PAPER • OPEN ACCESS

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To cite this article: Rui Oliveira *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012061

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CO₂ experimental measurements towards the development of a predictive framework using user actions in smart buildings

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Abstract. A transition towards smart buildings is one of the challenges of the 21st century. To achieve this goal, the use of smart sensors and smart appliances can be crucial. Although research about linking real-time monitoring and the operation mode of building appliances have been carried out by other researchers, the focus was on the energy performance relegating indoor air quality and thermal comfort to the background. This paper focuses on the analysis of the preliminary results on experiments performed in a real test room to evaluate the CO_2 distribution within a single zone. The strategy is to include the concerns regarding indoor air quality in a global framework where weather forecast, users' actions and building simulation will be combined in a real-time predictive methodology. The experiments included the evaluation of the air change rate using metabolic-related CO_2 as tracer gas into the test room. The attained results show an average air change rate value of $0.55h^{-1}$. Moreover, the variability of the CO_2 concentration throughout the space was also analysed for different positions, using CO_2 data loggers calibrated as the reference and real-time sensors. It was concluded that no optimal position of sensors was observed for a single zone, due to the small swing attained for different sensors positions.

1. Introduction

The future of buildings, both new and existing, is highly influenced by the technological evolution and availability of innovative solutions for energy management systems. The opportunity of increasing the high level of connectivity and smart systems implementation in buildings has been pointed as the main target with respect to the energy efficiency of buildings [1]. However, the indoor environmental conditions in smart buildings must be highly influenced by the users preferences and habits [2].

Smart buildings enable the control and monitoring of buildings using smart sensors, which can provide real-time information, as well as a centralised platform, providing consolidated data collection, analysis, and reporting [3]. The smart sensors are the new generation of sensors, allowing the monitoring

and control. Moreover, they enable more accurate and automated collection of data with fewer errors on the recorded information [4].

In the perspective of Indoor Air Quality (IAQ) the CO_2 concentration works as an indicator to achieve healthy building and user wellbeing [5]. In low energy buildings, mainly in well insulated modern and airtight buildings not equipped with mechanical ventilation, the CO_2 monitoring play a key role in natural ventilation control, by windows openings. For instance, the smart sensors measuring in real-time can detect the CO_2 concentration and provide air quality alerts to the user [6]. On the other hand, by measuring the indoor CO_2 concentration the ventilation performance can be indirectly estimated [7]. However, the accuracy of CO_2 measurements has limitations depending of the sensors positions, since not able to detect variations of ventilation rates [8]. Buggenhout et al (2009) [8] findings showed that large errors are related with the variability of ventilation rates, especially concerning the tracer gas method application.

The goal of the paper is to estimate the accuracy of the real-time sensors using real data from an experimental research. The effect of sensors position(s) for the CO_2 concentration determination into a single zone test room was also evaluated. Two different types of sensors were tested in the experiments. The current research is a preliminary CO_2 model study of a predictive methodology and framework addressing the energy and indoor environmental concerns for better user's wellbeing, quality of life and healthy smart buildings.

2. Experimental setup

2.1. Test room definition

A test room, located in Aveiro region in Portugal, near to the coast (18 km), was selected as case study. The test room (Figure 1) is composed by a single zone, representative of a typical room of residential building. The most relevant geometric properties are resumed in Table 1. The constructive solutions adopted for the test room represent a traditional massive constructive solution commonly found in Portugal. The floor is composed by a concrete slab without thermal insulation and the roof is a lightweight slab with 12 cm of external thermal insulation. The wall consists of single brick masonry wall with 6 cm of external insulation. The window solution (without solar protection) is composed of 24 mm double glazing (6 mm clear glass + 14 mm air + 4 mm clear glass) and a wooden frame. The U_{value} of the constructive solutions are presented in Table 2.

Figure 1. Experimental test room view.

Table 1. Geometric proprieties of test room.

Orientation	Southeast
Area (m^2)	12.00
Volume (m^3)	32.40
Window area (m^2)	1.50
Door area (m^2)	1.73

Table 2. Thermal characterisation of constructive solutions.

Solutions	U_{value} (W/m^2·ºC)
Floor	1.25
Walls	0.36
Window/Door	1.90
Roof	0.28

In the test room there are no mechanical or natural ventilation system or ventilated grids. The ventilation of the test room is driven naturally, according to the external conditions, as infiltration by the window or door.

2.2. CO₂ measurements test

Two different CO_2 sensors were used in the experiments. The first one is a reference commercial data logger sensor (A), which is defined as the reference case for comparison purposes. According to the manufacturer, the equipment's accuracy is ±50 ppm or ± 5% of reading (in the range of 0 – 2000 ppm). The second one is a prototype sensor (B) to be included in smart management systems, which uses IoT technology, enabling the data access via internet and has an accuracy of ±30 ppm or ± 3% of reading (in the range of 0 – 2000 ppm). Both use the high precision Non-Dispersive Infrared (NDIR) technology to measure the CO_2 concentration levels.

