CO_2 MEASUREMENTS FOR UNCONVENTIONAL MANAGEMENT OF INDOOR AIR QUALITY

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ABSTRACT

Carbon dioxide (CO_2) is a known global pollutant and is responsible for the global warming that the planet has been experiencing for the last few decades. On a local scale, outdoor CO_2 does not pose any risk for the environment and humans. Risks are usually far from involving human beings in the majority of indoor environments, although high CO_2 concentrations may entail temporary adverse effects that are similar to the typical symptoms of the so-called "sick-building syndrome". Such effects become even more important on workplaces or at school/university, since high CO_2 levels may negatively influence the productivity and the learning capability of individuals. To understand the magnitude of the problem, a monitoring campaign was carried out in four classrooms and in a library of a university in northern Italy. Three of the classrooms under observation were not equipped with an air extraction system. The CO_2 concentration was monitored with low-cost non-dispersive infrared digital sensors in two periods of the year: between February and March and at the end of May. During those periods, the number of occupants, temperature and relative humidity were also monitored, as well as any opening of the windows (where available). The results showed that, where automatic air extraction is not available, CO_2 concentrations can exceed 5,000 ppm. In general, the lower the ratio between the room volume and the number of occupants, the higher the concentrations achieved. The installation of low-cost sensors might prove useful to prevent the negative effects from the exposure to high CO_2 levels and help achieve more sustainable conditions in indoor spaces, since the sensors could inform lecturers and students on the need for opening doors and/or windows when air extraction is not provided.

Keywords: carbon dioxide, indoor air quality, comfort, exposure, sustainability, ventilation, air quality monitoring.

1 INTRODUCTION

According to the World Health Organization (WHO), on average, people spend about 90% of their daily time in indoor environments [1]. In the light of such outcome, the air quality in schools, workplaces, houses and other indoor spaces is then crucial to limit the personal exposure to air contaminants [2]–[5]. In addition, cohort studies revealed that indoor air pollution is correlated with an increase in mortality, due to respiratory morbidity [6]. Poor indoor air quality is at the basis of the so-called sick-building syndrome (SBS), i.e. an ensemble of symptoms (e.g. loss of attention, fatigue, pains and allergic symptoms) that are associated with the staying of an individual in his/her workplace or house [7], [8]. Contrarily to the outdoor space, indoor environments, if not adequately built, may contribute to increase the concentrations of air contaminants that comes from outside [9] or that are generated indoors, especially if the ventilation and the rate of exchange of the indoor air are weak. Indeed, similarly to outdoor environments, ventilation acts as the main dispersion mechanism in indoor spaces [10].

The indoor air can enrich with several air pollutants: particulate matter [6], volatile organic compounds [11], nitrogen dioxide [12] and ozone [13] are some of the most common air contaminants that have been studied in indoor environments so far. Such pollutants can enter an indoor space from outside by infiltration through doors and windows or simply when doors and windows are opened. If the outdoor concentration of contaminants is higher than

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the indoor concentration, the latter increase. If no forced aeration system is present, the contaminants may stagnate inside the indoor environment. Consequently, the human exposure to air pollutants may increase with respect to outdoors [14]. As an example, Gonzalez-Flesca et al. [15] found out that the personal exposure to benzene measured in four French urban areas was 3.5 times higher than the mean outdoor concentration.

In addition to external contributions, the indoor air is strongly influenced by indoor sources. Cooking, biomass burning for heating and cooking purposes, natural-gas burners, cigarette smoke and new furniture are known sources of particulate matter, carbon monoxide, nitrogen dioxide, polycyclic aromatic hydrocarbons, dioxin and volatile organic compounds [16]. Besides those air contaminants, in the recent years the scientific community has paid growing attention to a substance that has not been traditionally accounted for when investigating the air quality of confined environments: carbon dioxide (CO_2). The global effects of such substance on the environment are well known. On a local scale, with the exception of specific workplaces (e.g. fermentation tanks), CO_2 does not pose direct risks for human health. However, in indoor environments, CO_2 may assume the features of an indoor pollutant, since it promotes the occurrence of some of the symptoms of the SBS. Indeed, high concentrations of CO_2, within certain limits, induce negative (though reversible) effects on humans, such as decrease of attention, reduced productivity and physical discomfort [17].

