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Natural ventilation level assessment in a school building by CO_2 concentration measures

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Abstract

This paper considers the topic of natural ventilation in school buildings that is faced not only for energy saving, but also for the fundamental exigency of the indoor comfort. This analysis is developed by measuring the concentration of carbon dioxide as a significant indicator of IAQ when pollution is mainly due to the presence of people. In this paper are presented the results of a monitoring campaign of the CO_2 levels carried on in classrooms. The measures show the criticality of IAQ with values often much higher than the limits specified by standard, but also the possibility to act effectively with the manual ventilation without excesses that could create comfort problems or waste of energy.

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Keywords: natural ventilation; school, indoor air quality, carbon dioxide, monitoring.

1. Introduction

The scholastic environment is the place where the school age population spends from 5 to 8 hours daily. In European countries children spend in classrooms about one third of their entire day, in Italy from 29 to 33 hours weekly. If the home environment is excluded, school is the place of greater permanence for the child population.

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In the European Community primary and secondary schools have 71 million students and almost 4.5 million teachers, representing about the 20% of the entire population. In Italy 10 million people, as students and teachers, study and work every day in about 45,000 buildings distributed in the entire national territory.

It is evident that time spent in classroom represents a possible problem and it is very important to grant an adequate level of air quality inside buildings to improve the user wellness. Overcrowded classrooms and scarce ventilation increase the risk of exposure to pathogens. The poor air quality in schools can determine serious sanitary problems among children which are more sensitive than adults to the pollution consequences [1, 2]. In addition studies have recently highlighted that a bad air quality can affect negatively the learning performances of the students.

In the closed spaces where the pollution is fundamentally caused by the presence of persons, the measure of the carbon dioxide concentration can be used as an indicator of the quality of the ventilation. In fact in this case other indoor generated pollutants, especially bio effluents, are correlated to the CO_2 concentrations [3, 4, 5]. Medical science indicates as dangerous for the mechanism of breathing CO_2 values over 5000 ppm with consequent risks of physiological damage in the weakest individuals. But already above 2000 ppm increases the frequency of nausea and drowsiness effects, certainly deleterious to the operational efficiency of people [6, 7]. However addition to the physiological aspects already at much lower levels, there is the problem of comfort. In the past the ASHRAE standard suggested a maximum CO_2 level of 1000 ppm which is the value recommended by the old study of Pettenkorfer already in the XIX century. For ASHRAE this concentration is able to ensure a percentage less than 20% of the people which express dissatisfaction. More recently ASHRAE recommended a difference between indoor and outdoor concentration not more than 700 ppm [8]. According to European standard EN 13779 [9] indoor air quality is considered achieved with less than 400 ppm above the outdoor level, medium quality in the range between 400-600 ppm, moderate from 600 to 1000 ppm and low above 1000 ppm. However in the United Kingdom, the authority for the public school has fixed a limit of 1500 ppm for the average CO_2 concentration during the daily occupancy period [10]. The same value is prescribed as a maximum by other numerous regulations such as German and Swiss standard [11, 12]. Therefore the CO_2 concentration of 1500 ppm has been considered as acceptable limit in this analysis.

In the southern part of Europe the most part of the schools uses only manual airings for the ventilation also during the heating season. Therefore the problem of a correct management of the air changes involves other important exigencies like the thermal comfort and the energy saving especially in the coldest periods. The optimization of the natural ventilation is consequently connected to the elaboration of multitasking criteria.