According to some authors [8], the sampling position is an important factor for the results of tracer gas measurements. However, the geometric complexity of the space must also be taken into account. In order to study the influence of the sensors' location on the CO_2 concentration, three experiments were carried out, following the configurations presented in Figure 2. In the same horizontal plane, the sensors were positioned in five points (P1 to P5), taking the occupant(s) position as reference: left, right, front, rear and above the occupant(s). In a vertical profile the sensors were located in three positions: 1) the lower position at a height of 0.5 m above the floor; 2) the middle position at a height of 1.35 m above the floor; and 3) the upper position with the sensors at a 0.3 m beneath the roof. For a simple identification of the positions, the following 2-digit code was implemented: first the horizontal place is identified and second the position number in the vertical plane, as shown in the experimental apparatus (see Figure 3). In total, 15 locations were assessed. The CO_2 concentration at each position was recorded with a time step of 5 minutes. An additional sensor was used to continuously record the outdoor CO_2 concentration.
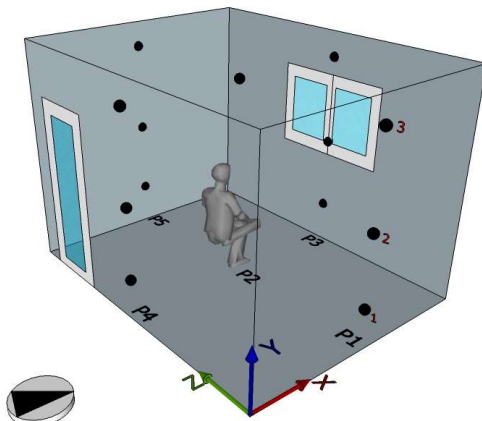

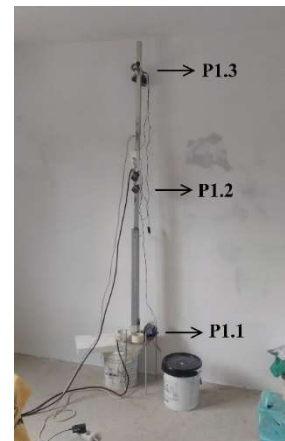Figure 2. 3D configuration of the sensors in the test room.

Figure 3. Experimental apparatus – P1.1, P1.2 and P1.3 positions.

The experiments started with the window and door closed and the CO_2 concentration increased due to the occupants' metabolism. When the CO_2 concentration in the room reached the interval between 1200-1700 ppm, the occupants left the room and the fresh air from the infiltrations led the decreasing of CO_2 concentration. The experiment stopped when the half of initial CO_2 concentration decay was attained. With this methodology it is possible to estimate the air change rate (*ACH*) of the space by applying the decay technique to the unoccupied period (see section 2.3).

The differential equation that establishes the general mass balance of a gas (CO_2 in this case) is the following [7]:

$$V \cdot \frac{dC_i(t)}{dt} = G_{CO_2}(t) \cdot 10^{-6} + D(t) \cdot C_e(t) - D(t) \cdot C_i(t) \tag{1}$$

where V is the test room volume (m³), t is the time (h), $Ci(t)$ is the indoor CO_2 concentration at a time t (ppm), D is the volumetric airflow rate into (and out of) the space (m³/h), $C_e(t)$ is outdoor CO_2 concentration (ppm), $G_{CO2}(t)$ is the CO_2 generation rate in the space at time t (m³/h).

If $G_{CO2}(t)$, $C_e(t)$ and $D(t)$ are assumed constant during the time t-t_0, Eq. (1) can be solved by integration obtaining the equation (2) for $C_i(t)$ with initial condition at t_0:

$$C_i(t) = C_e + \frac{G_{CO_2}}{D} + \left(C_i(t_0) - C_e - \frac{G_{CO_2}}{D}\right) \cdot e^{-\frac{D}{V} \cdot t} \tag{2}$$

where $C_e = C_e(t_0)$, $G_{CO_2} = G_{CO_2}(t_0)$ and $D = D(t_0)$.

