could be seen, the mean difference between the CO_2 values before and after the tests was not more than 4%, so this assumption was considered acceptable.

The air exchange rate in the classroom was obtained by using the following expression:

$$ACH = \frac{3600 \cdot Q}{V} \tag{7}$$

Once the real ventilation rate per test was obtained, the outdoor airflow rate per person was calculated. Real outdoor airflow rate, V_R (l/s per person), was calculated as:

$$V_R = \frac{10^{-3} \cdot Q}{No.\ persons} \tag{8}$$

2.5.2. Determination of the steady-state objective CO_2 concentration

Objective CO_2 is defined as the predictable CO_2 concentration based on enclosure volume and occupancy if a given number of ACHs of clean air from the enclosure were to be performed (Allen et al., 2020). If the measured CO_2 concentration is similar to the steady-state concentration, the ventilation objective is satisfied. If the CO_2 concentration is higher than the steady-state concentration, the air exchange target is not reached and ventilation conditions should be revised. Given the variations in concentrations over the measured period, it is reasonable to assume a 20% deviation from the objective value before taking drastic actions (Minguillón et al., 2020). The target CO_2 value allows the establishment of a limit reference for ventilation control, as it indicates the CO_2 level that must not be exceeded to guarantee an adequate level of ventilation, as proposed by Ilyas et al. (2015).

The calculation of the steady-state target CO_2 concentration was carried out considering the values of the outdoor CO_2 concentration (C_{ex}) and CO_2 generation rate per person described in the previous section. Steady-state objective CO_2 (ppm) concentration was obtained using the following formula, where $ACH_{objective}$ is the number of ACH required to ensure adequate ventilation.

$$C_{steady-state\ objective} = C_{ex} + \frac{3600 \cdot N \cdot G_p}{ACH_{objective} \cdot V} \tag{9}$$

In this work, steady-state objective CO_2 concentration was calculated considering two situations, in the first case, the values of this parameter were determined for 5 ACH and in the second, the values for reaching an outdoor airflow of 14 l/s per person. In this second case, it was previously necessary to determine the number of renovations required for this outdoor air supply per person, applying Expression (7) (Allen et al., 2020; ASHRAE, 2019; Minguillón et al., 2020).

2.5.3. Thermal comfort study

Thermal comfort is the state in which people consider themselves to be satisfied with their environment and can be assessed by a quantitative analysis through the heat balance model. It is therefore related to the overall heat balance of people and depends on physical activity and clothing, as well as air temperature, average radiant temperature, air velocity and relative humidity (AENOR, 2006).

PMV and PPD indicators are associated with the heat balance model. Former represents the predicted mean vote on the wind chill scale of a group of people exposed to a certain environment (Fig. 4). This implies considering as dissatisfied people those who voted cold (−3), cool (−2), warm (+2) or hot (+3) (AENOR, 2006; Fanger, 1970).

PPD establishes a quantitative prediction of the percentage of people who will not feel ambient satisfaction by noticing hot or cold sensations (Fanger, 1970). This was quantitatively calculated using Expression (10).

$$PPD = 100 - 95e^{\left[-\left(0.3353PMV^4 + 0.2179PMV^2\right)\right]} \tag{10}$$

Thermal comfort conditions during the tests could be affected due to the ventilation strategies adopted and the low temperatures outside during the time of the year under study, with temperatures below 10 °C inside the classrooms, so it is recommended to assess the risk of cold stress by calculating the IREQ (required clothing insulation) index. IREQ index is defined at two levels of physiological overload. On the one hand, IREQ minimum defines the thermal insulation required to maintain the thermal equilibrium of the body at a lower than normal average body temperature level and, on the other hand, IREQ neutral defines the insulation for a thermal equilibrium temperature level (AENOR, 2009).

For both PMV and IREQ calculations, the clothing of the classroom occupants was considered to correspond to the insulation of 1.56 clo and their metabolic activity level was assessed as a sedentary activity with a value of 69.78 W/m^2.

2.5.4. Analysis of the evolution of environmental parameters and thermal comfort indicators

Temporal evolution of CO_2 concentration levels and air temperature as a function of the number of students present in classrooms at each moment was analyzed for a sample of the most representative exams carried out according to the selected ventilation strategy. In addition, percentage dissatisfied (PPD) variation was collected as a function of the

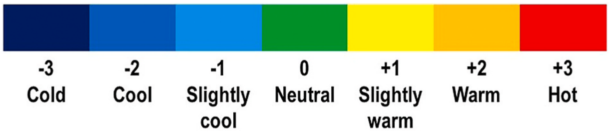

Fig. 4. Thermal value scale according to UNE-EN ISO 7730:2006 Standard.

existing environmental conditions and it was found how the reduction in occupancy over time affected the concentration of carbon dioxide.

The relationship between the different environmental and ventilation parameters was also assessed for each test, taking into account the classrooms in which exams were held and the average outdoor temperature.

3. Results and discussion

3.1. *Assessment of environmental conditions*

Table 4 shows the results obtained for relative humidity, temperature and air velocity before, during and after the performance of all the tests studied. Pre- and post-test measurements were taken outside near the school.