The concentration of CO_2 in the outdoor environment is normally in the range 300–400 ppm. The generally weak ventilation that characterises indoor environments with occupants leads to higher values. According to the German Indoor Air Hygiene Commission and the Working Group of the Supreme Health Authorities of the Federal States, CO_2 concentrations may be regarded as “hygienically insignificant” (<1,000 ppm), “hygienically evident” (1,000–2,000 ppm) and “hygienically unacceptable” (>2,000 ppm) [18]. The German Federal Environment Agency’s Indoor Air Hygiene Commission declares that rooms exceeding a CO_2 concentration of 1,000 ppm should require an exchange of air. Such an advice becomes an obligation if the concentration exceeds the value of 2,000 ppm [19]. Further works concluded that concentrations above the “hygienically insignificant” range might negatively influence the learning ability [20]. Headache, loss of attention and sleepiness are symptoms related to higher concentrations, up to 5,000 ppm [21]. As previously mentioned, mortality is associated with extreme conditions, i.e. where CO_2 is so abundant that oxygen becomes limited [22]. Although such extreme levels are not proper of houses, offices or schools, other symptoms like headache, sleepiness and decreased attention may often occur in crowded and non-ventilated public places.

The dependence of CO_2 concentrations on the air exchange rate of a room made some authors conclude that CO_2 can also be a good indicator of the presence of other substances [17] and, according to Fanger [23], “may in many cases also provide a first indication of a possible health risk” from toxic air contaminants. Monitoring CO_2 concentrations in indoor spaces can help highlighting critical situations requiring an exchange of air (where automatic ventilation systems are absent) or an increase in the air exchange rate (where automatic ventilation systems are present), in order to reduce the exposure of the occupants to potentially toxic substances and decrease the level of discomfort directly induced by CO_2 inhalation.

Schools and universities, especially, have the role of educating the future ruling class. High CO_2 concentrations in crowded rooms may influence the learning quality and may pose a risk to the achievement of this goal. Recent researches carried out in primary and secondary schools showed that CO_2 could achieve mean concentrations higher than 1,000 ppm, which thus highlight a “hygienically evident” problem [24], [25]. Other studies showed that peak concentrations close to [26] or higher than 4,000 ppm [27] may be achieved in schools, and highlighted the positive role of natural ventilation in taking the concentrations back to acceptable levels. In spite of the importance of keeping the learning capability at high standards, the number of studies on the CO_2 concentrations in schools and, especially, in universities is still low.

In the light of the previous considerations, this paper wants to share the results of a monitoring campaign of indoor CO_2 carried out in an Italian university and highlight the higher levels of concentrations that may be achieved in classrooms when no automatic ventilation systems are installed. This work is intended to shed a light on an underestimated factor that negatively affects the sustainability in working and teaching environments. Continuous CO_2 monitoring can turn useful to plan renovations in school and university environments or to inform teachers/professors on the need for exchanging the air (e.g. by opening doors and/or windows) when air extraction is not provided.

2 MATERIALS AND METHODS

2.1 Air quality monitoring campaign

The air quality monitoring campaign was carried out in a building of the University of Trento. Trento is a town with about 117,000 inhabitants located in an Alpine valley in northern Italy. The building considered in this study is located on a hill, about 80 m above the town, in an area that could be regarded as an urban background zone from the point of view of air quality, the main emission source being a secondary street (lowest distance: 91 m) and the university parking (Fig. 1). The building hosts a total of 24 classrooms with different size. Four classrooms and the library were selected to be representative of all the typologies of rooms present in the building and frequented by students. The layouts of the selected rooms are presented in Fig. 2. All the rooms, with the exception of room T3, lack of an automatic air extraction system, but are equipped with air conditioning. Only the doors of room M2 have a small grid in the lower part that connect the rooms with their respective corridor. Only rooms M2, D1 and D2 have windows that can be opened. The features of the rooms monitored are reported in Table 1. The monitoring sessions lasted between 8 and 11 days and took place in two periods: the classrooms were monitored between February and March 2017, whereas the measurements in the library were carried out at the end of May 2017. During each session, the number of occupants, as well as the opening of windows (in rooms M2, D1 and D2), were also monitored. The number of occupants was evaluated on a 1-hour time resolution, by counting the people inside the rooms. For each classroom, the occupants were the professor and the students attending their classes. In the case of the library, the occupants were mainly students, with the occasional presence of a few researchers and professors.

