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Natural ventilation measurements in a multi-room dwelling: Critical aspects and comparability of pressurization and tracer gas decay tests

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Abstract

Ventilation in built environments is essential to guarantee a good indoor air quality and a reduced probability of infection related to virus transmission. Measuring ventilation-related parameters is not easy and currently two methods can be adopted: pressurization and tracer gas decay. The pressurization test measures the airtightness of the building, whereas the tracer gas decay test measures the actual (site- and climate-specific) air exchange rate. Finding a relationship amongst the results provided by the two tests would be very useful in view of an exhaustive characterization of the building ventilation, but it still remains an open challenge for the scientific literature. The present paper aims at investigating the criticalities in correlating the two methods; thus, an experimental campaign was performed in a multi-room dwelling performing both air permeability and air ex- change rate measurements in the entire dwelling and in parts of it. A detailed uncertainty budget of the two methods was also carried out in order to perform metrological compatibility analyses.

The results of the campaign highlighted that the actual air exchange rates of the dwelling present a huge variability (from <0.2 to almost 1 h-1) due to the weather conditions. Consequently, the conversion factor be- tween the air exchange rates at 50 Pa, provided by the blower door tests, and the actual air exchange rates, obtained through the tracer gas decay tests, ranged from <20 to >100, with an exponential decrease as the wind velocity increases. Thus, adopting constant conversion factors could significantly overestimate the actual ventilation of the building.

Keywords:

Blower door test, Tracer gas decay test, Pressurization test, Ventilation, Air exchange rate, Uncertainty budget

1. Introduction

The ventilation represents a key aspect in the building design as it is related to both energy saving and indoor air quality of built environments [1-11]. Indeed, the current inclination of the recent technical standards and regulations in the field of energy performances of buildings is reducing the energy losses as much as possible [12-25], then leading to even more airtight buildings aiming at minimizing the ventilation losses too.

Nonetheless, reducing the outdoor-to-indoor air exchange rates of built environments has led to worse indoor air quality, i.e. made slower the exfiltration of indoor generated pollutants towards outdoors [26-29]. This is even more true for countries characterized by temperate climates where ventilation mainly relies upon the leakages of the building (natural ventilation) and the manual opening of the windows based on the air quality perception of residents (manual airing), whereas no mechanical ventilation systems are typically adopted [12, 30-33]. The ventilation strategy of the buildings has recently gain popularity due to the COVID-19 pandemic, in fact, a number of papers demonstrated the airborne transmission route of the virus [34-36], then confirming the key role of increasing the air exchange rates to reduce the probability of infection indoors and, then, to limit the spread of the pandemic [37-39].

Knowing the ventilation rates of buildings would be extremely useful to perform both (i) proper estimates of the energy consumption of the buildings and (ii) predictive risk assessments for people exposed to pollutants or infectious agents emitted indoors. As regards the energy consumption, actual values of ventilation rates would allow calculating the actual energy losses due to ventilation, which represent the main cause of energy losses in well insulated buildings [4,7,14,22]. Concerning the exposure to pollutants and infectious agents, and the related risk assessment, measured ventilation rate values would allow the estimate of indoor concentration of pollutants/infectious agent (if the pollutant emission rates of the source are known [38,40,41]) just adopting simplified mass balance equations; then, corresponding dose and risk could be evaluated adopting ad-hoc dosimetry and dose-response models [38,39,42-45].

1.1. Measurement of ventilation rates in buildings

Measuring the ventilation-related parameters of the building is not an easy task, indeed two different methods can be adopted to characterize the ventilation of built environments (and both present pros and cons): the pressurization method and the tracer gas decay method. The pressurization method (also known as Blower Door Test, BDT) is actually a measurement of the airtightness of the building. It is defined by the technical standard ISO 9972 [46], which allows to determine the ventilation rates through the building envelope under a fixed indoor-outdoor pressure difference, which is higher than the natural pressure differences. Indeed, in order to reduce possible artifacts related to the outdoor meteo-climatic conditions (e.g. wind), the pressurization method provides an air exchange rate under an indoor-outdoor pressure difference of (typically) 50 Pa. Therefore, the BDT is a repeatable test which is able to characterize the airtightness of the buildings and to classify them according to resulting quantities (e.g. the abovementioned air exchange rate at reference pressure difference, the air leakage rate at the reference pressure difference referred to the building envelope area or to the net floor area, etc.), however actual air exchange rates can hardly be derived from BDT data.

On the contrary, the tracer gas decay method, described by the standard ISO 12569 [47] allows to measure the actual air exchange rate of a confined space (considered as a single-zone) as a function of the specific meteo-climatic conditions of the measurement period. Indeed, buildings exposed to similar meteo-climatic conditions may present strongly different indoor to outdoor pressure differences due to height, orientation, and shape of the buildings as well as to the presence of shields and the use of the openings (doors, windows). The method is merely based on the measurement of the dilution rate of a tracer gas previously injected in the closed environment. Unlike BDT, the tracer gas decay method is not repeatable by definition as it provides actual air exchange rates as a function of the specific measurement conditions [48,49].