To the work carried out by Kephalopoulos et al., comfortable indoor classroom temperatures should be maintained, as far as possible, between 20 and 26 °C, regardless of the season and outside air temperature (Kephalopoulos et al., 2014). In this study, average indoor temperatures ranged from 6 to 21 °C. As can be seen, only three of the examinations (12, 15 and 16) had temperatures slightly above 20 °C and were therefore within the established range of comfortable operating temperatures. The maximum temperature obtained was in test 12, where 21.4 °C was recorded. It should be noted that in test number 4 the average temperature was 6 °C and there may be a risk of cold stress. The lowest temperature was recorded in this test (4.2 °C). According to the AEMET records for January, the average air temperatures were 8.6 °C. During the first half of the sampled days, average outdoor temperature was two degrees below the mean (6.5 °C) due to the presence of the Filomena squall and the subsequent cold snap (AEMET et al., 2021). The highest minimum temperature recorded indoors was 20 °C, which means that the minimum temperature for not feeling uncomfortable indoors, set by RITE at 21 °C in the winter season, was not achieved in any of the tests (European Parliament, 2002; RITE, 2007). In terms of indoor relative humidity, the average levels measured exceeded the recommended level for comfort inside the classrooms (42–50%) in 17 out of the 18 tests (Kephalopoulos et al., 2014), exceeding in two of them (14 and 15) the upper limit (70%) established by RITE for indoor spaces. Average outdoor relative humidity was 75%, while the absolute minimum and maximum indoor values were 36.1% and 73.8%, respectively. Average air velocity inside the classrooms did not exceed the 0.2 m/s set by RITE for enclosed spaces in any case (European Parliament, 2002; RITE, 2007). Test 4 recorded the absolute maximum value (0.57 m/s). Outside, an average velocity of 1.75 m/s was produced. In the study by Villanueva et al. where ventilation strategies were in place to prevent COVID-19 infection in classrooms, the average indoor temperature ranged between 18.7 and 21.2 °C. These values were significantly higher mainly due to the time of year in which the measurements were taken (30th September 2020 to 27th October 2020). Average relative humidity was around 45% in all cases (Villanueva et al., 2021). In other studies carried out during the winter season in Mediterranean climates, average indoor temperatures were recorded to be around 20 °C with outdoor temperatures between 10 and 14 °C. Relative humidity inside the classrooms was approximately 54%, whereas outside it was 60% on average (Almeida and De Freitas, 2014; Baloch et al., 2020).

3.2. *Assessment of ventilation conditions*

Table 5 shows the results for ventilation indicators. Outdoor CO_2 measurements taken before and after the tests gave an average value of 450 ppm.

Taking into account the method of assessing the concentration of CO_2 levels, none of the average values exceeded 700 ppm, so ventilation during the tests was sufficient. In most cases, 600 ppm was not exceeded, so the air quality was very good, in line with IDA category 1, except in one case. Maximum CO_2 concentration value (808 ppm) was measured during test 5, however, the tolerable limit of 950 ppm for IDA category 2 was not exceeded (AENOR, 2008). This point value was due to the ventilation strategy followed during this test, as detailed in section 3.5 of this work.

Villanueva et al. found average CO_2 concentrations of 539 ppm in pre-school classrooms, 565 ppm in primary classrooms and 661 ppm in secondary classrooms. These values were very similar to those obtained in this work (Villanueva et al., 2021). However, in the case of the research carried out in schools in Switzerland and Latvia, CO_2 concentration was much higher, with average values of around 2000 ppm, and consequently, air renewal in both cases was insufficient (Vassella et al., 2021; Zemitis et al., 2021). Comparing CO_2 concentrations, it can be verified that ventilation conditions in the present study are significantly better than those reported in most of the existing literature. CO_2 levels recorded in this research were, on average, 3 times lower than those recorded in these European classrooms. Moreover, CO_2 concentrations were found to be much lower, even compared to concentrations measured in classrooms located in other regions of Spain

Table 4
Environmental conditions.