2.2 Instrumentation

The CO_2 measurements were carried out by using two identical portable real-time monitoring devices (ENERair v7.0, Enerconsult srl, Italy) equipped with a non-dispersive infrared digital sensor with self-calibration. The sensor is able to measure CO_2 concentrations in the range 0–5,000 ppm, with an accuracy of ± 30 ppm (± 3%) and a resolution of 1 ppm. The device contains an in-built datalogger, which locally stores the data on a micro-SD card and transmits the measurements to a central server via Ethernet connection or WiFi. The device is also equipped with additional sensors that turn useful to monitor other parameters for indoor air quality, such as temperature and relative humidity, which were measured by a

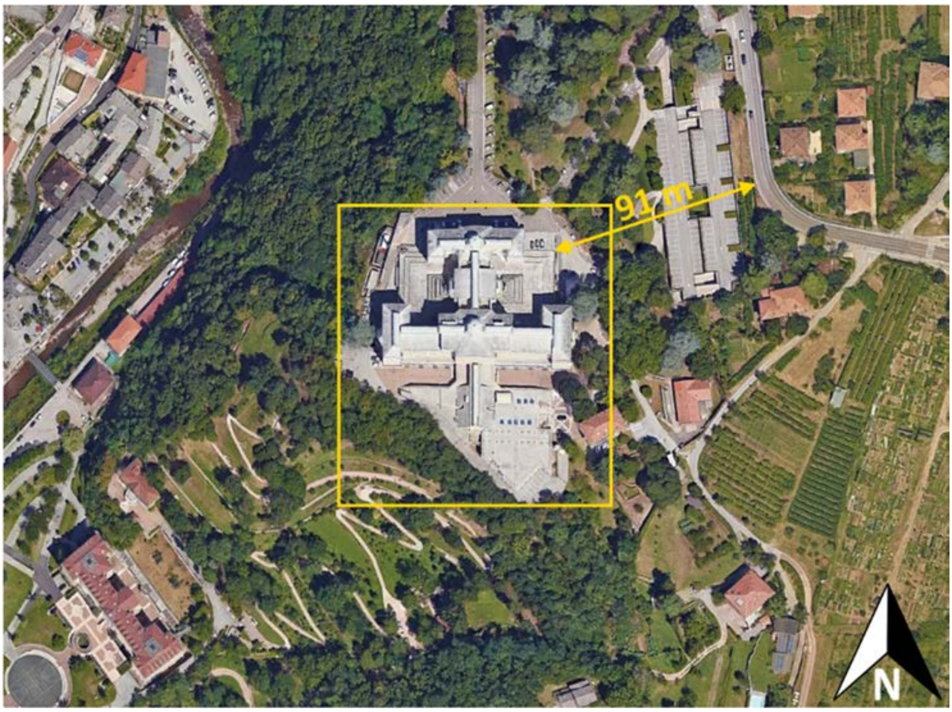

Figure 1: Map of the building with detail of the distance from the closest emission source (a secondary street).