Nomenclature

$C(t)$	CO_2 concentration in the end of interval t (ppm)
C_0	CO_2 concentration in the beginning of interval t (ppm)
C_{ext}	mean outside CO_2 concentration during the interval t (ppm)
t	time interval [s]
G	mean CO_2 inside generation during the interval t (m^3/s)
V	volume of the room (m^3)
ACH	air change per hour (h^{-1})

2. The monitoring

An experimental campaign was carried on in two secondary schools located in two cities of North Italy, climatic zone E, during winter period 2015-16. Schools characterized by traditional radiator heating system with centralized climatic control. The ventilation is performed by manual airing. The first building was built in 1959 and designed for the final destination of school building. Therefore all the classrooms have similar features as concerning shape, dimensions, design occupancy and exposure to the outside. In particular the number of windows is normally four for each class. As shown in Fig. 1 each window, replaced in 2008, is composed by one sash window and an openable transom (width 1.10 m, height 1.62 m). The window presents aluminum frames separated by thermal break made of

a) Classroom 3C b) Classroom 1A c) Ceiling of classroom 1A

Fig. 1. Views of the classrooms

polyamide and double-pane. The external walls aren't insulated. The second school is located in the historical center and is part of a monumental complex in origin built as a convent. Since the 19th century the building is used as school. It has dimensions and structures typical of an ancient building with vaulted ceilings as shown in Fig. 1c with height of 4.80 m on the top. With the refurbishment of the 19th century each classroom has been equipped with three windows as shown in fig. 1b. Each window presents double sashes and an openable transom (width 1.05 m, height 1.56 m) with double pane and old wood frames characterized by no sealing and poor maintenance.

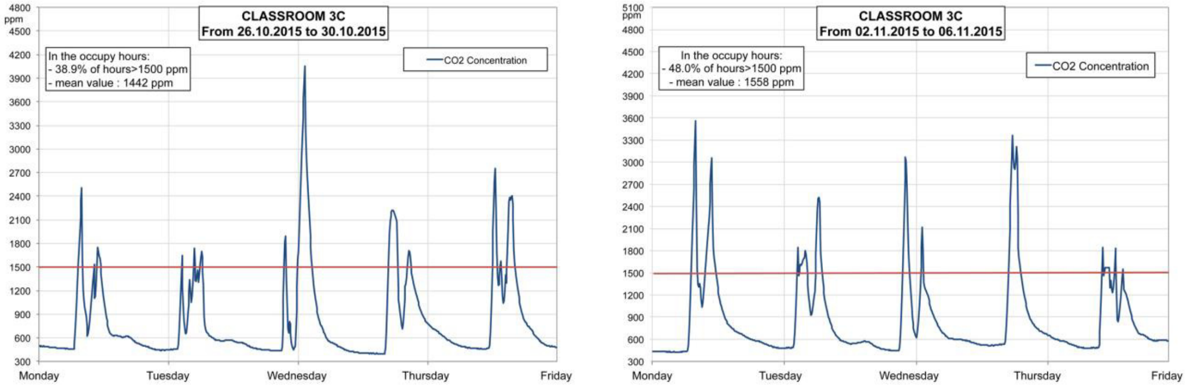
The present study refers to the elaboration of the data collected in two classrooms, named 3C and 2F, of the first school and in one, named 1A, of the second school. Dimensions and occupancy characteristics of these three classroom are showed in table 1. These three classrooms have been selected because in the periods here analyzed they had similar occupancy density as resulted by the daily check of the real presences.

Table 1. Characteristics of the classroom

Classroom	3C	2F	1A
Surface (m^2)	48.8	49.3	42.6
Height (m)	3.1	3.1	4.8
Volume (m^3)	153.6	155.4	204.6
Volume per person (pers/m^3)	6.1	6.0	9.3
Occupancy (pers/m^2)	2.0	1.90	1.94

The measures were performed by using various portable instruments (Testo models 435-2 or 435-4) equipped with IAQ probes able to measure simultaneously indoor temperature, relative humidity and CO_2 concentration. As regards measurement accuracy of the IAQ probes, the NTC temperature sensors have an accuracy of ±0.3 °C in the range 0-50°C, the capacity humidity sensors ±2% in the range 2-98% r.h. Non dispersive infrared (NDIR) sensors were used for the CO_2 concentration with an accuracy ±(50 ppm±2% of the measure value) until 5000 ppm and ±(100 ppm±3% of the measure value) in the range 5001-10000 ppm. The IAQ sensors were always installed on a desk, at a height of 80 cm from the floor, distant from windows or doors and in a central position in the classroom. The data were recorded every ten minutes.