No.	Temperature (°C)					Relative humidity (%)					Air velocity (m/s)				
	Outdoor conditions		Indoor conditions			Outdoor conditions		Indoor conditions			Outdoor conditions		Indoor conditions		
	Before	After	Average	SD	Max, Min	Before	After	Average	SD	Max, Min	Before	After	Average	SD	Max, Min
1	10.85	11.29	12.43	0.0516	13.3, 12.6	35.87	34.07	45.23	0.2622	45.9, 44.8	3.90	2.50	0.003	0.0360	0.19, 0.00
2	0.85	3.12	12.23	0.2339	12.6, 11.7	91.72	81.52	46.11	0.7947	48.3, 45.0	0.00	0.83	0.020	0.0259	0.20, 0.00
3	8.37	6.97	17.13	0.3910	19.0, 17.8	72.84	78.96	46.67	0.6957	48.8, 45.3	1.39	1.11	0.010	0.0159	0.18, 0.00
4	0.43	2.84	5.99	0.9888	8.4, 4.2	90.57	80.16	56.47	3.7080	63.7, 46.4	0.00	0.00	0.120	0.0726	0.57, 0.01
5	0.37	4.24	11.09	1.5278	14.1, 8.3	86.38	72.28	44.22	1.7957	48.6, 39.9	0.00	0.00	0.020	0.0331	0.24, 0.00
6	1.64	13.48	11.00	1.0920	13.1, 8.2	78.32	46.30	49.72	3.2809	55.0, 44.0	0.83	1.67	0.030	0.0515	0.43, 0.00
7	13.32	9.04	16.43	0.2932	16.8, 15.4	46.92	57.57	38.75	1.6399	42.1, 36.1	1.11	0.83	0.010	0.0078	0.12, 0.00
8	0.74	6.58	12.71	0.2922	13.1, 12.2	78.41	65.66	42.01	0.3598	43.0, 41.4	0.00	1.11	0.010	0.0135	0.10, 0.00
9	9.96	12.07	14.63	0.2519	15.2, 14.0	86.44	83.10	61.91	0.5917	63.5, 60.1	2.50	3.06	0.070	0.0563	0.37, 0.00
10	11.57	14.12	17.27	0.2344	17.6, 16.9	90.01	82.75	63.44	0.8759	65.7, 62.2	1.94	4.17	0.010	0.0162	0.11, 0.00
11	15.98	14.99	18.12	0.5472	20.4, 17.5	71.27	74.01	60.20	0.8867	61.4, 57.1	1.11	0.83	0.040	0.0537	0.27, 0.00
12	14.31	14.92	20.71	0.3138	21.4, 20.0	86.79	88.62	59.43	0.5240	60.7, 58.4	3.33	3.89	0.010	0.0182	0.12, 0.00
13	17.69	16.23	19.10	0.2668	19.5, 18.5	73.36	83.77	65.75	1.6659	69.1, 63.5	5.00	4.72	0.070	0.0658	0.39, 0.00
14	14.01	16.26	18.82	0.1683	19.2, 18.4	91.53	88.04	70.46	0.8770	72.0, 68.7	3.33	2.78	0.005	0.0120	0.08, 0.00
15	17.76	17.53	20.08	0.1301	20.2, 19.6	85.86	85.70	71.46	0.8674	73.8, 70.3	1.94	1.67	0.010	0.0175	0.18, 0.00
16	17.34	16.67	20.13	0.1341	20.6, 19.9	78.23	78.99	69.69	1.6338	71.3, 65.1	1.11	1.39	0.004	0.0142	0.11, 0.00
17	11.28	12.99	17.92	0.3017	18.5, 16.8	90.94	85.13	62.71	0.4693	64.2, 61.7	0.56	0.00	0.010	0.0157	0.13, 0.00
18	14.28	13.45	18.85	0.4807	19.8, 17.9	81.21	83.98	59.77	0.7298	61.3, 58.2	1.11	2.50	0.010	0.0154	0.12, 0.00

Table 5
Ventilation conditions.

No.	CO_2 Concentration (ppm)					Real ACH	Real outdoor air flow rate (l/s per person)	ACH (14 l/s per person)	Steady-state CO_2 5 ACH	Steady-state CO_2 14 l/s per person (ppm)
	Outdoor conditions		Indoor conditions							
	Before	After	Average	SD	Max, Min					
1	417.11	437.68	458.22	45.0084	596, 447	7.59	35.73	2.9756	784	872
2	430.84	473.80	581.12	20.5632	657, 537	6.33	36.03	2.4613	654	862
3	436.03	466.66	663.77	53.0558	766, 535	6.74	19.03	4.9594	856	859
4	441.59	449.13	476.56	17.9744	523, 426	19.36	104.11	2.6037	678	893
5	461.09	466.41	606.99	61.8121	808, 494	11.56	39.56	4.0915	799	873
6	467.82	465.81	588.17	35.6623	666, 474	9.01	42.39	2.9756	711	877
7	441.35	467.57	523.88	36.9387	612, 433	5.39	60.81	1.2399	556	865
8	470.47	448.48	590.49	26.1810	684, 539	2.89	32.90	1.2306	562	877
9	415.17	438.65	545.39	19.1457	605, 502	13.77	53.61	3.5956	721	835
10	433.46	445.37	567.49	20.7505	655, 517	6.34	33.68	2.6371	655	849
11	423.26	449.92	481.70	13.5933	508, 428	5.01	94.29	0.7439	498	850
12	435.20	452.89	487.17	12.1219	517, 448	5.10	71.04	1.0060	527	858
13	440.36	449.57	552.94	35.5575	627, 482	8.23	42.26	2.7277	668	854
14	443.79	465.47	540.46	21.6903	591, 488	5.96	51.74	1.6118	578	836
15	455.83	460.46	517.38	17.6648	568, 479	5.15	55.40	1.3023	532	741
16	445.63	447.34	463.17	10.1623	490, 434	5.28	99.37	0.7439	508	860
17	473.52	454.94	624.51	54.3999	714, 508	6.16	20.46	4.2155	808	872
18	440.66	468.88	509.07	17.3631	554, 472	10.56	99.33	1.4878	577	865

(Fernández-Agüera et al., 2019; Krawczyk et al., 2016) or in countries with similar climatic conditions, such as Portugal (Madureira et al., 2016). As indicated above, the calculation of steady-state CO_2 concentration provides an indication of the levels that should not be exceeded depending on classroom volume and the set air renewal rate and depending on minimum air supply per person. As could be seen, only in test number 8, the measured mean CO_2 concentration exceeded the steady-state objective for 5 ACH. Nevertheless, with the results for this parameter calculated for an input of 14 l/s per person, it could be seen that the situation was not problematic in any case the margin in all cases was quite wide, this was proven by the results corresponding to the estimated external flow, which exceeds the 14 l/s per person by far and the associated stable CO_2 levels, well above those measured in almost all cases. This showed that the recommendation to ensure at least 5 ACH may not be a good indicator when the occupancy of a classroom is low, as in the case of test 8, with adequate ventilation conditions and an actual number of renovations of 2.89.