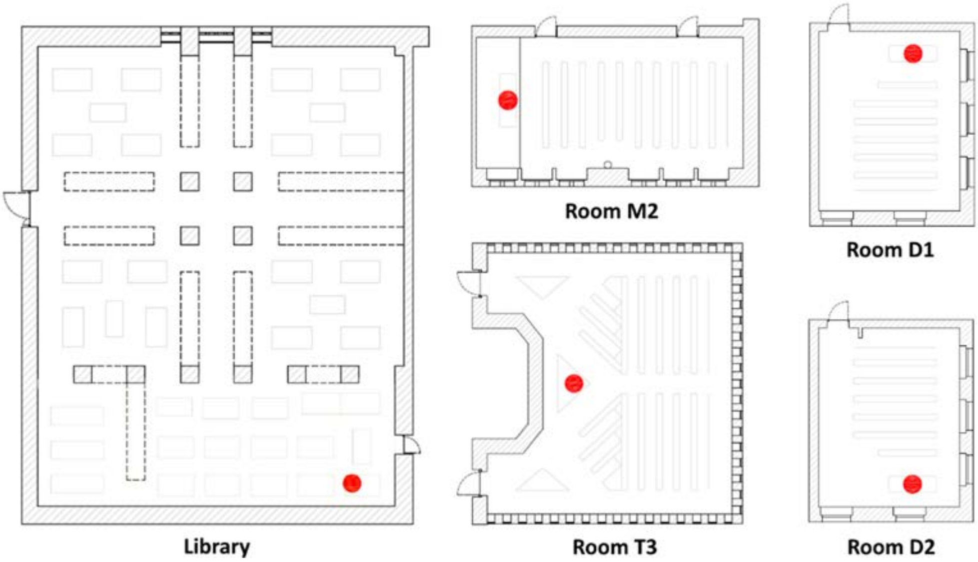

Figure 2: Layouts of the rooms monitored. The red dots indicate the location of the monitoring device.

Table 1: Features of the rooms monitored.

	Library	Room T3	Room M2	Room D2	Room D1
Net surface (m^2)	520	145	85	62	62
Net volume (m^3)	1,460	760	280	205	205
Floor	0	0	2	2	1
Orientation	SE	E	S	SE	SE
Maximum number of seats	162	98	88	47	47
Windows	Cannot be opened	Cannot be opened	Can be opened	Can be opened	Can be opened
Sampling period	02.08–02.17	02.17–02.26	02.17–02.26	02.27–03.08	02.27–03.08

semiconductor I2C-bus sensor. The sampling time can be personalised and was set as equal to 15 s for the whole duration of the tests. In all the classrooms, the device was placed on the desk, with exception of the library, where the device was located on a table of the room.

3 RESULTS AND DISCUSSION

The trends of CO_2 concentration, temperature (T), relative humidity (RH) and the number of occupants during the monitoring campaign that took place in the library are presented in Fig. 3. The trends of T and CO_2 concentration follow that of the number of occupants. As expected, the trend of RH is antithetical with respect to T. During the whole monitoring period, the CO_2 concentration remained in the acceptable range (<1,000 ppm), although no air extraction is present and in spite of the relatively low value of the minimum ratio between volume and number of occupants (13.6 m^3/person). This can be explained by the fact that the library is widely used during the whole day by students that often open the main door to enter/exit the room, and by the fact that the airtightness of the building envelope is quite low.

The situation gets slightly worse when considering the largest classroom (T3). Here, on the eighth day from the beginning of the monitoring campaign, the CO_2 concentration reached a peak of 1,507 ppm after four hours of lessons (Fig. 4). That day, the minimum ratio between volume and number of occupants was 16.5 m^3/person, i.e. similar to the value measured in the library. This difference in the CO_2 peak concentration is probably due to the fact that this room has been built after the main building, in place of an original inner courtyard, so with higher attention to constructive quality (better airtightness) but with supply and return air conditioning elements mainly concentrated in the upper part of the space (the roof is not horizontal but presents a slight sloping and a maximum inner high of about 6.50 m) and non at the users level, so with non-optimal air fluxes.

Higher concentration values were measured in classroom M2 (Fig. 5). Here the CO_2 peak concentration (1,791 ppm) was achieved on the fifth day of measurements, in the correspondence of the highest number of occupants (30 people). In this situation, the ratio between volume and number of occupants was 9.3 m^3/person. Room M2, like rooms D1 and D2, has windows that can be opened by the occupants. During this peak episode, the windows were opened and the CO_2 concentration soon decreased to <700 ppm.

