Testing of a Tracer Gas Based Measurement Procedure to Assess Air Change Rates in Buildings

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ABSTRACT

Buildings energy audits ask for a thorough analysis of the audited object. According to standards EN 16247, all the factors affecting actual energy consumption must be assessed and estimated. One of the hardest contributions to be quantified is air change rates of buildings, particularly when no mechanical air supply system is installed. In this case, just air leakages through the external envelope and users' behaviour (e.g. opening of doors and windows) will determine the actual figures of air change rates. As a consequence, no direct measurement can be made. Among the indirect measurement approaches, the procedure using the decay of indoor carbon dioxide concentration provided good results, as described in literature. However, a number of disturbing factors must be considered, because they affect the transient behaviour of air exchange between indoor and outdoor.

This paper will provide more insights into the possibility of developing a testing kit for the energy auditor, so that they can evaluate air change rates of buildings through quick on-site surveys in the audited object, then the information thus collected can be used as an input for the energy audit process. Such a challenge requires the development of a quite cheap, easy to install and low invasive monitoring kit, which is based on state-of-the-art wireless and low power monitoring technology. In addition, data analyses must be quick and partially automated. Finally, a preliminary test performed in a room of the Engineering Faculty at the Università Politecnica delle Marche in Ancona (Italy) will be reported.

Keywords –

Energy audit; Air leakages; Tracer gas

1 Introduction

The purpose of an energy audit process of existing buildings is to evaluate actual energy consumption, to perform an overall diagnosis and suggest how energy behaviour of buildings can be improved. According to standards of the series EN 16247, several requirements must be fulfilled and many contributions must be considered while looking for energy saving opportunities [1]. Among these contributions, the assessment of air leakage through the building's envelope seems quite hard to estimate, moreover wherever no mechanical air supply system is running.

The purpose of this study is to test a methodology for the energy auditor to experimentally investigate air leakage rates through buildings. This same methodology may be applied at any time during the life cycle of buildings, so as to investigate the degradation, in terms of air leakage, of the overall building's envelope, as it changes performances over time.

The approach to the problem was suggested by the work of Andrew K. Persily, who presented some techniques to evaluate building ventilation and indoor air quality, that involve the measurement and analysis of indoor carbon dioxide concentration [2]. The methodology described in that research project exploits a tracer-gas decay technique, in which the tracer gas is the carbon dioxide generated by the occupants of a single zone space, and the measurement is conducted when people leave the building.

The standard approach regarding measurement of concentration decay is described in the ASTM Standard E741 [3]. This test method applies to a place or set of places defined as "single zone" spaces, where the tracer gas concentration can be maintained at a uniform level and the air exchanges are only allowed with the outdoors.

Another application of the CO_2 tracer-gas method for air leakage was presented by C.J. Ghazi and J.S. Marshall [4]. Their study, supported by laboratory tests, analyzed the accuracy of this method for detecting and characterizing leakage flow through a selected area or component in a structure, such as a hatch or a window. The drawbacks reported by the authors about this concentration-decay test are: need for large amounts of tracer gas, which should be equally mixed within the entire test volume; provisory unavailability of the testing area for usual activities; need for enduring presence of operators on site during the tests. The experimental method, that will be described in the following of this paper, attempts to overcome those constraints, because it can be carried out while users are performing their normal activities. It is made possible thanks to the use of a non-invasive and cost effective sensor setup, and by the use of the carbon dioxide generated by the occupants as gas-tracer. Finally, the methodology tested in this paper concerns the overall evaluation of air leakages in a room or environment, that will be not specifically targeted to particular units of a building envelope.

The state-of-the-art is discussed in Section 2, followed by a description of the experimental method in Section 3. Data gathering, processing and analysis of results are provided in Section 4. Conclusions are given in Section 5.

2 State of the Art

The development of the experimental method started from the suggestions received by Andrew Persily's article about the evaluation of indoor air quality and ventilation of buildings [2]. It is useful to consider this aspect in some situations, such as building commissioning, proactive building management, diagnosis of indoor air quality complaints, investigation of building energy consumption, as Persily stated in his contribution. In his work the focus of the evaluation is targeted to the measurement and analysis of indoor carbon dioxide concentrations, that will serve some specific applications, including the energy audit of buildings.