1.2. Research gaps and needs

In view of estimating the actual ventilation rates of the buildings under different boundary conditions, e.g. different meteo-climatic conditions, correlating BDT results and actual air exchange rates from tracer gas decay tests would be crucial. Indeed, if a relationship between BDT and tracer gas results were determined, the actual air exchange rate as a function of the weather conditions could be determined a-priori just performing (i) a single pressurization test of the building to characterize its airtightness and (ii) measurements of site-specific weather conditions, which could easily be obtained from a local weather station, to gather information regarding wind direction and velocity at each moment.

Actually, a few number of scientific studies attempted to find a correlation between the air permeability and air exchange rate results in order to provide simplified relationships (or conversion factors) to estimate the air exchange rate of a building just using air permeability results provided by a single BDT [31,50–55]. The most comprehensive attempt was carried out by Sherman [54] who derived a conversion factor map for the United States considering the typical site climates of each area of the country, he estimated an annual conversion factor of about 20 with (roughly ranging from 10 to 30). Similar ranges of con- version factors were then obtained for European homes [50]. Nonetheless, such poorly differentiated conversion factors (in terms of sites, averaging times, and weather conditions) remark that finding proper and detailed relationships between blower door and tracer gas tests is still an open research question worthy of further investigations.

An additional aspect to be mentioned and investigated is the effect of the geometry of the zone tested; indeed, both pressurization and tracer gas decay methods can be carried out either in single rooms or in entire dwellings if building preparation and test constraints suggested by the standards are met (e.g. guaranteeing homogeneous tracer gas concentrations within the single zone under testing, sealing unexpected openings during the blower door test, etc.). Nonetheless, no particular indications about performing such tests in dwelling characterized by multiple rooms and complex dwelling layouts are provided.

1.3. Aims of the work

In view of the research gaps and needs mentioned above, in the present paper the two measurement methods are discussed and the criticalities in correlating the results they provide are analyzed. To this end, an experimental analysis was carried out on a private multi-room dwelling located in the Central Italy performing both air permeability and air exchange rate measurements in the entire dwelling and in parts of it. In particular, the specific novel aspects investigated in the paper are: (i) the evaluation of the airtightness gradients within the building through blower door test performed in the entire buildings and in the single rooms separately, (ii) the evaluation of the effect of the meteo- climatic conditions on the actual air exchange rates through tracer gas decay tests under different weather conditions and for different rooms,

(iii) the estimate of a conversion factor between pressurization and tracer gas test results as a function of the meteo-climatic conditions. In order to properly compare the different measurement results a very detailed uncertainty budget of the two methods was also carried out.

2. Materials and methods

2.1. Site description

The experimental analysis was performed in a private multi-room dwelling located in the urban area of Frosinone (Central Italy) in the period December 2018–February 2019. The dwelling is at the second floor of a building built in the '70s whose walls are made up of hollow clay bricks-air gap-hollow clay bricks for a total width of 45 cm. The building presents two façades: a South-West facade facing a wide square and a (smaller) sheltered facade facing North-East. The dwelling, whose plant is reported in Fig. 1, has a floor area of 135 m2 and a volume of 378 m3; it is made up of nine rooms, one main door, seven windows. The windows are single glazed wooden windows which belong to the lowest air permeability class defined by the standard EN 12207 [56]. No mechanical ventilation systems were installed in the buildings; thus, the ventilation just relies upon the natural ventilation guaranteed by the air permeability of the building envelope and by manual airing.

2.2. Description of the tests

In order to measure the air permeability and the actual air exchange rate of the dwellings/rooms, the following tests (also summarized in Table 1) were performed:

a) one Blower Door Test of the entire dwelling to measure its air permeability;
b) five Blower Door Tests, one for each room with a window (hall & studio, kitchen & living room, bathroom, single bedroom, double bedroom) to measure their air permeabilities;
c) fifteen tracer gas decay tests for each room with a window (hall & studio, kitchen & living room, double bedroom) to measure their actual air exchange rates for the specific meteo-climatic conditions encountered at those very moments;
d) three tracer gas decay tests of the entire dwelling (using two different sampling points) to measure its actual air exchange rate for the specific meteo-climatic conditions encountered at that very moment.

