Indoor CO₂: potential criticalities and solutions

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Abstract. Carbon dioxide (CO₂) has been conventionally regarded as a global problem, due to the well-known effects of fossil fuel combustion to the climate of our planet. However, this paper aims at highlighting the role of CO₂ from another perspective, i.e. by considering the effects of CO₂ on the health and well-being of the occupants of indoor spaces. The exposure to CO₂ air concentrations > 1,000 ppm causes symptoms like headache, dizziness, sleepiness and loss of attention, which may negatively influence the learning capability and the productivity of students and workers. In this sense, schools and universities are particularly vulnerable, due to the high density of occupants in classrooms and to the importance of the role of education in training the future members of the society. In the light of this issue, the present paper will provide examples of the incorrect design of indoor environments and, meanwhile, will propose simple solutions to monitor the problem of indoor CO₂ concentration and improve the indoor environmental quality of public places.

1 Introduction

In the last decade, indoor air quality (IAQ) has become an issue of increasing concern in the everyday life, in parallel with the growing attention to the general topic of air pollution. Recent estimates state that air pollution causes the death of about 7 million people per year in the world [1]. The effects of air pollutants on the health of human beings are related both to the time of contact between the human body and the contaminants and to their concentration [2]. This process is known with the term “exposure” to air pollutants. When dealing with air contaminants, the primary route of exposure to most of air pollutants is in inhalation. Specific group of air pollutants, however, tend to accumulate in animal tissues and therefore can enter the food chain [3-4]. This is the case of persistent organic pollutants and heavy metals. For these two categories, the diet may represent the dominant route of exposure.

In addition to cause mortality, air pollution involves huge societal costs, due to hospitalization, therapies and to actions for the remediation of contaminated soils and water resources. To this regard, a methodology for the assessment of the so-called external costs

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was developed and updated in the last 15 years by the European Union [5]. The focus, however, has always been pointed at the problem of outdoor air pollution. Indeed, outdoor sources of air contaminants are usually more evident than indoor sources, probably because they are more visible and noisy than other sources. In the last centuries, after the beginning of the industrial revolution, air pollution was clearly visible and could be easily associated with industrial combustion processes. Nowadays, outdoor emission sources are significantly different from the past, being road traffic and big industrial plants the major contributors [6], and the consciousness towards the implications of air pollution has raised the attention to any form of exposure to air contaminants.

Since exposure depends on the contact time between air contaminants and the human body, indoor environments may be particularly critical for the development of adverse health effects, because people generally tend to spend most of their time in closed environments like workplaces and houses [7]. IAQ has been the core topic of an increasing number of scientific publications in the last two decades. Many of them focussed on the so-called sick-building syndrome, intended as a group of symptoms that may occur following the stay of an individual in indoor environments with emission sources of air pollutants or weak ventilation and exchange of air [8]. Such symptoms include general problems (*e.g.*, fatigue, headache and loss of attention), skin problems (*e.g.*, dry skin and itchy ears) or mucous membrane symptoms (*e.g.*, irritation of airways and eyes) [9]. Besides the presence of indoor sources of pollutants, IAQ can be affected by the penetration of air pollutants from outside [10], whose negative impacts can be especially significant in megalopolises. In indoor environments, one the most effective mechanism to reduce the concentrations of air pollutants is ventilation [11], *i.e.* the exchange of indoor air with fresh (or at least less polluted) outdoor air, preferably filtered by air treatment systems. Ventilation in indoor spaces acts as atmospheric dispersion in the outdoor environment.

The majority of scientific papers on IAQ have focussed on macro- and micro-pollutants like particulate matter, nitrogen dioxide, carbon monoxide, volatile organic compounds and sulphur dioxide [12-16]. However, the quality of life in indoor environments can be significantly affected by another compound that is usually neglected when dealing with IAQ: carbon dioxide (CO₂). The emission of such compound from the combustion of fossil fuels is universally known as the major cause of global warming. It should be noted that CO₂ is the key component of industrial and transport emissions. Its impact usually was not considered in the methodologies of environmental damage assessment, because CO₂ is a non-toxic substance. However, the significance of the problem of CO₂ immense emission to the atmosphere and its correlation with the toxic emissions in the process of fuel combustion necessitate accounting it in the evaluation of negative externalities [14-19]. Besides, the exposure to high concentrations of CO₂ may cause adverse health effects, and such characteristic allows considering CO₂ as a local air pollutant. In outdoor environments, the CO₂ concentration is typically in the range 300–400 ppm, nevertheless in megalopolises high traffic density may cause local substantial increase in CO₂ and corresponding decrease in oxygen concentration in the breath zone (down to 18.4% and even less). This makes sense to improve the economic mechanism for stimulating CO₂ emission reduction by vehicles [20]. In indoor environments with weak ventilation and air exchange, the CO₂ concentration can reach values of thousands of ppm [21]. In indoor environments with the absence of specific sources, the excess CO₂ that may accumulate above its natural levels is due to the human metabolism. If not adequately controlled, the inhalation of air with high CO₂ concentrations (within certain limits) may cause reversible, though negative, effects on the people exposed. The exposure to concentrations > 1,000 ppm may decrease the learning capability of students and workers [22]. Thus, the exposure to unnatural levels of CO₂ may cause a decrease in the productivity and, consequently, an economic loss to the society. At concentrations up to 5,000 ppm, symptoms like sleepiness,