The criticality of the carbon dioxide concentration parameter is due to a couple of aspects. The first one concerns emission of carbon dioxide by users, which depends on their physical activity and their size. This process affects the concentrations of carbon dioxide mainly in terms of body odour acceptability. The second one is the use of carbon dioxide as a tracer gas whose decay will allow to evaluate building's ventilation rate. Three techniques that can support the second aspect were described. The first one focuses on the evaluation of the percentage of outdoor air intake at an air handler; the second one calculates air change rates of a building using the tracer gas decay method; the third one estimates outdoor air ventilation rates based on equilibrium analysis [2]. More specifically, the focus of this paper is on the tracer gas decay measurements and the technique in which occupants are the source of carbon dioxide.

For the calculation methods and the requirements to comply with, the main reference is the ASTM Standard E741 [3]. This standard test method describes three techniques to determine the air change rate of a single zone by means of a tracer gas dilution. A single zone is a place or a set of places in which the uniformity of tracer-gas concentration is guaranteed. The three discussed techniques are: constant injection, constant concentration and concentration decay [3]. Constant injection is a procedure to calculate the average air change flow; it involves injecting uniformly a tracer gas into a zone at a constant rate, ensuring a uniform concentration and measuring tracer gas concentrations at predetermined time moments. Constant concentration is a procedure to evaluate air change flow, which is necessary to keep a zone at a constant concentration of a tracer gas. Concentration decay involves a small volume of a tracer gas which is introduced uniformly into a zone. The uniformity of the concentration is controlled and measurements of the tracer-gas concentrations are recorded at predetermined time moments [3].

Our study is relative to the procedure for the concentration decay test method. The Standard E741 provides all the information to prepare the test, the requirements about the testing area and the sampling methods. It also provides the equation to calculate the air change rate. In the standard's appendix there is a list of available tracer gases, even if no reference was found here about carbon dioxide generated by occupants.

A real application of the tracer-gas dilution method was developed in the Ghazi and Marshall's study [4]. They designed and performed a method to verify the accuracy of the tracer-gas method to detect air leakage rate of a single building component. Their work is supported by laboratory experiments and numerical simulations. Results are in agreement with each other and also complied with empirical equations found in literature. Hence this method can be used to define the local air leakages. However, they underline some negative aspects of the tracer gas method linked to the development of the method in a large scale for assessing the overall performances of buildings. The main difficulties are: the need for a large amount of tracer gas; the necessity of maintaining uniformity of gas concentration and of avoiding breaks in the occupants' activities.

In the following sections an experimental method to overcome these problems will be presented. In these tests, the CO_2 generated by the occupants of the testing area will be used as tracer gas. This choice allows to reduce costs and the quantity of injected gas. As a seamlessly installable equipment to remotely monitor tracer-gas concentrations was used, this procedure prevents the interruption of normal activities within buildings. Finally, the recorded measurements of the CO_2 concentration decay, which will be discussed later, showed that this tracer gas is capable of diffusing uniformly around the test area.

3 Experimental Method

The test of our method was carried out in the Engineering Faculty at the Università Politecnica delle Marche, Ancona, Italy. The testing area was a classroom, located at an altitude of 155 m above sea level.

Among the techniques using tracer gas dilution, according to ASTM Standard E741, the concentration decay was chosen, in order to determine the classroom's overall air change rate. This method evaluates air change rates expressed as 1/h or 1/s, provided that a large amount of gas-tracer detections are analysed. On the contrary of what suggested by the ASTM Standard, the tracer gas used for this test was the carbon dioxide emitted by the occupants of the testing area, because this is one of the novel aspects suggested by this paper. Instead, all the other instructions by the standard were followed. Among them, the concentration uniformity requirement was to ensure that the tracer-gas concentration at any point was no more than 10% different from the average value of the concentration in the test room.