2.3. CO_2 concentration decay method – ACH calculation

In the experiments, the *ACH* was measured through the tracer gas decay method, using the occupant-generated CO_2 concentration as a tracer gas. According with standard guide ASTM D6245 (2012) [11] and ASTM E741 (2000) [12], the measurement of *ACH* is started after the occupants leave the space. The tracer gas decay method assumes that the outdoor tracer gas concentration is neglected, which is not the case of the outdoor CO_2 concentration. However, if the outdoor CO_2 concentration is constant during the test, then the tracer gas decay method can be used by substituting the difference between the indoor and the outdoor CO_2 concentration. Assuming that the outdoor concentration (C_e) is constant and no incidental sources of the tracer gas are present during the decay measurement, the equation (2) can simplified by the equation (3):

$$C_i(t) = C_i(t_0) \cdot e^{-\frac{D}{V} \cdot t} \tag{3}$$

Rearranging the equation (3), the *ACH* can be by the equation (4):

$$-ACH = -\frac{D}{V} = \frac{ln\left(\frac{C_i(t)}{C_i(t_0)}\right)}{t} \tag{4}$$

From the equation (4) the decay curve for the CO_2 concentration can be plotted, in which ln(C(t)) in function of time t produces a straight line of slope equal to $\left(\frac{D}{V}\right)$, representing the *ACH* during the experiment period (see section 3.1).

3. Results and discussion

3.1. Air change rate results

The air change rate of the test was assessed through three experimental tests. The results ranged between 0.44 and 0.66 h^{-1} (see Table 3) with an average value of 0.55 h^{-1}. The low variability recorded (coefficient of variation was 16.5%) is an indicator of a good agreement between tests. Nevertheless, the difference between tests is expected, since the ACH result is highly influenced by the outdoor conditions, namely the wind speed and direction. For these tests, only one CO_2 sensor was used and positioned in the centre of the test room. Figure 4a shows the evolution of the CO_2 concentration throughout the test and Figure 4b highlights the logarithmic decay plot, ln(C(t)), used for the *ACH* determination, including the maximum and minimum error values taking into account the accuracy of the sensors. This procedure allowed to estimate the uncertainty on the results. The red line represents the maximum slope and the green line the minimum slope of the test 3 (see Figure 4b). Table 3 shows the *ACH* results with the respective value of uncertainty associated to the accuracy of the sensors given by the technical datasheet.

Table 3. *ACH* of the tests.

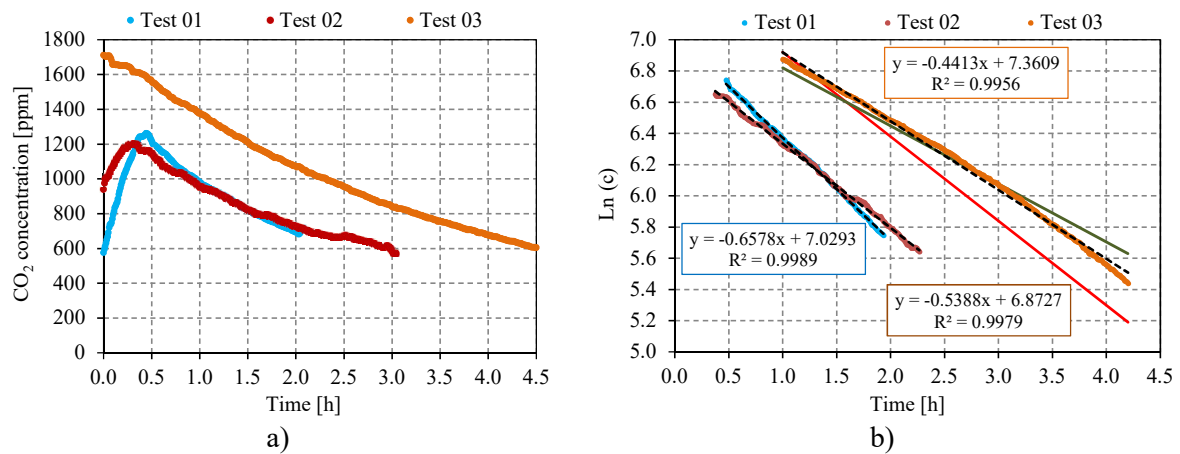| Test#	*ACH* (h^{-1})
01	0.66 ± 0.15 (23.1%)
02	0.54 ± 0.13 (24.0%)
03	0.44 ± 0.08 (19.1%)

Figure 4. CO_2 decay: a) Measured CO_2 concentration and b) logarithmic plot of the decay curves.