headache and loss of attention become evident [23]. The level of 5,000 ppm is the concentration limit for occupational exposure to CO₂, as established by the Association Advancing Occupational and Environmental Health [24]. At much higher concentrations (> 20,000 ppm), the exposure to CO₂ is responsible for symptoms with growing gravity, like increased respiration rate and neurological disturbances like loss of consciousness, causing death when the CO₂ concentration reaches 25% in volume [25]. Concentrations of 1,000 ppm and 2,000 ppm were set by the German Federal Environment Agency as guide values to indicate respectively the suggestion and the obligation to exchange the air of an indoor environment [26]. The same Agency established that a concentration < 1,000 ppm can be considered as “hygienically insignificant”, concentrations between 1,000 and 2,000 ppm should be considered as “hygienically evident” and higher concentrations must be regarded as “hygienically unacceptable” [21]. High CO₂ concentrations may be an indicator of inadequate ventilation [27]. Besides CO₂, temperature is another important parameter affecting the well-being of the occupants of indoor spaces, since it has effects on the thermal comfort of people. High CO₂ concentration may be an indicator of thermal discomfort, since both situations are favoured by weak ventilation of indoor environments. In addition, high CO₂ concentrations may indicate critical levels of other indoor air pollutants [12].

The present pupils and students will be the ruling society and the decision makers of the future. Since they are trained in schools and university, it is essential that the education system guarantees the best conditions for their learning. However, the learning capability is affected by the environmental quality of classrooms [28]. In the light of the importance of a correct management of the CO₂ concentration in indoor spaces, the present paper intends to provide some examples of critical situations for CO₂ exposure in a university environment. In addition, the paper will present proposals for improving the current criticalities, for controlling and managing the exposure to CO₂ in indoor environments.

2 Criticalities in a university environment

As anticipated, high CO₂ concentrations and thermal discomfort are common issues in schools and university environments. In their review, Salthammer et al. [29] reported on indoor CO₂ concentrations between 352 ppm and 5,049 ppm in several classrooms of different European countries. Other studies on classrooms confirm these results, reporting maximum concentrations of 2,000 ppm [30], 2,746 ppm [31] and above 5,000 ppm [32].

The theme of indoor environmental quality has been recently taken into consideration by the University of Trento (Italy), located in the Alpine region. This university is part of the Italian University Network for Sustainable Development [33], a national network of Italian universities that joined together to develop and spread the culture of environmental sustainability, pursue sustainability goals, share methods and actions, promote good behaviours and act as a model for other public bodies and the society. The University of Trento has recently drafted an environmental sustainability plan to implement actions for improving the level of sustainability of the university. A CO₂ monitoring campaign is scheduled in the plan. This activity will help performing the following actions:

- detect hotspot areas in indoor environments;
- identify the causes of the hotspots;
- plan renovations to solve the criticalities.

The planned monitoring campaign follows preliminary results that showed concentrations above the “hygienically insignificant” value in some classrooms. A preliminary survey on the building, where this first monitoring activity was carried out, showed some critical issues that justify the high concentrations monitored. The survey revealed that an essential requirement for appropriate automatic ventilation is the absence

of obstacles between the rooms where CO₂ concentrates and the air intake of the extraction system, where present. Fig. 1 shows two different situations that are currently ongoing in one building of the university. Such situations refer to two corridors of different floors, where the air intake of the extraction system are visible on the ceiling and classrooms are present. The first door represented in Fig. 1a is equipped with a grid in the lower part, whose aim is to let the air of the classroom being extracted by the air extraction system. The corresponding door on the other floor of the building (Fig. 1b) has no grid for this purpose. Thus, if the door were kept closed during classes, the only way to reduce the CO₂ concentration consists in the natural ventilation by window opening.