The classroom has a rectangular shape, whose area is approximately 110 m^2 and whose volume is 383 m^3. Two doors are located on the shorter side of the classroom to connect it with the hallway and a windowed wall is located on the opposite side.

As far as it concerns the measurement set, automatic samplers were used, they were integrated in five sensors: three of them were placed on the long sides of the room (S701, S703 and S704); another sensor (S705) was placed in the hallway and another one was located outdoors, installed on the window's glass (S702), as shown in Figure 1. The analysis of CO_2 concentrations was made automatically during the sampling and performed in the classroom using a laptop. However, the system is such that it allows to process those data even remotely.

The five samplers installed Cozir Ambient sensors, a third generation product from Gas Sensing Solutions Ltd. Cozir is an ultra low power (3.5mW), high performance CO_2 sensor, with a low noise measurement (<10ppm) and a measurement range of 0-2000ppm, 0-5000 ppm, and 0-1% accuracy level. In addition to the CO_2 sensors, three pressure-temperature sensors (P152, P153, P154) were placed, respectively, one inside the classroom, one outside and one in the hallway, as depicted in Figure 1. They are digital pressure sensors (BMP085 manufactured by Bosch) with a pressure range between 300-1100 hPa. Other relevant features are: temperature measurement included; a low power (5µA at 1 sample/sec. in standard mode) working mode; a low noise measuring mode (0.06hPa -0.5m- in ultra-low power mode, 0.03hPa -0.25m- in ultra-high resolution mode). These pressure sensors were arranged in the testing area to take into account boundary conditions, such as temperature and pressure. In fact, the decay of a gas is affected by these parameters, so their values must be known when the results from measurement must be compared with other tests.

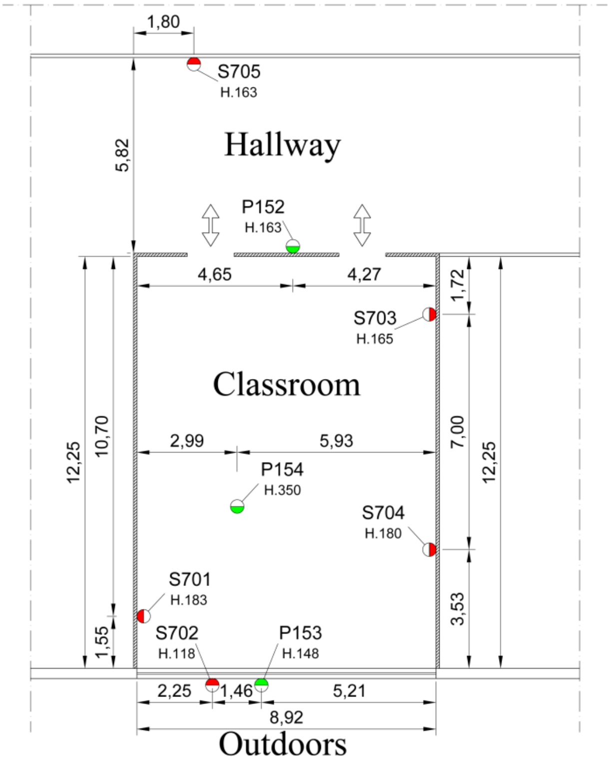

Figure 1. Plan diagram of the testing area and the arrangement of the sensors

The communication system was based on the SmartNetwork Platform, an ultra-low power wireless technology [5]. This wireless architecture includes three levels of devices: one or more coordinators, routers and sensors. Routers forward messages across the network devices, they provide network area coverage and also backup routes in case of network congestion or device failure. Interaction among the three levels of devices make the overall communication possible. The PAN coordinators are used to initiate network formation; routers are responsible for performing multi-hop routing of messages; end devices act as multi-purpose sensors and do not have routing capabilities. This technology allows to reduce the consumption of batteries, down to the order of a few years [5].