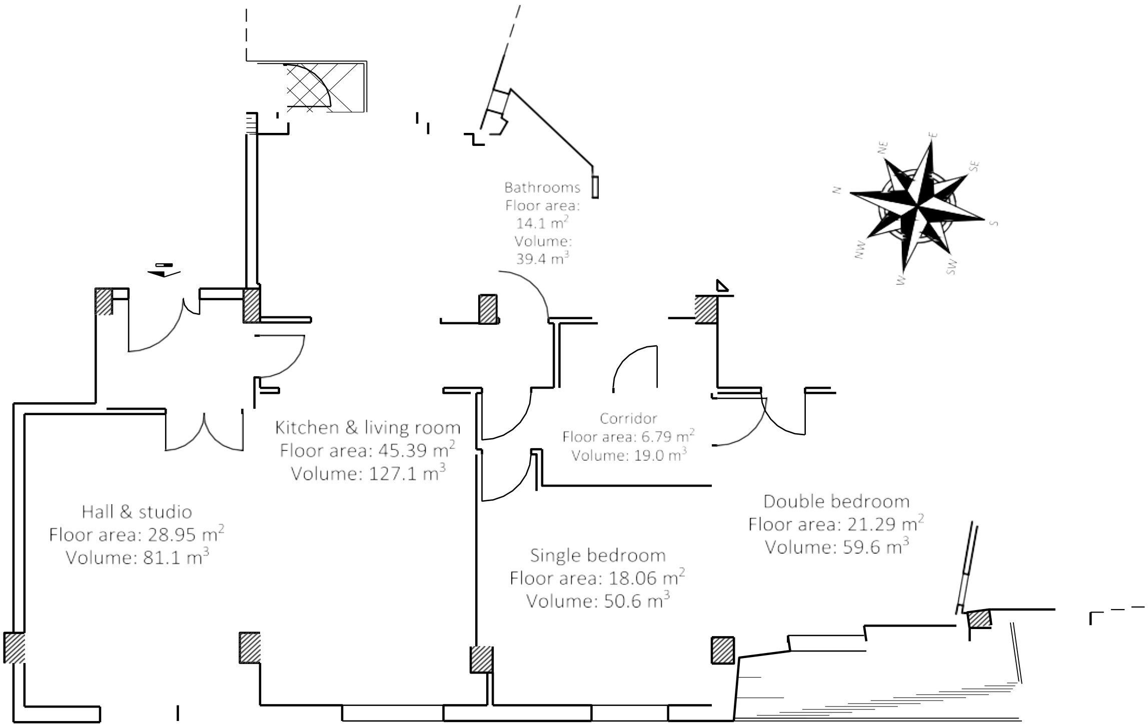

Fig. 1. Plant of the dwelling under investigation: identification and dimensions of the rooms.

Table 1 - Summary of the tests performed during the experimental campaign

Test	Measurement method	Room under test	Notes
a	Blower Door Test	Entire dwelling	1 measurement
b	Blower Door Test	- hall & studio (test b1) - kitchen & living room (test b2) - bathroom (test b3) - single bedroom (test b4) - double bedroom (test b5)	1 measurement for each room
c	Tracer gas decay test	- hall & studio (test c1) - kitchen & living room (test c2) - double bedroom (test c3)	15 measurements for each room/test
d	Tracer gas decay test	Entire dwelling, two sampling points placed in: - kitchen & living room and double bedroom (test d1) - kitchen & living room and hall & studio (test d2) - kitchen & living room and corridor (test d3)	1 measurement for each test

2.2.1. Blower door tests

The air permeability of the dwelling/rooms (tests a) and b)) was measured through the pressurization test (i.e. BDT), described in the technical standard ISO 9972 [46], using the method known as "method 1", i.e. the test of the "building in use", which prescribes that the ventilation opening have to be closed (not sealed) and the whole building mechanical ventilation or air conditioning opening have to be sealed. In order to characterize the airtightness of the single rooms (test b), only the internal doors between rooms (if any, as occurring in kitchen & living room and bathroom) were sealed.

The BDT is performed through a room pressurization/depressurization in order to provide the ventilation rates through the envelope (q_{env}, m^3 h^{-1}) under a fixed indoor-outdoor pressure difference (Δp, Pa), which is higher than the natural pressure differences. The pressure-flow relationships for the pressurization (q_{env_p}) and depressurization (q_{env_d}) tests are calculated as:

$$q_{env_p} = C_{env\_p} \cdot \left(\frac{T_0}{T_{in}}\right)^{1-m_p} \cdot (\Delta p)^{m\_p}$$

$$q_{env\_d} = C_{env\_d} \cdot \left(\frac{T_0}{T_{out}}\right)^{1-m\_d} \cdot (\Delta p)^{m\_d} \quad (1)$$

where m and C_{env} are the air pressure exponents and the flow coefficients, respectively, estimated by means of a simple linear regression for pressurization and depressurization tests as reported in the ISO 9972 [46], V is the volume of the room under test, T_{in} and T_{out} are the indoor and outdoor average air temperature, T_0 is the absolute temperature at standard conditions. Equations (1) allow to calculate the air leakage rate, $\boldsymbol{q_{50}}$, at a reference pressure difference of 50 Pa: then, the air exchange rate at 50 Pa for pressurization (n_{50_p}) and depressurization (n_{50_d}) tests are obtained dividing the $\boldsymbol{q_{50}}$ values (q_{50_p} and q_{50_d}) by the room volume (Eq. (2)). Thus, the n_{50} of the room is calculated as average value of n_{50_p} and n_{50_d}:

$$n_{50\_p} = C_{env\_p} \cdot \left(\frac{T_0}{T_{in}}\right)^{1-m\_p} \cdot \left(\frac{50\ Pa}{V}\right)^{m\_p}$$

$$n_{50\_d} = C_{env\_d} \cdot \left(\frac{T_0}{T_{out}}\right)^{1-m\_d} \cdot \left(\frac{50\ Pa}{V}\right)^{m\_d} \quad (2)$$

$$n_{50} = \frac{n_{50\_p} + n_{50\_d}}{2}$$

The experimental apparatus used to perform BDTs includes: (i) an airproof fan at calibrated flow rates fitted to the door by means of an extensible frame sealed into a door jamb allowing the measurement of pressure differences (positive and negative); (ii) a flow rate regulation system producing indoor-outdoor pressure differences by varying the fan speed; (iii) two primary elements for the flow rate measurement with an uncertainty of about 3%; (iv) a digital micromanometer with an uncertainty of about 1 Pa, to measure the pressure difference both indoor/outdoor and up/downstream to the primary element (in order to calculate the flow rate); (v) a thermo-hygrometer for air temperature and humidity measurements with an uncertainty of about 0.2 ◦C and 2%, respectively, to correct flow rates at standard conditions. Further details on the BDT methodology are reported in our previous papers [29-31].

The authors point out, once again, that the air permeability measurement does not provide directly information on the actual air exchange rate of the building/room, nonetheless, as mentioned above, a rough estimate of the air exchange rate can be obtained according the "rule of thumb" reported in the scientific literature, and quite acceptable for US buildings, which estimates the air exchange rate (n, h^{-1}) dividing the n_{50} value by a factor N (on average equal to 20, but varying from 10 to 30) [53-55].

The authors emphasize that the BDT of the entire dwelling provides an average airtightness of the zone considered. Therefore, in the case of dwellings characterized by large volumes, and/or multiple rooms, and/or complex dwelling layout, partial retrofit of walls and openings, the n_{50} value resulting from the BDT of the entire dwelling cannot highlight possible airtightness gradients within the dwelling itself. In other words, the BDT can just provide an average airtightness of the dwelling.

Therefore, in order to check for the effect of possible non-uniform airtightness of the dwelling, the n_{50} of the entire dwelling obtained from the test a) was also compared to the n_{50} of the entire dwelling obtained as room volume-weighted average (hereinafter reported as n_{50_w}) on the basis of the n_{50} data of each room gathered from the test b).

2.2.2. Tracer gas decay tests

The measurements of the actual air exchange rate of the dwelling/rooms were performed through the "single zone" tracer gas decay method according to the standard ISO 12569 [47]. The CO_2 was adopted as tracer gas; thus, a CO_2 tank was employed as source and mixing fans were used to homogenize the tracer gas concentration in the dwelling/room under investigation. CO_2 concentration measurements were performed through non-dispersive infrared analyzers (Testo ambient CO_2 probe; concentration range: 0-10000 ppm) with 1 s sampling frequency.

Since CO_2 concentration in the room is uniform and no other CO_2 sources (such as people, combustion, chemical reactions) are present, the air exchange rate (n, h^{-1}) of the dwelling/room was determined according to the exponential decay equation [57]:

$$n = \frac{1}{\Delta t} \cdot \ln \frac{CO_{2\_peak} - CO_{2\_out}}{CO_{2\_final} - CO_{2\_out}} \quad (3)$$

where $CO_{2\text{-peak}}$, $CO_{2\text{-final}}$ and $CO_{2\text{-out}}$ represent the initial peak, final, and outdoor CO_2 concentrations and Δt the time interval between $CO_{2\text{-peak}}$ and $CO_{2\text{-final}}$. Outdoor CO_2 concentrations were also measured before and after the decay test through a further non-dispersive infrared sensor: $CO_{2\text{-out}}$ here used represents the average value.

For the test c) (tracer gas decay test of the rooms) the measurements were performed keeping window of the room closed and sealing the internal doors in order to carry out an actual single-zone decay test (i.e. nullifying the flow rates between adjacent rooms); the CO_2 probe indoor was installed in the middle of the room not directly exposed to the source. The CO_2 concentration in the room was led to >2000 ppm, then the source and the fan were stopped and the concentration was measured continuously for about 2 h.

For the test d) (tracer gas decay test of the dwelling) the measurements were performed as described for the abovementioned test c) and keeping all the internal doors open. Due to the high volume under investigation, two measurement points were considered for each of the three tests. Thus, two identical ambient CO_2 probes were used simultaneously. Two mixing fans were also used in order to improve the CO_2 concentration uniformity within the entire dwelling. Different measurement points for the three tests were considered; in particular, the two probes were installed in kitchen & living room and double bedroom for the test d1, in kitchen & living room and hall & studio for the test d2, and in kitchen & living room and corridor for the test d3 as summarized in Table 1.