A simple mathematical model was used to evaluate the mean ventilation rate and consequently the air change per hour (*ACH*). The Eq. (1) provides the CO_2 concentration after a time interval t and it derives from a simple balance of the indoor concentration of carbon dioxide taking into account indoor generation and the exchange with the outside ambient. Starting from the measures of indoor and outdoor CO_2 concentrations and the calculation of the generation G on the basis of the presences, the same equation can give the ventilation rate if used with an iterative



a) First week b) Second week

Fig. 2. Weekly trends of classroom 3C.

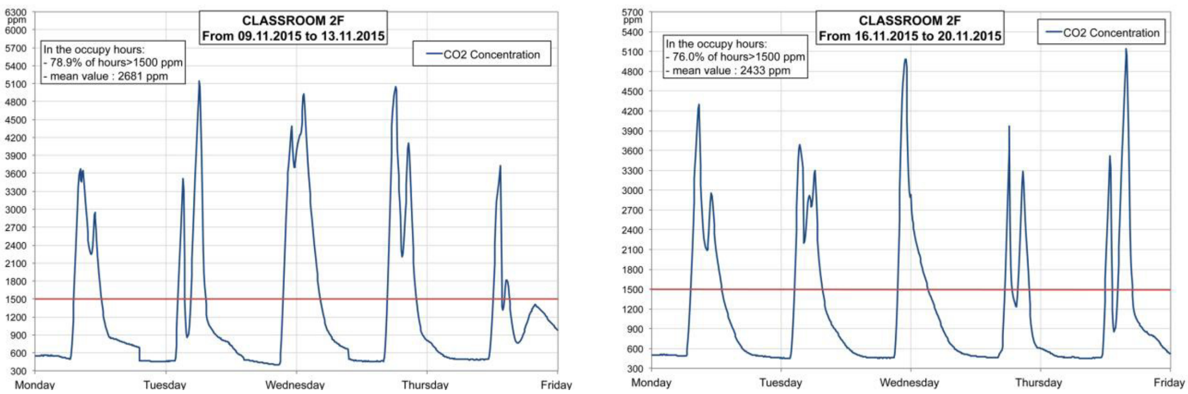
procedure fixing tentative values of *ACH* until convergence on final CO_2 concentration *C(t)*. Generation rate was estimated 0.0041 l/s for the pupils and 0.0054 l/s for the teacher [13]. During no occupancy hours the generation *G* is equal to zero and then the simplification of the Eq (1) can give directly the mean *ACH* in the interval *t* by Eq. (2).

$$C(t) = C_{ext} + \frac{G \cdot 10^6}{(ACH \cdot V)/3600} - \left(C_{ext} - C_0 + \frac{G \cdot 10^6}{(ACH \cdot V)/3600} \right) \cdot e^{-ACH \cdot t/3600} \quad (1)$$

$$ACH = -\frac{3600}{t} \cdot \ln\left(\frac{C(t) - C_{ext}}{C_0 - C_{ext}} \right) \quad (2)$$

3. The results

In the Fig 2, 3 the trends of the measured concentrations of carbon dioxide are showed for some representative weeks for the classroom 3C and 2F respectively. For each week the figures also report the percentages of the



a) First week b) Second week

Fig. 3. Weekly trends of classroom 2F.