The test was broadly divided into two main parts:

during the first one, the tracer-gas was allowed to accumulate and distribute throughout the test room, and it lasted for four hours; the second one included sampling and gathering of experimental data for the estimation of air change rate, that ran for seven hours. This second phase was carried out once that the two doors had been sealed and while the area of analysis was kept empty. All the activities within the classroom were monitored, with particular concern to those affecting the results from the test, such as doors and windows opening. The windowed surfaces were kept closed for all duration of the test. As a result, the main phases of the test are reported in Table 1. Figure 2 shows that our test was conducted without interrupting the didactic activities.

Table 1. Operational phases of the entire test

Time	Actions
08.15 am	Switching on of the sensors
08.50 am	Beginning of the lecture and of the main measurements (windows closed from now on)
09.45 am	Occupants in the classroom were 58
09.48 am	Break during the lecture (doors open and windows closed)
10.00 am	Lecture started again (both doors and windows closed)
10.32 am	End of the Lecture (doors open and windows closed)
11.00 am	Start of the second lecture (both doors and windows closed)
11.30 am	Occupants in the classroom were 38
11.42 am	Break during the second lecture (doors open and windows closed)
11.51 am	Second lecture started again (both doors and windows closed)
12.33 pm	End of the second lecture (doors open and windows closed)
12.42 pm	Closing of doors and their sealing with adhesive tape, that determined the beginning of the decay test
07.15 pm	Doors opened again and end of the decay test

Figure 2. The accumulation phase of the test and the displacement of the indoor CO_2 sensors.

4 Experimental Campaign

The data collected during the test were necessary to calculate the air change rate. This phase of sampling can be divided in two parts: the first one is the testing, with the collection of data; the second one is the presentation and analysis of the results.

4.1 Testing

The first part of the test concerned the tracer-gas accumulation, generated by the occupants of the classroom. It lasted over four hours, from 08:15 am to 12:42 pm, but the main phase of the measurement period started at 08:50 am. The data collected by the three indoor sensors for the CO_2 concentration were 222, that is about one record per minute. Data of concentrations (C) were measured in ppm, then they were expressed in m^3/m^3 (tracer-gas volume/ room volume). Once they had been processed, they were reported in logarithmic scale, according to ASTM E741. Following the Standard requirements, the uniformity of the CO_2 concentration at the beginning of sampling (8.5.2 and 12.4.1 of the Standard E741) was checked, too. In our case was the beginning of the sampling phase superimposed with the end of the accumulation phase. It was checked that respective values, as detected by the three sensors, didn’t differ more than 10% from the average value of the concentration [2], as shown in Table 2.

Table 2. Checking of the uniformity of the CO_2 concentration at the end of the accumulation phase

Type of Data	lnC
S701	-6.413
S703	-6.443
S704	-6.596
Average	-6.484
10%	-0.648
Max Value acceptable	-5.836
Min Value acceptable	-7.133

As visible from Table 2, each sensor used confirmed the uniformity of the gas-tracer concentration required.
In the accumulation period, measurements were taken under known boundary conditions, that consisted in an average indoor temperature equals to 24,35°C and an outdoor one equals to 14,6 °C; the average indoor and outdoor pressure values were, respectively, 99895,64 Pa and 99919,90 Pa.

The second part of the test was that one pertaining to concentration decay. It lasted about seven hours, from 12:43 pm to 7:40 pm. From these seven hours long monitoring phase, the data were extracted and processed to get the results of the test. The data collected by the three indoor sensors for the CO_2 concentration were 400, that is about one record per minute. The data about the concentration (C) were measured in PPM, then were expressed in m^3/m^3 (tracer-gas volume/ room volume). Then, they were reported in logarithmic scale to calculate the air change rate, according to ASTM E741. At the end of the sampling, the uniformity of the CO_2 concentration (8.5.2 and 12.4.1 of the Standard E741) was checked again. It was verified that detected values didn't differ more than 10% from the average value of the concentration, as shown in Table 3.

Table 3. Checking of the uniformity of the CO_2 concentration at the end of the decay phase

Type of data	lnC
S701	-7.509
S703	-7.528
S704	-7.603
Average	-7.547
10%	-0.755
Max Value acceptable	-6.792
Min Value acceptable	-8.301

As reported in Table 3, the uniformity of the gas-tracer concentration was guaranteed. During the decay period, the test was conducted with an average indoor temperature of 21,6°C and an outdoor one of 13 °C; an average indoor pressure of 99922,72 Pa and an outdoor one of 99924,70 Pa.