Fig. 1. Examples of a) correct and b) incorrect choice of classroom doors to ensure an appropriate indoor air ventilation; the yellow circles identifies the intake of the air extraction system on the ceiling and the grid on the door, which is absent in the second case.

3 Proposals for the control and management of CO₂ exposure

Following episodes that lead to an accumulation of CO₂ in indoor spaces, CO₂ concentrations could be taken back to the “hygienically insignificant” range if a regular ventilation or a sufficient exchange of air was granted. In this sense, automatic air extraction systems are the best option to ensure adequate air exchange. However, renovations must consider every detail so that the investment does not reveal as useless. An example is the case presented in Section 2, where air extraction grids are located outside the room and the latter is not equipped with grids on its doors. As an alternative, if the installation of automatic air extraction systems were unfeasible from the economic and structural points of view, the simple opening of doors/windows would help gradually decreasing the indoor CO₂ concentration of the room. Window opening is the most effective method for the exchange of air in buildings where automatic air extraction is absent. However, window opening may affect the thermal comfort of an indoor environment: a recent study revealed that, with an outdoor temperature < 16 °C, window

opening reveals as inappropriate [34]. Winter is usually the most critical season of the year, due to the tendency of the occupants of indoor spaces to keep windows closed. This problem is especially exacerbated in regions with a cold climate (Russia, Canada, Scandinavian countries, etc.). Thus, in the worst-case situation (absence/unfeasibility of automatic air extraction and low outdoor temperature), door opening remains the only option.

Another strategical aspect for the correct management of indoor CO₂ concentration is represented by CO₂ monitoring. Low-cost CO₂ monitoring sensors could be conveniently used in school/university rooms where automatic air extraction systems are absent and when their installation is not feasible. The monitoring of the CO₂ concentration would reveal possible critical episodes. If the indoor CO₂ concentration exceeded the “hygienically insignificant” threshold, the teacher/lecturer could put some simple actions into practice, like opening windows, doors and proposing a break to the students. The exceedance of the threshold could be detected by a visual signal or a sound emitted by the sensor in use. The most known low-cost method for CO₂ monitoring is based on non-dispersive infrared digital sensors, which are commercially available and which normally measure the CO₂ concentration in the range 0–5,000 ppm, which is suitable for most of the cases. The technological advances of the last years have decreased more and more the size of air quality sensors, allowing for converting fixed sensors into portable devices, like the recent Sensordrone [21]. Besides CO₂, as previously mentioned, it is important to consider the role of temperature and humidity. Those parameters can be easily measured by low-cost thermo-hygrometers. The monitoring of temperature and humidity can help preventing the achievement of concentrations exceeding the “hygienically insignificant” threshold, by inducing the occupants to open windows/doors at specific values that can be set and signalled by the sensors.

4 Conclusions

CO₂ concentrations may reach critical levels in indoor environments characterised by high density of occupants. The classrooms of schools and universities usually respond to such feature. Although the typical CO₂ concentrations reported in the literature for such contexts are far from causing serious health outcomes, CO₂ concentrations may achieve values that can negatively affect the performance of students in terms of learning capability.

Considered the key role that schools and universities play in training the future leading class, public and private education structures should implement technical expedients to manage the indoor environmental quality of classrooms. Critical levels of indoor CO₂ may be associated with thermal discomfort and both are favoured by inadequate air exchange rates. The most effective action to reduce the accumulation of CO₂ in indoor environments consists in the implementation of automatic ventilation based on air extraction. However, renovations require specific attention to technical details that, if not adequately considered, could make the installation of an automatic ventilation system ineffective. Alternatively, if the work required to install new air extraction system were not technically feasible or economically sustainable, natural ventilation (i.e., the manual opening of doors and windows) remains the only applicable strategy. The technological advances in the production of air quality sensors could facilitate the management of the indoor environmental quality of classrooms. Indeed, low-cost sensors could be installed in classrooms to automatically control air extraction systems or, if the latter were absent, to alert the occupants on the need for opening windows and/or doors.

In order to better understand the potential damages of indoor CO₂ exposure in terms of loss of productivity and learning capability, questionnaires or psychological tests could be

distributed to pupils/students before and after classes, with or without the adoption of ventilation strategies.

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