frequencies when the CO_2 is over 1500 ppm referring to the total measures during the occupancy period in the week. The mean value during the same interval is also indicated. In detailed Fig. 2 refers to the measures in the classroom 3C in the weeks from 23^{th} to 28^{th} October and from 29^{th} October to 5^{th} November. In this case the values are not so critical because of a frequent use of the manual airing by the windows and door. As matter of fact the mean value over the occupancy period is around 1500 ppm and at least half of the occupancy hours presents a CO_2 concentration not greater than 1500 ppm. In Fig. 3 are reported the measures in the classroom 2F in two weeks of November, from the 9^{th} to the 13^{th} and from the 16^{th} to the 20^{th}. The situation is extremely worse. In the occupancy period CO_2 concentration is over 1500 ppm for the 78.9% and 76% of the measured data in the first and in the second week respectively. The corresponding mean values are 2681 ppm and 2433 ppm respectively. Some peak values are over the limit of 5000 ppm. The strong differences between the audits in the two classroom similar for dimensions and occupancy highlight the effects of different human behaviors. This phenomenon has been studied in detail by the comparison of single days for the two classrooms.

In Fig.4 the daily trends of CO_2 concentration and indoor temperature obtained from monitoring are reported for the 2^{th} of October for classroom 3C and for the 10^{th} of November for classroom 2F. In both the cases the trends of *ACH* were calculated by using Eq. (1) and (2). *ACH* are reported in Fig. 4 with the same time step of the measures. During these two days the behavior of the users is similar: the classroom are ventilated only during the time breaks. The opening of the windows causes a quick lowering of the CO_2 level that come back within the limits imposed by standard. For classroom 3C from 3556 ppm to 1051 ppm and for classroom 2F from 3515 ppm to 856 ppm. In a quarter of an hour a drop of over 2000 ppm can be noticed.

The sudden decrease of indoor temperature confirms that this effect was caused by the contemporary opening of the windows. In the case of classroom 3C this event does not involve comfort problem as the temperature remains anyway near 20°C. Instead the temperature of classroom 2F reaches a value near 16°C and in the following restarting of the lesson it remains under 20°C for about an hour not ensuring comfort condition in that period. This fact points out a ventilation perhaps excessive for classroom 2F during the break. The calculated *ACH* during this time interval arrive to peak values of 6.5 h^{-1} for room 2F and 5.2 h^{-1} for 3C. Although this circumstance does not involve a better behavior of 2F in the remaining occupancy period where the peak values of CO_2 concentrations anyway exceed 5000 ppm. On the contrary the greater air changes of the 3C in the last occupancy period underline a better management of window openings for this classroom. In this case the peak value is 3056 ppm and even lower than the peak value in the first period of the morning which is 3556 ppm. As consequence in the total occupancy daily period the *ACH* mean value is 1.8 h^{-1} and the CO_2 mean concentration is 1853 ppm for classroom 3C. The corresponding values for classroom 2F are 0.5 h^{-1} and 2566 ppm respectively. Therefore a high ventilation rate caused by a full opening of the windows for a limited period causes a strong and quick fall of the internal CO_2, but

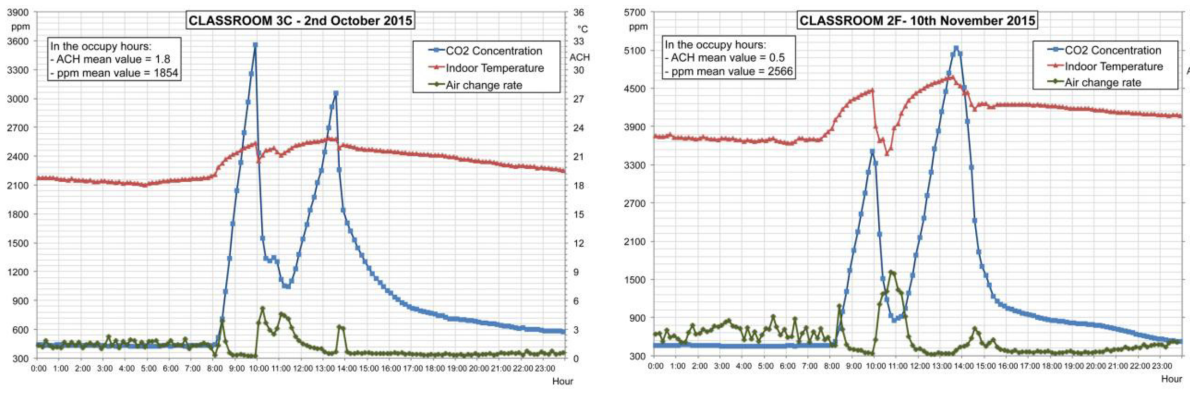


Fig. 4. Daily trends of classrooms 3C and 2F.