In the next section the results from the test are presented and the graphs of the tracer-gas accumulation and decay are provided.

4.2 Analysis of the results

The aim of the test consisted in finding the decay curve of the carbon dioxide and the air change rate, as described in the "Procedure for the Concentration Decay Test Method" in ASTM Standard E741[3] and also reported in the paper by A. K. Persily [2].

The air change rate (Ā) was calculated by the average method [2], whose equation is:

$$\bar{A} = \frac{\ln C(t_2) - \ln C(t_1)}{t_2 - t_1} \quad (1)$$

where C(t) is dimensionless, as already said in section 4.1, and it represents the tracer gas concentration at the beginning of the test $C(t_1)$ and at the end of the test $C(t_2)$; $(t_2 - t_1)$ is the difference between end time and starting time expressed in hours, that in our case is 7 h. Three values of average air change rate are given, one for each sensor placed in the testing area:

Ā = 0.157 h^{-1}, as of the S701 sensor;
Ā = 0.158 h^{-1}, as of the S703 sensor;
Ā = 0.145 h^{-1}, as of the S704 sensor.

The rates are presented in absolute value, in fact $\ln C(t_2) - \ln C(t_1) < 0$ because it concerned a decay test, so the air change rate is a negative value. In the following, the plots of tracer gas accumulation and decay are shown and discussed.

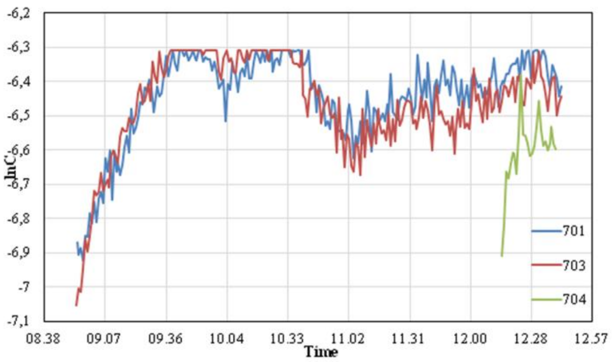

Figure 3. The CO_2 concentrations recorded by the three sensors during the accumulation phase

Figure 3 shows the trend of the carbon dioxide during the accumulation phase, recorded by the three sensors inside the classroom and expressed by means of the natural logarithm of the concentration. The graph of the sensor S704 starts at about 12:09 pm because it was not working prior to that time. However this occurrence did not compromise the possibility to work out the final coefficients.

In this first phase, the highest recorded concentration of CO_2 is 2001 ppm (lnC= -6.310) and it was reached already in the first lecture in the morning, before falling to lower values during the break; the faster descent occurred during the switching time between the two lectures. For the sake of completeness, the highest values of the other two sensors are provided: 582 ppm outdoors and 1041 ppm in the hallway.

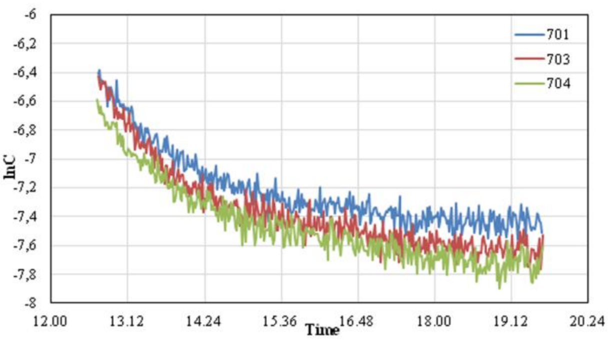

Figure 4. The CO_2 concentrations recorded by the three sensors during the decay phase

Figure 4 shows the decay of the carbon dioxide expressed by means the natural logarithm of the concentration, recorded by the three sensors inside the testing area. Similar results were obtained by the three CO_2 sensors. It was found out that the most significant decay occurred between 1:00 pm and 3:00 pm.