Since the actual air exchange rate of the building/room is strongly affected by the meteo-climatic conditions, wind direction and velocity data were gathered from a climate monitoring station near to the building under investigation. On the contrary, previous studies showed that the effect of the indoor-outdoor temperature differences was not significant with respect to the wind effect, thus indoor and outdoor temperatures were not considered in the present experimental analysis [48]. The authors highlight that, in contrast to BDTs, the tracer gas decay tests allow to evaluate possible non-uniform air exchange rates within the dwelling as a function of such outdoor conditions. On the basis of the n_{50} values (test b) obtained from BDTs and the actual air exchange rates (test c) obtained through the tracer gas decay tests, the n_{50}/n ratio for each room was evaluated and compared to the factor N = 20.

2.3. Uncertainty budget

In order to compare the air permeability and actual air exchange data between the different rooms and the entire dwelling an uncertainty budget of the two measurement methods was carried out. Indeed, as an example, the metrological compatibility of the data, assessable as normalized error [58], can be evaluated only if the uncertainty of the data under comparison is carried out [59]. Thus, in the following sub-section the uncertainty budgets for BDTs and tracer gas decay tests were described.

2.3.1. Blower door test uncertainty budget

The uncertainty budget of the BDT allows to evaluated the n_{50} uncertainty value considering the relationship reported in equations (1) and (2). The uncertainties of n_{50_p}, n_{50_d} and, consequently, of n_{50} can be evaluated, according to the Guide to the Expression of Uncertainty in Measurement [59], and considering the uncertainty contributions uncorrelated, as:

$$u_{n_{50\_p}} = \sqrt{\left(\frac{\partial n_{50\_p}}{\partial V}\right)^2 \cdot (u_V)^2 + \left(\frac{\partial n_{50\_p}}{\partial C_{env\_p}}\right)^2 \cdot \left(u_{C_{env\_p}}\right)^2 + \left(\frac{\partial n_{50\_p}}{\partial m\_p}\right)^2 \cdot \left(u_{m\_p}\right)^2 + \left(\frac{\partial n_{50\_p}}{\partial T_{in}}\right)^2 \cdot \left(u_{T_{in}}\right)^2}$$

$$u_{n_{50\_d}} = \sqrt{\left(\frac{\partial n_{50\_d}}{\partial V}\right)^2 \cdot (u_V)^2 + \left(\frac{\partial n_{50\_d}}{\partial C_{env\_d}}\right)^2 \cdot \left(u_{C_{env\_d}}\right)^2 + \left(\frac{\partial n_{50\_d}}{\partial m\_p}\right)^2 \cdot \left(u_{m\_d}\right)^2 + \left(\frac{\partial n_{50\_d}}{\partial T_{in}}\right)^2 \cdot \left(u_{T_{in}}\right)^2} \quad (4)$$

$$u_{n_{50}} = \sqrt{\left(u_{n_{50\_p}}\right)^2 + \left(u_{n_{50\_d}}\right)^2}$$

The uncertainty contributions of m (u_{m_p} and u_{m_d}) and C_{env} (u_{Cenv_p} and u_{Cenv_d}) were assessed through the method suggested in the Annex C of the ISO 9972 standard [46]. In particular, the standard defines the method to evaluate the confidence intervals of such quantities, then the corresponding standard uncertainties were evaluated considering a Gaussian distribution of the values within such intervals. The authors point out that m and C_{env} are obtained as a result of the regression of pressure difference and flow rate values measured during pressurization and depressurization tests. Thus, the confidence intervals (and the resulting uncertainties) of m and C_{env} include the type A and type B uncertainties of pressure differences and flow rates. The uncertainty contributions of room volume (V) were gathered from the paper [31] where a detailed analysis of the uncertainty contributions of the BDT was carried out. Finally, the uncertainty of the indoor and outdoor air temperature (T_{in} and T_{out}) measurements were obtained from the metrological performances provided by the instrument manufacturer (resulting in ±3% of measured value).

Moreover, since the n_{50} of the entire dwelling obtained from the test a) was compared to the n_{50} of the entire dwelling obtained as room volume-weighted average evaluated from the n_{50} data of the rooms (test b), the uncertainty of such volume-weighted average n_{50_w} value was determined in order to check the metrological compatibility of the two measurements. The uncertainty of the room volume-weighted average n_{50} was determined as:

$$u_{n_{50\_w}} = \sqrt{\sum_{i=1}^{5}\left[\left(\frac{\partial n_{50\_w}}{\partial n_{50i}}\right)^2 \cdot \left(u_{n_{50i}}\right)^2 + \left(\frac{\partial n_{50\_w}}{\partial V_i}\right)^2 \cdot \left(u_{V_i}\right)^2\right]} \quad (5)$$