This can be explained by the fact that ACH does not depend on the number of enclosure occupants and should only be used for occupancies in the average range. ACH values required for an input of 14 l/s per person calculated were less than 5 in all tests, with values of up to 0.74 ACH in tests 11 and 16, the tests with the lowest occupancy ratio (0.01 persons per m^3). These values contrast with real ACH values that were much higher in almost all tests. Exam number 4 had the highest number of real ACH (19.36 renewals) and the maximum outdoor airflow per person (104.11 l/s per person). As could be seen, the lowest temperatures were also recorded in this test, compromising the thermal comfort of the occupants. All other ACH values and outdoor airflow per person were higher than those established to try to avoid COVID-19 infections inside the classrooms (Allen et al., 2020). Along these lines, in other studies carried out for higher education buildings, between 3.7 and 39.8 outdoor air renewals were obtained depending on different ventilation configurations (de la Hoz-Torres et al., 2021).

3.3. Assessment of thermal comfort conditions

Table 6 presents corresponding results for the assessment of thermal conditions during the exams held in January.

As inferred from the results, more than half of the tests were carried out in comfortable conditions and the rest in slightly cooler conditions. Only one of the tests (exam 4) was carried out in conditions outside the discomfort zone. In this case, it was assessed whether the situation during the test could be qualified as cold stress. $IREQ_{min}$ and $IREQ_{neu}$ calculation values were 2.3 clo and 2.6 clo, respectively, and a recommended minimum exposure duration of 1.1 h and 1.5 h, respectively, which implies that with the test duration and clothing insulation considered, unsuitable situations could result (AENOR, 2009). Measured values indicated that PPD in tests was just over 17%, values that are not considerably higher than those considered in the comfort range (limited by a 10% dissatisfaction rate). In tests with discomfort, PPD was estimated to be between 25 and 35%. Average PPD in exam 4, the worst conditions, was just over 70%, although there were times when virtually all test takers were dissatisfied with the thermal environment conditions. In studies carried out by other authors in the same pandemic and

Table 6
Thermal comfort conditions.

No.	PMV			PPD (%)			Thermal sensation
	Average	SD	Max, Min	Average	SD	Max, Min	
1	−1.01	0.0195	−0.99, −1.17	26.39	0.8628	33.78, 25.64	Slightly cool
2	−1.04	0.0406	−0.99, −1.27	27.83	1.7997	38.50, 25.64	Slightly cool
3	−0.26	0.0613	−0.17, −0.58	6.46	0.7557	12.06, 5.63	Neutral
4	−1.90	0.9635	−1.41, −2.67	71.12	9.4957	96.36, 46.18	Cool
5	−1.20	0.1567	−0.85, −1.58	35.81	7.4978	55.35, 20.12	Slightly cool
6	−1.20	0.1330	−0.95, −1.67	35.58	6.4992	60.14, 24.22	Slightly cool
7	−0.43	0.7403	15.30, 13.80	8.93	1.0272	14.77, 7.87	Neutral
8	−0.97	0.0492	−0.90, −1.05	24.81	1.9976	28.47, 22.28	Slightly cool
9	−0.56	0.2737	−0.48, −0.96	11.62	1.7219	24.29, 9.84	Slightly cool
10	−0.12	0.0418	−0.06, −0.20	5.32	0.2210	5.87, 5.07	Neutral
11	0.05	0.0825	0.27, −0.22	5.20	0.3170	6.54, 5.00	Neutral
12	0.43	0.0360	0.50, 0.33	8.92	0.6524	10.31, 7.30	Neutral
13	0.24	0.0514	7.07, 0.03	6.24	0.4673	7.07, 5.02	Neutral
14	0.22	0.0194	0.27, 0.17	6.04	0.1675	6.50, 5.62	Neutral
15	0.43	0.0145	0.44, 0.29	8.79	0.2378	9.05, 6.79	Neutral
16	0.43	0.0128	0.45, 0.37	8.80	0.2060	9.22, 7.80	Neutral
17	0.06	0.0360	0.12, −0.07	5.09	0.0724	5.30, 5.00	Neutral
18	0.21	0.0511	0.32, 0.11	6.01	0.4644	7.08, 5.26	Neutral

climate context as this work, they showed that more than 60% of the hours analyzed there were situations of thermal discomfort, with PPD ranging between 20% and 70% (Alonso et al., 2021).

On the other hand, in the work carried out by Kumar Verma and Netam in a set of school buildings in India during three different times of the year, a PPD of 55% was obtained during the winter season. On the other hand, 95% of occupants voted for slightly cool and cold conditions (Kumar Verma and Netam, 2020). Wang et al. conducted surveys and