The situation was even worse when considering the smallest classrooms monitored. Room D2 showed a maximum concentration of 3,855 ppm on the third day of measurements (Fig. 6). In that occasion, the number of people was 44, corresponding to a ratio between volume and number of occupants of 4.7 m^3/person. After this peak episode, the windows

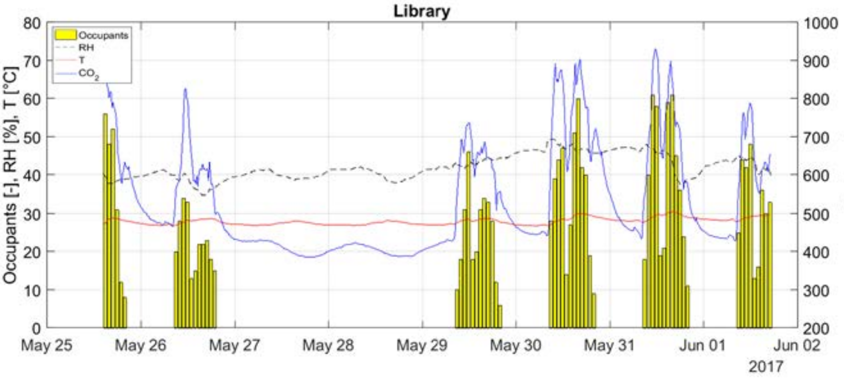

Figure 3: Trends of CO_2 concentrations, T, RH and number of occupants in the library during the monitoring campaign.

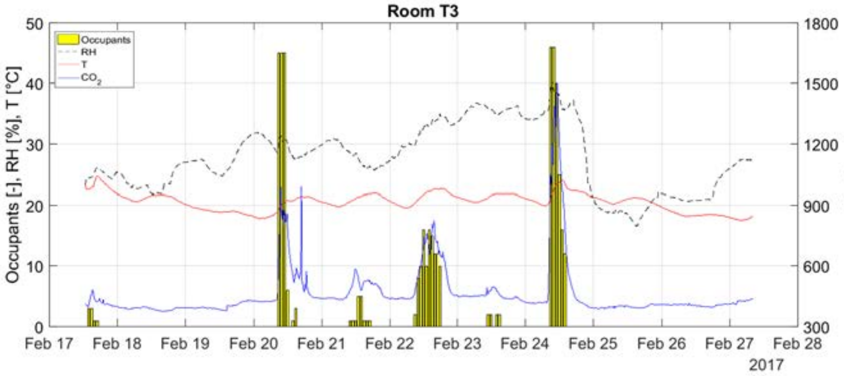

Figure 4: Trends of CO_2 concentrations, T, RH and number of occupants in room T3 during the monitoring campaign.

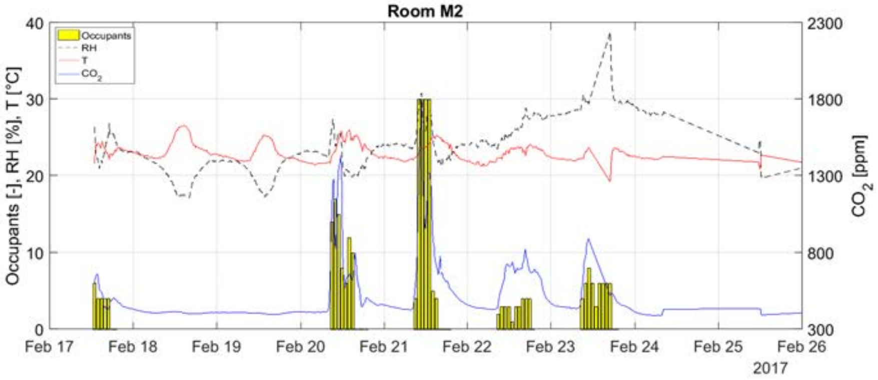

Figure 5: Trends of CO_2 concentrations, T, RH and number of occupants in room M2 during the monitoring campaign.