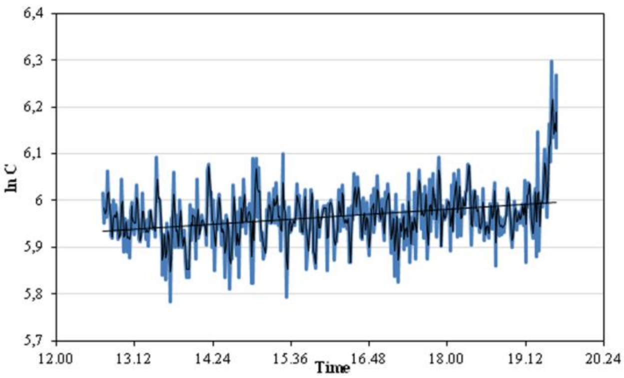

Figure 5. The CO_2 decay monitored by the sensor S702 outside

In Figure 5 the trend of the concentration decay outside is plotted; it is to be noticed how the curve increases as the CO_2 falls inside. Anyway this plot is not useful to calculate the decay as provided by the ASTM Standard, because it is a trend of the gas concentration outdoors. The plot of CO_2 decay in the hallway is not depicted because the recorded data were affected by the continuous presence of people stationed too much close to the S705 sensor.

In order to provide an overall picture of all the parameters taken into account, the trend of the indoor/outdoor temperature-pressure during all the test was also shown (see Figures 6-7). As already said, these boundary conditions could influence on the air leakage, thus in the next tests the average air change rate may be put in relation with them.

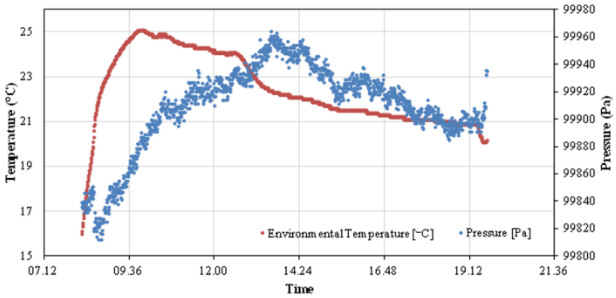

Figure 6. Data collected of indoor temperature and pressure

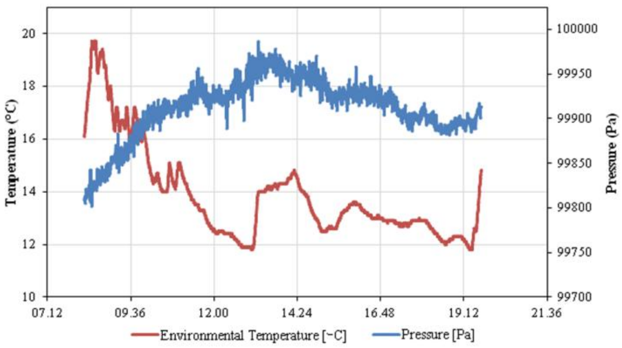

Figure 7. Data collected of outdoor temperature and pressure

5 Conclusions

It is important for an energy auditor to analyze ventilation performance of a building and to detect the air leakages, which contribute to the energy losses and consequently to the increase of energy consumption.

The evaluation of carbon dioxide concentration based on the tracer-gas technique can be useful to obtain such information. In this study a different but effective application of the CO_2 tracer-gas method has been proposed. The test was conducted according to the Standard ASTM E741 except for the injection method of CO_2, generated by the occupants. The average air change rates were calculated for each sensor and their values demonstrated the reliability of the test, of the assumptions and of the displacement of the sensors setup. In fact the maximum gap between the average air change rates is no higher than 9% (= $(\bar{A}_{max} - \bar{A}_{min})/\bar{A}_{min}*100$).

Since it has been tested the reliability of this experimental method, in our future research another decay test may be carried out to monitor the trend of the CO_2 in the same zone for a longer time, over several days. In addition further tests may be carried out while monitoring the behaviour of other parameters and boundary conditions.

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