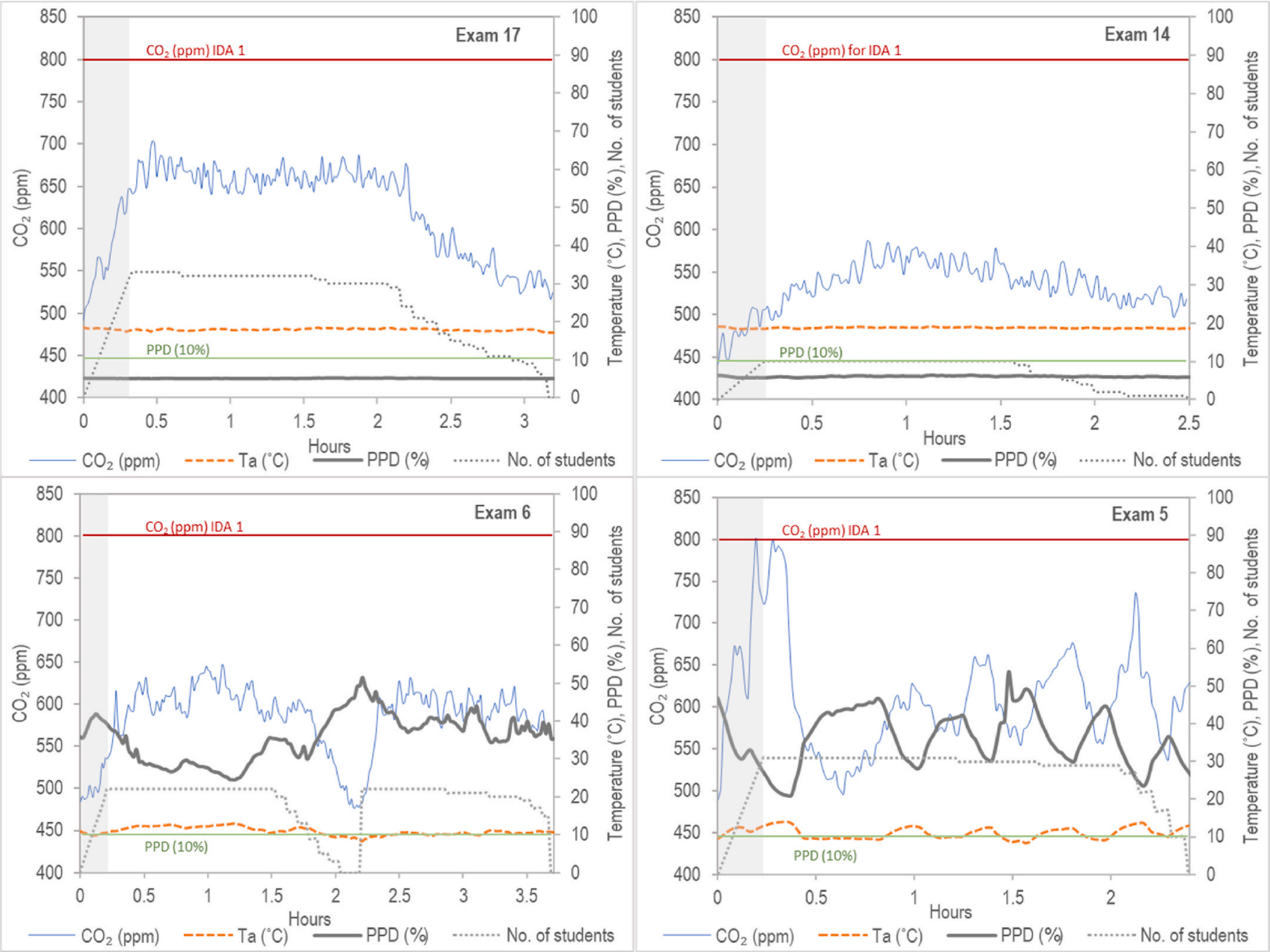

Fig. 5. Evolution of average CO_2, air temperature, PPD and number of students during tests 14, 6, 17 and 5.

took measurements in winter in three regions of China. The most similar climatic conditions to those studied in this study are in the Shaanxi area, where 38.1% of the students rated the environment as neutral, and 31.9% rated it as slightly cool, so the percentage of votes of 1 and 0 was 70%, while 16.9% of the students rated the environment as cool or cold. Among the 177 male students, the average wind chill was 0.42, and among the 168 female students, it was 0.48 (Wang et al., 2017).

3.4. Evolution of environmental parameters and indicators of thermal comfort

Fig. 5 shows the time evolution of different parameters measured in tests 14, 17, 6 and 5, respectively. This selection has been chosen as the most representative tests for CO_2 concentration, air temperature, percentage of dissatisfied and number of students. Each of these exams was conducted following different ventilation strategies and in one case with an intermediate break. In all cases, the shaded band shows the measurement period prior to the exam starting with durations of 20–30 min with a progressive entry of students into the classroom.

Exam 14 was conducted following the general strategy of opening doors and windows in the classroom to maximize ventilation. It took place in the morning and lasted 2.25 h. The number of students remained constant for just over an hour and then gradually decreased, with only two students remaining in class for the last half hour. In relation to CO_2 concentration evolution in the classroom, a continuous increase of this parameter could be observed, which approximately stabilized 1 h after the beginning of students' entry into the classroom. In the case of tests 17, 6 and 5 CO_2 concentration increase was faster, this could be due to the higher number of students present in these tests compared to test 14. Maximum CO_2 values did not reach 600 ppm and the average was 540.46 ppm so it can be considered as a situation with optimal IAQ conditions, it could also be observed that there was a decrease in the concentration as the students left the classroom (AENOR, 2008). Another relevant factor to consider is the ACH produced, which was 5.6 with an outdoor air intake value of 51.74 l/s per person, both values above the recommendations to limit the possibilities of COVID-19 contagion (Allen et al., 2020; Minguillón et al., 2020). Other studies using this same ventilation strategy have had between 7.4 and 9.4 outdoor air renewals for a 500 m^3 classroom and an occupancy of 48 people, 0.1 people per m^3. (de la Hoz-Torres et al., 2021). In relation to the thermal environment, a test was carried out with PPD values below 10% so conditions were comfortable (AENOR, 2006; Fanger, 1970), with classroom temperature being close to 20 °C throughout the duration.