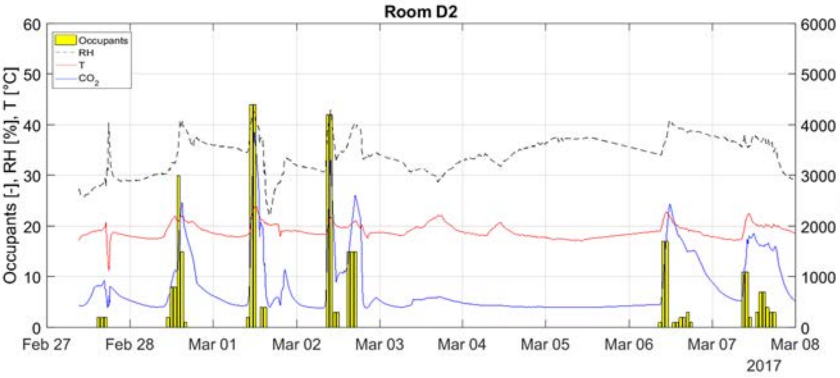

Figure 6: Trends of CO_2 concentrations, T, RH and number of occupants in room D2 during the monitoring campaign.

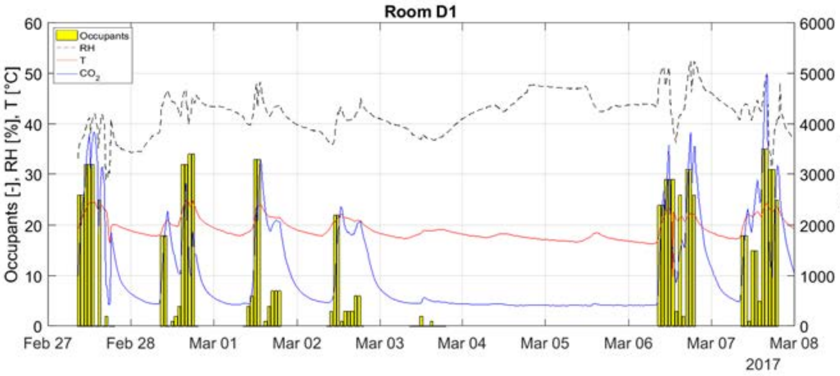

Figure 7: Trends of CO_2 concentrations, T, RH and number of occupants in room D1 during the monitoring campaign.

were opened by the occupants. The highest concentration value was recorded in room D1 on the last day of measurements (Fig. 7), when the value reached the instrumental end of scale (5,000 ppm). The number of occupants in that situation was 30. The corresponding ratio between volume and number of occupants was 6.8 m^3/person. This peak episode was recorded after five hours of lessons without opening the windows. The high concentration values made the occupants open the windows to refresh the air. Following windows opening, the concentration dropped to about 1,000 ppm. Contrarily to room M2, rooms D1 and D2 are not equipped with any grid on the entrance door and this may partly explain the higher concentrations measured.

4 CONCLUSIONS

The monitoring campaign carried out on university rooms highlighted that high concentrations of CO_2, generated by the human metabolism, might be easily achieved during classes in the absence of air extraction systems. The critical levels of CO_2 concentrations (>1,000 ppm) that can be achieved in such situations entail adverse (though reversible) effects on the occupants, who might experience decreased their learning capability, fatigue, sleepiness, loss of attention, headache and other symptoms that recall those of the SBS. The use of low-cost equipment, such as non-dispersive infrared digital sensors, could prevent the occurrence of CO_2 levels that might become critical to students, lecturers and, in general, employees working in relatively crowded rooms and/or in the absence of air extraction systems. Low-cost sensors could make people aware of the need for simple actions, like opening windows and doors, which could rapidly take the CO_2 concentration back to the "hygienically insignificant range" (<1,000 ppm).

In this paper, CO_2 is thus seen from a different perspective, i.e. not as a global pollutant, but as a local contaminant that humper the achievement of sustainable conditions in workplaces and school buildings. Conversely, the low-cost CO_2 monitoring approach presented in this paper can help the identification of critical environments that may require renovations (e.g. installation of automatic ventilation systems) or can alert the occupants when it is opportune to favour the natural ventilation of indoor spaces (e.g. by opening windows and/or doors).

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