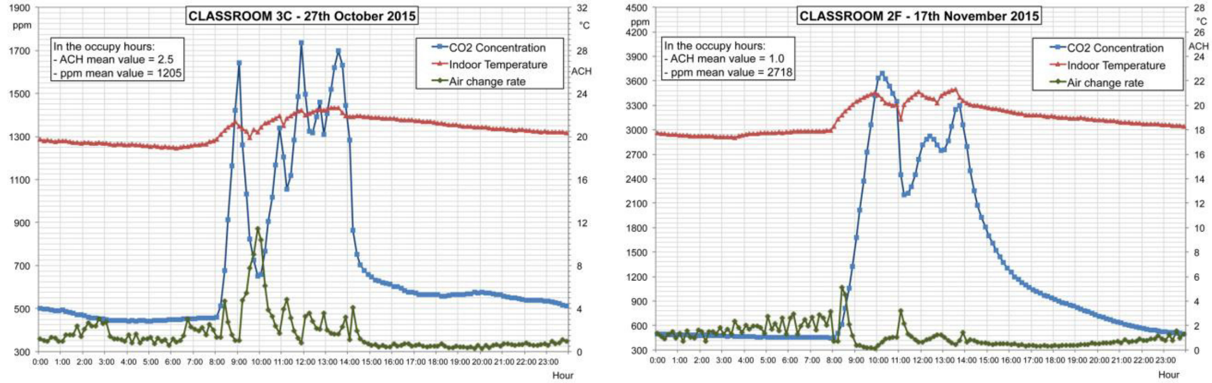


Fig. 5. Daily trends of the classroom 3C and 2F.

this is not particularly useful. Instead it increases energy consumption and discomfort occasions. Most effective appear shorter ventilation openings but more frequent.

By analyzing the air changes calculated during the monitoring periods, two days characterized by ventilation openings more frequently have been chosen and reported in Fig. 5 in order to compare the results for the same two classrooms previously analyzed in Fig. 4. For 3C in the total occupancy daily period the mean *ACH* is 2.5 h^{-1} and the CO_2 mean concentration is 1205 ppm. The corresponding values for classroom 2F are 1.0 h^{-1} and 2718 ppm respectively. In this case the peak value is 1738 ppm for 3C and 3691 ppm for 2F. These values are less than the equivalent values in Fig. 4 and they confirm the better behavior connected to the more number of openings. Even the more appreciable performance of 3C than 2F in Fig. 5 can be referred to the same reason. It is again remarkable the trend of the indoor temperature which shows the timing of the openings with precision. It can be observed that in this case the short openings does not involve temperature decrease able to create comfort problems as for 2F in Fig.4.

About the monitoring of classroom 1A the Fig. 6 shows the CO_2 concentrations referred to the week from 14th to 18th March. As well evident from the figure, this week has been chosen because the behavior of the user is different if compared to those analyzed until now in the other two classrooms. In 3C openings were frequent and short, in 2F windows are opened only during the break. Differently in the classroom 1A windows are never opened in this week. The CO_2 level reaches high values with peaks over 4500 ppm with an average of 1881 ppm during occupancy hours in this week. But it is detectable a lower speed in the increase with respect to the other two classrooms. This effect is connected to the greater volume per person of this classroom that involves a higher CO_2 dilution. In addition, unlike