Exam number 6 was conducted following the same strategy as the previous one, but in this case, there was an intermediate break with all students leaving the classroom for a period of about 20 min. The students remained constant in number until half an hour before the break when they were phased out and then all returned to the classroom. In this case, students' exit after the end of the exam was less progressive than in the case of exam 14. In relation to the evolution of CO_2 concentration in the classroom, it could be seen that this is marked by the evolution of students' numbers inside the room. There were two rises associated with students entering the classroom at beginning of the exam and after the break, with maximum values approaching 650 ppm and an average of 588.17 ppm. It could also be seen that, although the students leaving the classroom before the break and rest time allowed a reduction in CO_2 levels below 500 ppm, the values rose very quickly back up to pre-break concentration values. This showed that the effect of this stop was not significant on the IAQ during the test. The same effect was also found in the work of Zemitis et al. (2021). In relation to air renewals, these were 9.01 with a clean air supply per occupant of 42.39 l/s per person (values well above the minimum recommendations to guarantee adequate air quality and minimise COVID-19 infections) (Allen et al., 2020; Minguillón et al., 2020). Exams 6 and 14 were held in classrooms E and B respectively, with identical dimensions, but with a slight variation in the configuration of doors and windows. This factor, in addition to the fact that the number of students in exam 6 was more than double compared to exam 14, could have influenced the differences in the CO_2 concentrations measured. In relation to the thermal environment, according to the Fanger method, the conditions were uncomfortable, slightly cold, with an average dissatisfaction rate of 35.58%, so it can be concluded that this test was carried out in relatively uncomfortable conditions (AENOR, 2006; Fanger, 1970). This test was carried out in outside temperatures of a few degrees above zero, which meant that the conditions inside the classroom, with all the windows and doors open, were not suitable.

Exam number 17 was held in room C, a room with the same characteristics as room E (where exams 5 and 6 were held) but located on the ground floor instead of the first floor. It lasted 3 h and had 33 students. In this case, ventilation conditions were modified and only one of the existing windows was opened. CO_2 concentration evolution followed a similar profile as in test 6 but in the case of test 17, CO_2 levels reached were higher, with maximum concentrations of more than 700 ppm and average values of 624.51 ppm, values that were still within the quality parameters for air classified as IDA 1 and within the recommendations to avoid COVID-19 infections (AENOR, 2008). Considering the ACH, 6.16, and the clean air supply per person, 20.46 l/s, also these criteria indicated that those conditions (although tighter than in the previous review) remained within recommendations (Allen et al., 2020; Minguillón et al., 2020). In relation to the thermal environment, it was not problematic, average PPD of 5.09% (AENOR, 2006; Fanger, 1970). In this case, in addition to the different ventilation strategies, the outside temperature, which averaged about 12 °C, played a decisive role.

Finally, exam number 5, which, like exam number 6, took place in room E, lasted 2.40 h and was taken by a total of 31 students, more than the 21 students who took exam number 6. In this case, windows were opened and closed according to the CO_2 levels measured (windows were opened when CO_2 values approached 650 ppm). CO_2 concentration evolution followed a profile of rises and falls associated with the moments with and without window opening, with a maximum peak at the beginning of the test slightly exceeding 800 ppm (value corresponding to IDA 1) and successive lower peaks between 650 and 700 ppm, with the average concentration during the test being 606.99 ppm, all values above those recorded in tests 6 and 14. In this case, the air renovations were 11.56 and the outdoor air supply was 39.56 l/s per person, conditions that can, as in the other tests described above, be considered adequate (Allen et al., 2020; Minguillón et al., 2020). Along the same lines, Vassella et al. showed that opening the windows for 10–15 min every hour reduced the average CO_2 concentrations to the values that would be obtained if the windows were kept constantly open, thus maintaining the indoor temperature of the classroom at appropriate levels (Vassella et al., 2021). In relation to thermal comfort, the opening and closing of the classroom windows led to similar discomfort values in tests 5 and 6, with outside temperatures between 4 and 5 °C lower. In any case, although reduction of ventilation improved indoor thermal conditions, they remained uncomfortable (AENOR, 2006; Fanger, 1970).

After describing and comparing the evolution of different parameters for four tests performed, the results were compared considering the average values measured in the different classrooms.

Fig. 6 shows the mean values measured for PPD and the air changes for the tests carried out in each of the classrooms analyzed. Also shown in the graph are two lines marking the recommended ACH levels (AENOR, 2008; Minguillón et al., 2020) and PPD levels to be in the comfort zone (AENOR, 2006; Fanger, 1970). The graph shows, as already indicated, that more than half of the classrooms had a dissatisfied percentage of less than 10%, indicating that they were conducted in comfortable conditions, with an ACH higher than the 5 recommended by the RITE (except in one case) (European Parliament, 2002; RITE, 2007). On the other hand, although not decisive, an increase in discomfort was observed in many cases when the ACH was increased, in cases where a

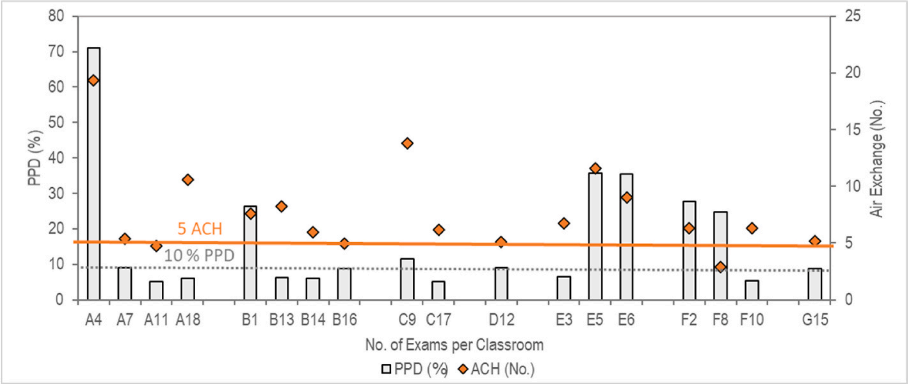

Fig. 6. PPD and ACH for different tests (Letter - Classroom type, Number - Exam No.).

cold outside temperature was combined with a high number of ACH, which produced the worst situations of discomfort (tests 4, 5 and 6). In particular, test 4, the worst test for comfort conditions, was the one with the lowest combined outdoor temperatures and highest ACH values. However, in those situations where the outside temperature was higher, the renovations did not significantly affect discomfort. Comparing tests 1 and 13, both with a similar number of renewals, it could be seen that outdoor temperatures of around 11 °C in test 1 compared to values close to 17 °C in test 13, caused the number of dissatisfied people to rise significantly in the former case.