where the i-th n_{50i} and V_i values represent the n_{50} and volume of the five different rooms tested in the test b. The uncertainty contribution of the volume can be considered reasonably insignificant with respect to the n_{50} one, thus the second term in the sum of eq. (5) can be considered negligible. The metrological compatibility of the n_{50} values of the entire dwelling obtained as measurement on the entire dwelling (test a) and room volume-weighted average of the rooms (test b) was checked through the normalized error En defined in the ISO 10012 standard [58] as:

$$E_n = \frac{|n_{50} - n_{50_w}|}{\sqrt{\left(U_{n_{50}}\right)^2 + \left(U_{n_{50\_w}}\right)^2}} \quad (6)$$

where U_{n50} and U_{n50_w} represent the expanded uncertainties of n_{50} values measured on the entire dwelling (test a) and calculated as room volume-weighted average, respectively; such expanded uncertainties are obtained multiplying the standard uncertainties (u_{n50} and u_{n50_w}) by the statistical cover factor $k = 2$ (confidence level 95%). The measurements were considered compatible for En<1.

2.3.2. Tracer gas decay test uncertainty budget

The uncertainty budget of the tracer gas decay test allows to evaluate the n uncertainty value (u_n) considering the relationship reported in equation (3) and the error propagation laws of each parameter reported in such relationship. Thus, the uncertainties of n can be evaluated, according to the Guide to the Expression of Uncertainty in Measurement [59], as:

$$u_n = \sqrt{\begin{array}{l}\left(\frac{\partial n}{\partial CO_{2\_peak}}\right)^2 \cdot \left(u_{CO_{2\_peak}}\right)^2 + \left(\frac{\partial n}{\partial CO_{2\_final}}\right)^2 \cdot \left(u_{CO_{2\_final}}\right)^2 + \left(\frac{\partial n}{\partial CO_{2\_out}}\right)^2 \cdot \left(u_{CO_{2\_out}}\right)^2 + \\ +2 \cdot \left(\frac{\partial n}{\partial CO_{2\_peak}}\right) \cdot \left(\frac{\partial n}{\partial CO_{2\_final}}\right) \cdot u_{CO_{2\_peak}} \cdot u_{CO_{2\_final}} \cdot r\left(CO_{2\_peak}; CO_{2\_final}\right) + \\ +2 \cdot \left(\frac{\partial n}{\partial CO_{2\_peak}}\right) \cdot \left(\frac{\partial n}{\partial CO_{2\_out}}\right) \cdot u_{CO_{2\_peak}} \cdot u_{CO_{2\_out}} \cdot r\left(CO_{2\_peak}; CO_{2\_out}\right) + \\ +2 \cdot \left(\frac{\partial n}{\partial CO_{2\_final}}\right) \cdot \left(\frac{\partial n}{\partial CO_{2\_out}}\right) \cdot u_{CO_{2\_final}} \cdot u_{CO_{2\_out}} \cdot r\left(CO_{2\_final}; CO_{2\_out}\right)\end{array}} \quad (7)$$

where the uncertainties of the CO_2 measurements ($CO_{2\text{-peak}}$, $CO_{2\text{-final}}$, $CO_{2\text{-out}}$) represent the uncertainties of the CO_2 probes. Such uncertainties were evaluated on the basis of the data provided by the manufacturer in terms of resolution (1 ppm), accuracy (±50 ppm + 3% of measured value, provided at T = 295 K), and temperature effect (±(T-295) × (2 ppm + 0.4% of measured value)/K), whereas the effects of static pressure and dew-point were considered negligible [60]. In this case the effect of CO_2 measurement uncertainties ($CO_{2\text{-peak}}$, $CO_{2\text{-final}}$, $CO_{2\text{-out}}$) cannot be considered uncorrelated, as they were performed with the same instruments; then, in the evaluation of the uncertainty of n, the correlation factors amongst the three CO_2 values were considered. In particular, we considered different correlation factors: i) r ($CO_{2\text{-peak}}$, $CO_{2\text{-final}}$) = 0.8, ii) r($CO_{2\text{-peak}}$, $CO_{2\text{-out}}$) = 0.5, iii) r($CO_{2\text{-final}}$, $CO_{2\text{-out}}$) = 0.5. Finally, the uncertainty contribution of the time interval Δt was considered negligible. The uncertainty budgets of n_{50} (test b) and n (test c) also allowed to evaluate the uncertainty of the n_{50}/n ratio for each room as:

$$u_{n_{50}/n} = \sqrt{\left(\frac{\partial n_{50}/n}{\partial n_{50}}\right)^2 \cdot \left(u_{n_{50}}\right)^2 + \left(\frac{\partial n_{50}/n}{\partial n}\right)^2 \cdot \left(u_n\right)^2} \quad (8)$$