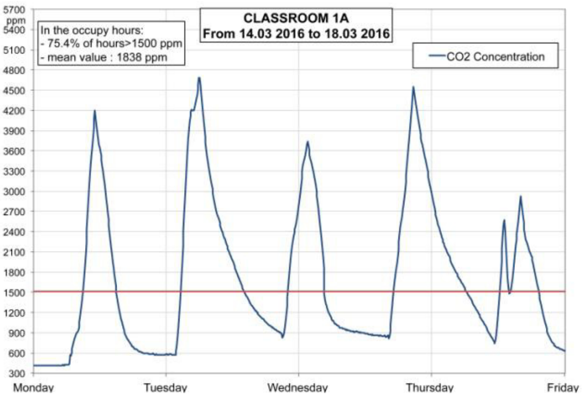


Fig. 6. Weekly trend of classroom 1A .

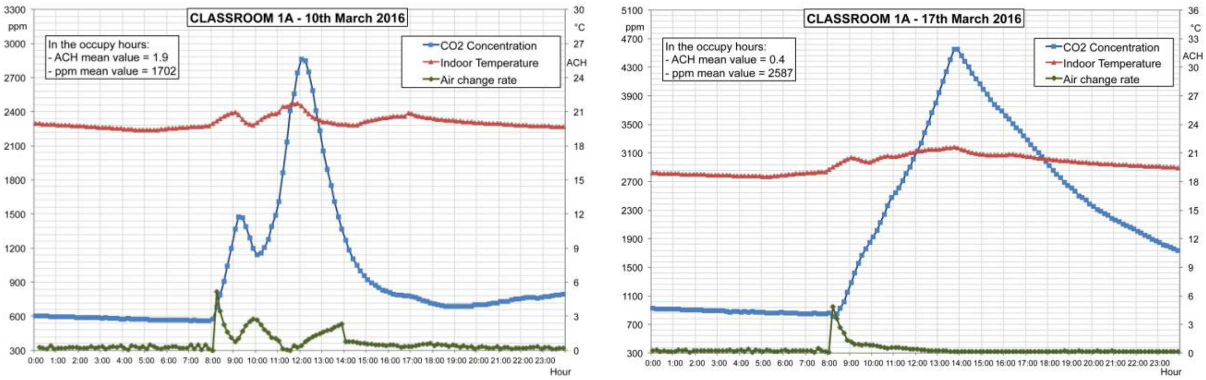
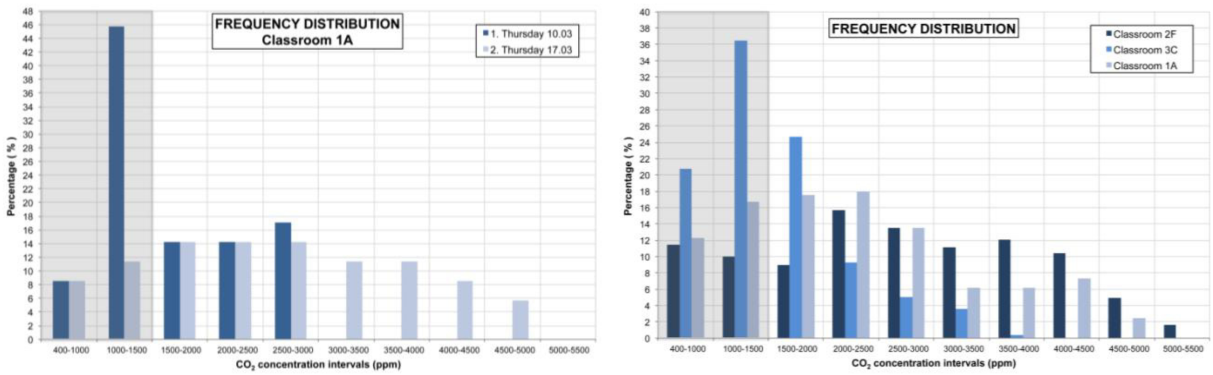


Fig. 7. Comparison of two days of classroom 1A.