Fig. 7 shows outside average temperature and ACH values versus PPD for each of the tests analyzed. Plotting the line of fit (with R^2 values of 0.5839 and 0.4576, respectively) shows a higher influence of the outside temperature on comfort than that of the ventilation level.

Fig. 8 presents the values corresponding to the minimum outdoor temperature, minimum indoor temperature and occupancy rate for the tests carried out in the different classrooms analyzed. Average indoor temperature was determined by the characteristics of the heating system, outdoor temperature, ventilation and classroom occupancy. Considering classroom F results in tests 2 and 8, in the first case similar average indoor temperatures were achieved with lower average outdoor temperature and occupancy values. This effect was smaller when average outdoor temperature values were increased, as was the case in all tests in classroom B where the differences in average indoor and outdoor temperatures were similar at quite different occupancy levels. About classroom E, it was observed that similar temperature levels were achieved in tests 5 and 6 with much lower outside temperatures in the first case. This may have been due to the higher occupancy level, but in this case, it was considered that it also affected the window opening and closing strategy during the test. The permanent closure strategy of part of the windows applied in tests 8 and 17 showed that the effective of this strategy, as mentioned above, had much less effect at higher outdoor temperature levels.

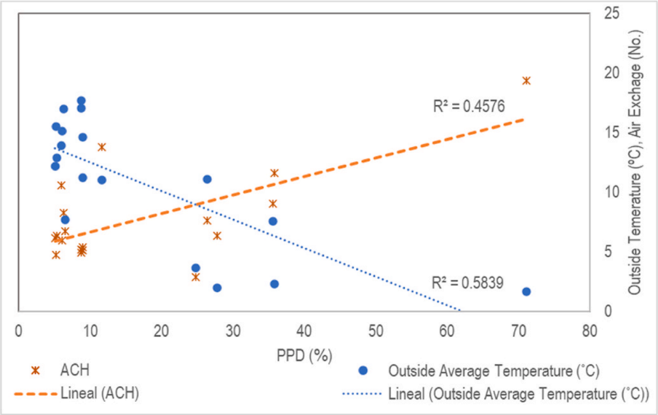

Fig. 7. Influence of temperature and ACH on PPD.

Fig. 9 shows the values for the parameters maximum CO_2 concentration, mean indoor temperature and PPD. Data were grouped according to whether the average external temperature was up to 6 °C, between 6 and 12 °C or above 12 °C. From an analysis of data, it was found that at outdoor temperatures above 12 °C in all cases the PPD indicated comfortable conditions (AENOR, 2006; Fanger, 1970). CO_2 concentration levels were in all these cases very close to 500 ppm, with the highest CO_2 concentration values occurring in test 17, where a strategy of closing part of the windows was applied, which in this case was not considered necessary. Similarly, temperatures below 6 °C have always caused discomfort conditions, in this case, strategies such as closing part of the windows or opening and closing them may be of interest, as they improve the environmental conditions even if comfort is not achieved. In the case of very low temperatures, as was the case in test 4, excessive ventilation was not justified as it led to very cold conditions without the required air quality or outside air supply. In the range between 6 and 12 °C, the comfort/discomfort conditions were determined by other factors such as occupancy, as in the case of test 3, which improved thermal environment conditions but worsened air quality.

3.5. Limitations and future work

The study focused on the analysis of the adequacy of ventilation by the general air quality recommendations for educational centers and those specified to limit coronavirus infections and how they influenced thermal comfort conditions during examinations in winter periods. This limits its extension to other situations where windows do not have to be permanently open or other seasons. It would be interesting to extend the study to other periods.

The building analyzed has a specific location and characteristics, so the results could not be fully extended to other university centers on the campus. It would be interesting to extend the study to other buildings to compare results.

About the methods used, each class was assumed to be a separate zone with well-mixed indoor air and could be characterised by a single measurement, this should be confirmed. The stationary method was chosen and a constant value for the CO_2 concentration of the inlet air was considered, it would be interesting to perform the analysis using other methods such as decay or transient mass balance and continuous measurement of the outside CO_2.

The use of occupant-generated CO_2 as a tracer gas has many advantages but can lead to untested measurement errors. The use of injected tracer gases could be of interest.

Concerning the assessment of thermal comfort, standard-based methods were used and it would be interesting to assess the actual perceptions of the occupants using questionnaires.