3. Results and discussions

3.1. BDT results

In Table 2 the air permeability results, obtained from the BDTs performed on the dwelling (test a) and rooms (test b), are reported in terms of air exchange rate at 50 Pa (n_{50}, h^{-1}). The n_{50} measured for the entire building was equal to 12.2 ± 2.3 h^{-1}, whereas the n_{50} values measured in the five rooms ranged from 13.6 ± 1.8 to 15.9 ± 4.1 h^{-1}. The main contributions to the overall uncertainty, summarized in Table 2, were due to the air pressure exponents (m) and the flow coefficients (C_{env}), both >40% for almost all the rooms tested in both the conditions (depressurization and pressurization); a minor contribution (<20% for most of the rooms) was due to the uncertainty of the room volume, whereas the temperature contribution resulted negligible. The main contribution to the uncertainty of m and C_{env} was somehow expected since these values result from the regression of the measured values of ventilation rates through the classroom envelope (q_{env}, m^3 h^{-1}) and indoor-outdoor pressure difference (Δp, Pa), thus they include both type A and B errors (e.g. due to the instruments and to the user) of the measurement itself. Indeed, the authors point out that a possible contribution to q_{env} and Δp (and then m and C_{env}) uncertainty is due to possible systematic errors on the measurand in conducting the tests (installation effects), as an example, possible leakages through the BDT frame itself as well as through unintentional micro-openings (e.g. ducts, electrical cables) could lead to unexpected infiltrations/exfiltrations slightly overestimating the n_{50} value. This could explain the lower n_{50} value obtained for the entire building with respect to the single rooms, as well as the slightly higher n_{50} values for kitchen & living room and bathroom, i.e. the rooms with multiple internal doors. A deeper investigation of the possible systematic errors due to such installation effect could help to reduce such error and then the corresponding uncertainty of the n_{50} data. Nonetheless, the n_{50} data of the rooms are quite similar, indeed the standard deviation of the five values is about 1 h-1 (i.e. <10% of the mean value); thus, the slight room-by-room differences in air permeability inside the dwelling can be considered negligible. In other words, the dwelling under investigation does not present differences in terms of air permeability. This was somehow expected since the same type of windows were installed in all the rooms and no partial retrofit of the dwelling were carried out over the years (i.e. the type of construction was the same for all the rooms).

The En obtained when comparing the measured n_{50} value for the entire building (test a, 12.2 h-1) and that calculated from the room volume-weighted average (n_{50_w}, 14.9 h^{-1}) resulted <1; thus, the estimate of the air permeability of a dwelling obtained as weighted average value from measurements performed in the individual rooms are metrologically compatible. Moreover, averaging over the room data allows obtaining, as expected, a lower uncertainty for n_{50_w} (1.7 h^{-1}, that is 11%) with respect the test n_{50} of the entire building (2.3 h^{-1}, that is 19%). Indeed, the average value reduces the contribution of larger uncertainties recognized in some rooms, such as the kitchen & living room which accounts for 78% of the n_{50_w} uncertainty due to its largest volume and uncertainty. As mentioned above the slight larger n_{50} value of the building estimated on the basis of the single room values, could be related to systematic installation errors leading to a slight overestimate of the air permeability.

Table 2 – Results of n_{50} obtained from Blower Door Tests performed in the dwelling/ rooms investigated (test a and test b) and room volume-weighted average (n_{50_w}) calculated for the entire dwelling from the test b) results. Data are expressed as measured values ± expanded uncertainty (Un_{50} and U n_{50_w} , confidence level 95%). The weights of the i-th uncertainty component (i.e. V, T, m, C_{env}) on the n_{50} uncertainty of the entire dwelling and of the rooms - evaluated as $(\partial n_{50}/\partial i)^2 \cdot (u_i)^2/(un_{50})^2$ - are also reported for pressurization (p) and depressurization (d) tests. The weights of the uncertainty of each room on the n_{50} value of the entire dwelling evaluated as room volume-weighted average (n_{50_w}) are also summarized.

Test	**Room tested**	**n_{50} (h^{-1})**	**weight of each uncertainty component (%)**			
			V (p; d)	T (p; d)	m (p; d)	C_{env} (p; d)
a	Entire dwelling	12.2 ± 2.3	10%; 15%	<1%; <1%	9%; 37%	81%; 48%
b1	hall & studio	13.8 ± 2.3	11%, 13%	<1%; <1%	44%; 42%	45%; 45%
b2	kitchen & living room	15.9 ± 4.1	4%; 6%	<1%; <1%	52%; 41%	44%; 53%
b3	bathroom	14.7 ± 1.9	52%; 7%	<1%; <1%	21%; 37%	27%; 56
b4	single bedroom	13.6 ± 1.8	7%; 5%	<1%; <1%	40%; 41%	53%; 54%
b5	double bedroom	15.4 ± 2.8	9%; 18%	<1%; <1%	42%; 37%	49%; 45%
Calculated from test b results	Entire dwelling-room volume weighted average (n_{50_w})	14.9 ± 1.7	**weight of each room on the entire dwelling uncertainty (%):** hall & studio = 10%; kitchen & living room = 78%; bathroom = 2%; single bedroom = 2%; double bedroom = 8%			

3.2. Tracer gas decay test results

3.2.1. Single room tests

In Table 3 the air exchange rates measured in the three rooms (test c1, hall & studio; test c2, kitchen & living room; test c3, double bedroom) through the tracer gas decay test are reported.