the other two classrooms, the internal CO_2 concentration doesn't lower rapidly when the classroom is empty and it keeps a value around 800 ppm until students arrival in the next morning. In the other two classrooms the CO_2 value lower rapidly during the night until the 420-450 ppm equaling the outdoor level. This is the consequence of the deliberate choice by the school management to impose the closure of all the openings and even the doors to the inner hallway when the classroom is empty. Fig. 7 shows CO_2 values measured in the 1A classroom during on two Thursdays, the 10^{th} and the 17^{th} of March. The two days, even though they have equal occupancy in the classroom, are characterized by a different user behavior. March 17^{th}, which is also present in the previous analysis of Fig. 6, has a reduced ventilation, in fact during the occupancy hour the average *ACH* is 0.4 h^{-1} and the mean CO_2 value reaches 2569 ppm. Instead, on the 10^{th} of March the mean *ACH* is much more higher, 1.9 h^{-1}, and consequently the average CO_2 concentration lowers to 1702 ppm. It should be noted that a constant but limited ventilation doesn't influence the internal temperature which is maintained around 20°C, granting comfort condition even in the second case. The presence of old windows that have more infiltrations doesn't influence significantly the trend of the CO_2 values which remains fundamentally connected to the effective people presence and to window openings. The *ACH* with closed windows remains around 0.15 h^{-1} during the occupancy period.

Fig. 8 shows the frequency distribution of the measurements in different CO_2 concentration intervals. These frequencies, in percent, are referred to the total collected measurements. In detail, in Fig. 8a are reported the frequencies relative to the two Thursdays (10th and 17th of March) for the measurements in the classroom 1A. In the Fig. 8b the frequencies are referred to the measurements collected in the entire monitoring period for each of the



a) Two days in classroom 1A b) The entire monitoring campaign

Fig. 8. Frequency distribution in the CO_2 intervals during the occupancy hours.

three classrooms. Referring Fig. 8a it is noted that on March 17th the 54,3% of CO_2 measured values is under 1500 ppm and on March 10th this value is lower than 20%. Between the values higher than the limit of 1500 ppm, the 9% of the measured values are between the 4000 to 4500 ppm. This fact never happens on March 10th when the maximum values are around 2500 to 3000 ppm and for the 17% of the recorded values. As concerns the entire experimental campaign, in Fig. 8b the percentage frequency of the occurrences when the limit of 1500 ppm is exceeded, is 57%, 21% and 29%, referring respectively to the 3C, 2F and 1A. Instead referring to the values under the limit of 1000 ppm suggested by ASHRAE, the percentage frequency is respectively 21%, 11% and 12%.

Processed data point out significantly different performances of the manual airing. The calculation of *ACH* provides realistic and coherent values if made later time on the basis of detailed monitoring data. Instead the use of Eq. (1), (2) as predictive models has proved to be not very reliable, because it depends on many extremely variable parameters such as the metabolic rates, the pressure difference between inside and outside and above all the human behavior in practice difficult to manage and to predict during the normal school activity. For example the real quota of opening area can be very different in presence of many windows with sashes and vasistas less or more open. Same considerations for the frequency of the openings of doors and the real presences.

From this point of view the recent development of IAQ instruments at costs decidedly acceptable can provide a simple answer to this problem. The real-time monitoring can be done directly by the user thanks to the installation in each classroom of a cheap meter, but anyway suitable for this aim, today accessible on the market at a cost around 150-200 €.

4. Conclusions

The analysis highlights the effectiveness of an appropriate manual airing and suggests frequent and short periods of window openings. But further research activity to elaborate more sophisticated mathematical models and detailed procedures able to indicate a precise ventilation management in each school application appears problematic and frankly unworkable. Instead the simplest and most practicable solution is to promote a conscious ventilation in each classroom by involving the teachers made aware by installing in each classroom a meter of CO_2 to inform of the IAQ condition. Thus realizing a self-management based on criteria of IAQ and thermal comfort, therefore also of the maximum compatible energy saving, directly evaluated by the user in real time.

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