No account was taken of how factors relating to differences in the

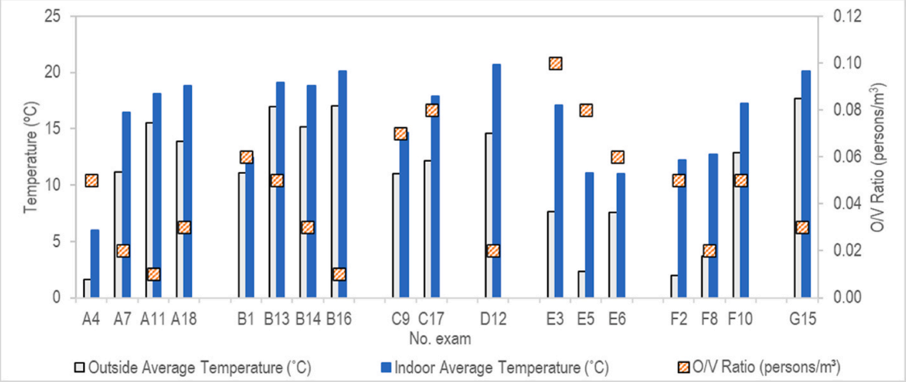

Fig. 8. Minimum indoor and outdoor temperature and occupancy rate for different exams (Letter - Classroom type, Number - Exam No.).

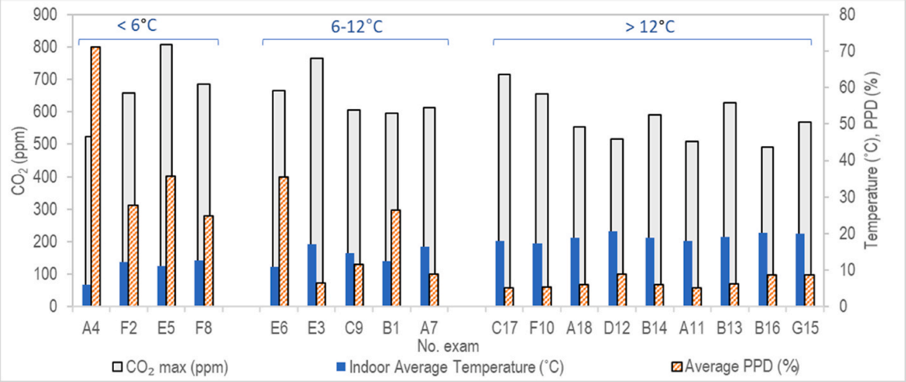

Fig. 9. Average CO_2 concentration, average internal temperature and PPD for different tests (Letter - Classroom type, Number - Exam No.).

shape and configuration of openings in the classrooms analyzed might affect them.

Finally, this study focused on the assessment of ventilation and thermal comfort, it could be interesting to extend it also to the measurement of particulate matter.

4. Conclusions

Like many other workspaces, on-site university teaching has been seriously threatened and modified in times of COVID-19. In this scenario, there are doubts about the appropriateness of returning to classroom-based teaching and assessment models. The uncertainty that a return to normality may cause justifies this study, which objectively analyses the risk of on-site assessment in times of pandemic.

After the analyses performed, it can be concluded that the different ventilation strategies were correct in terms of CO_2 concentration in all tests performed, with average CO_2 concentration levels of between 450 and 670 ppm. In no case was the limit value set for category IDA 2 buildings, corresponding to educational establishments, exceeded, and in almost all cases an optimal IAQ corresponding to category IDA 1 was achieved. The maximum CO_2 concentration value recorded in one of the tests was 808 ppm. However, these measures affected the thermal comfort of the occupants when outdoor environmental conditions were more unfavorable. In most cases, the number of real ACH above the recommended 5 for adequate ventilation was given. On the other hand, if the outdoor airflow per person is taken into account, in all cases values higher than the minimum established to try to avoid COVID-19 infection inside the classrooms, set at 14 l/s per person, were calculated. In this sense, it can be affirmed that the presential evaluation, in the terms in which it was carried out, does not put at risk the safety and health of students and teachers.

In other words, about the ACH value, it was considered that it is not a representative parameter for assessing IAQ when classroom occupancy was low. On the other hand, the occupancy ratio of all tests did not compromise the conditions set for a correct IAQ and had a slight influence on thermal comfort.

Analyzing in more detail the differences that occurred between different tests analyzed, when outside temperature levels were above 12 °C all tests were carried out in acceptable conditions of comfort irrespective of outside air supply or classroom occupancy, with a dissatisfaction rate of less than 10%. A significant influence on thermal comfort was observed for air changes when temperatures were below 6 °C, where a dissatisfaction rate of between 25 and 72% was observed. This influence was not noticeable at temperatures above 12 °C. At temperatures below 12 °C, it is recommended to establish a ventilation strategy with opening and closing of windows or to limit the number of open windows. This strategy should be complemented by the installation of CO_2 meters (preferably with measurement of concentration values) to manage the strategy. At temperatures above 12 °C, it is recommended to choose the complete opening of glazed openings if the risk situation is high, as thermal comfort is not significantly compromised. With low risks of infection, strategies of gradual opening and closing of windows can be chosen to avoid excessive energy losses.

Therefore, in moderate or hot climates, there is no high cost, in terms of comfort, to carry out on-site tests with security guarantees. However, it is recommended that these on-site tests be limited to times or time slots with very low outside temperatures, considering alternatives such as holding these assessment tests in afternoon hours (normally with milder temperatures) or avoiding them on the coldest days of the calendar. In seasons other than cold, the infection risk is not increased by using on-site evaluation while respecting distance and ventilation protocols, without compromising the thermal comfort of the students.

Ultimately, bearing in mind that ventilation protocols are still active in many countries, it is recommended that a strategy of generally opening windows when outside temperatures are mild should be considered in successive exams.

Declaration of competing interest

The authors declare no conflict of interest relating to the material presented in this article its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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