3.2. Analysis of CO_2 concentration for different sensor positions

Two sensor position scenarios for measuring the evolution of CO_2 concentration were defined in two separate tests: 1) same location in plan with the sensors at different height (see Figure 5a); and 2) different plan location with the sensors at different height (see Figure 5b).
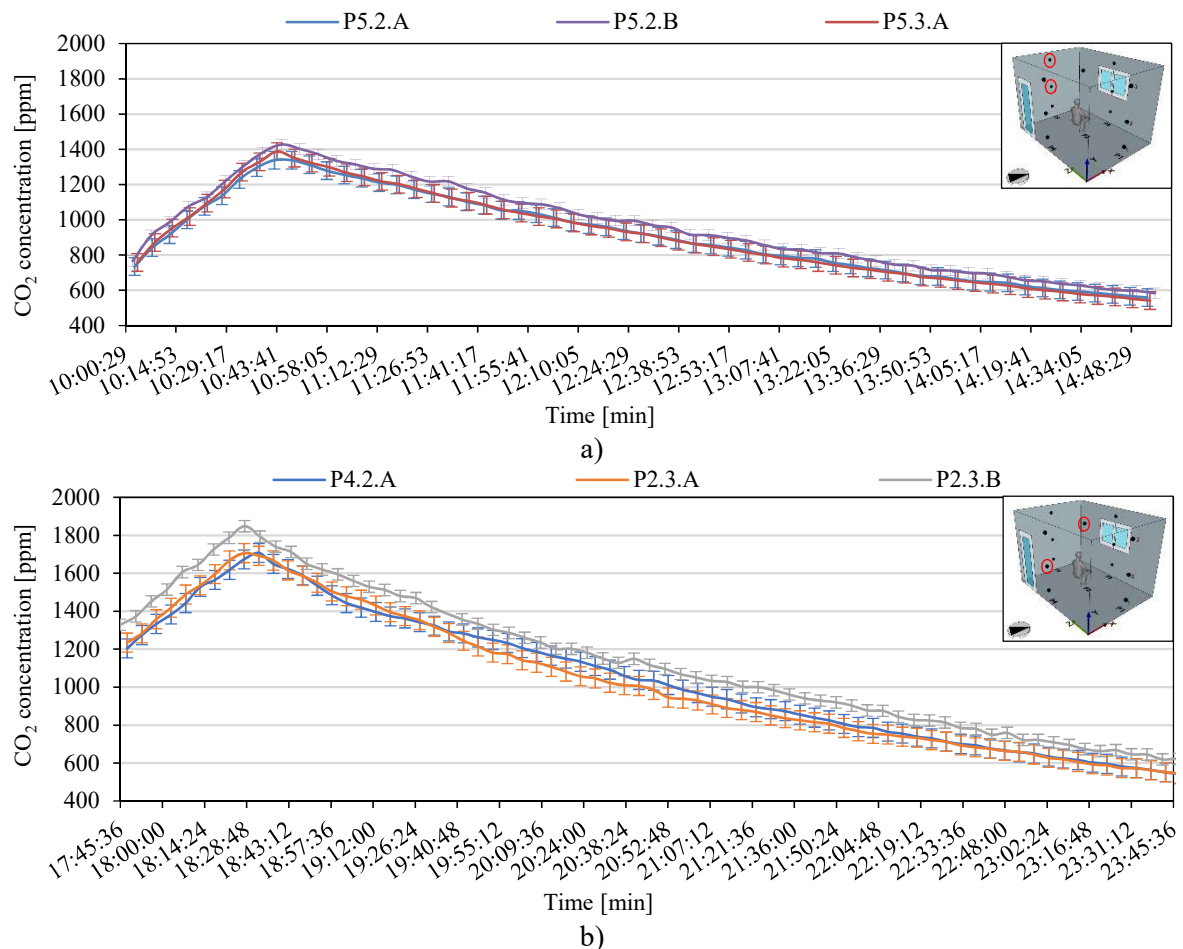

a)

b)

Figure 5. Evaluation of CO_2 concentration in different sensor position: a) same location in plan with the sensors at different height; and b) different plan location with the sensors at different height.

Regarding the plots (see Figure 5), the error bars represent the uncertainty given by the sensor manufacturer (see section 2.2). From the results plotted, the differences between sensors (A and B – see section 2.2) in the same position are within the uncertainty of sensors, visible by the overlapping error bars during the whole recording time (see Figure 5a). However, the CO_2 concentration recorded by sensor B presents slightly higher values in comparison with sensor A. Regarding the evolution of CO_2 concentration in scenario 2) (see Figure 5b), once again, the differences are within the uncertainty of sensors, in both CO_2 concentration readings for different sensor positions.

4. Conclusions and future work

Preliminary CO_2 experimental tests were conducted resourcing to the concentration decay method. Three tests were carried out to assess the CO_2 decay and the analysis of CO_2 concentration in five different positions inside the test room. From the results, two main conclusions can be stated:

- A good agreement of *ACH* tests was achieved with a coefficient of variation of 16.5% for an average value of 0.55 h^{-1}.
- The results from the different sensor position tests revealed a low variability of CO_2 concentration measurements for different sensor positioning.

This study presents the experimental test approach needed for the development of a real-time prediction methodology based on both physical models and artificial intelligence. Thus, the next step is to provide a calibrated and validated CO_2 physical model to implement in the CitySim software, for different scenarios using real test data.

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