Table 3 - Actual air exchange rates (n, h^{-1}) measured in each room through the tracer gas decay test (test c) and estimated n_{50}/n ratios: data are expressed as measured value ± expanded uncertainty (confidence level 95%). Wind conditions during the tests are also summarized, in particular, wind velocity, prevalent direction, and wind velocity component (u) perpendicular to the windows are reported.

Test	Room tested	Wind velocity (m/s) and prevalent direction	Wind velocity component u (m/s)	n (h^{-1})	n_{50}/n ratio
c1	hall & studio	1.4 m/s; S-SE	0.5 m/s	0.31±0.06	43.9±10.7
		3.3 m/s; E	3.3 m/s	0.44±0.07	31.5±7.3
		3.4 m/s; NE-SE	2.4 m/s	0.42±0.06	32.8±7.0
		1.0 m/s; SW	0.9 m/s	0.46±0.07	29.8±6.6
		2.1 m/s; S-SE	0.8 m/s	0.49±0.07	28.1±6.3
		2.4 m/s; E-SE	1.9 m/s	0.25±0.05	54.5±14.2
		2.4 m/s; E-SE	1.9 m/s	0.59±0.08	23.4±5.0
		1.3 m/s; W-SW	1.2 m/s	0.70±0.11	19.7±4.7
		1.5 m/s; E-SE	1.2 m/s	0.27±0.05	51.1±13.1
		1.5 m/s; N-E	1.1 m/s	0.14±0.03	100.6±27.4
		1.5 m/s; N	0.3 m/s	0.29±0.05	47.6±11.0
		1.5 m/s; S-SW	0.8 m/s	0.34±0.05	40.7±9.3
		2.6 m/s; SW	2.1 m/s	0.27±0.05	50.3±12.0
c2	kitchen & living room	1.3 m/s; S-SE	0.5 m/s	0.31±0.06	51.9±16.7
		5.7 m/s; S-SE	2.2 m/s	0.69±0.11	22.9±7.0
		4.4 m/s; S-E	3.1 m/s	0.54±0.07	29.3±8.5
		1.4 m/s; E-SE	1.2 m/s	0.68±0.09	23.3±6.8
		1.5 m/s; S-E	1.1 m/s	0.84±0.14	18.9±5.9
		1.6 m/s; S-SE	0.6 m/s	0.56±0.10	28.2±8.8
		1.3 m/s; S-SW	0.7 m/s	0.90±0.14	17.7±5.4
		1.6 m/s; W-SE	1.3 m/s	0.30±0.05	53.0±16.6
		1.6 m/s; S-SE	0.6 m/s	0.26±0.05	62.1±20.1
		2.6 m/s; S-NW	1.0 m/s	0.22±0.04	71.4±22.6
		1.3 m/s; W-SE	1.0 m/s	0.33±0.06	48.1±15.1
		2.6 m/s; SE-SW	1.8 m/s	0.50±0.08	31.8±9.7
c3	double bedroom	6.5 m/s; N-NW	2.5 m/s	0.96±0.13	16.0±3.6
		3.4 m/s; NW-NE	2.4 m/s	0.30±0.03	51.1±10.4
		1.5 m/s; W	1.5 m/s	0.73±0.11	21.2±5.0
		1.6 m/s; W	1.6 m/s	0.33±0.04	47.1±9.9
		1.7 m/s; W	1.7 m/s	0.42±0.05	36.5±8.0
		1.5 m/s; S-SW	0.8 m/s	0.21±0.04	72.0±17.6
		0.5 m/s; NE	0.4 m/s	0.18±0.04	85.9±22.9
		1.5 m/s; E	1.5 m/s	0.21±0.04	74.8±19.2
		1.0 m/s; E	1.0 m/s	0.16±0.03	94.7±25.0
		3.1 m/s; N	0.6 m/s	0.17±0.03	93.3±23.2
		5.4 m/s; NW	2.9 m/s	0.48±0.06	32.4±7.1
		3.6 m/s; N-NW	1.4 m/s	0.24±0.04	63.6±15.0
		1.6 m/s; S-SW	0.9 m/s	0.33±0.06	47.2±12.0

Due to measurement issues (i.e. malfunction of CO_2 probe and/or unavailability of meteo-climatic data) the remaining valid measurements for hall & studio, kitchen & living room, and double bedroom were 13, 12 and

13 (with respect to the fifteen performed), respectively. The data present a huge variability likely depending on the different outdoor wind conditions: indeed, n ranged from 0.31 ± 0.06 h^{-1} and 0.70 ± 0.11 h^{-1} for hall & studio, from 0.22 ± 0.04 h^{-1} and 0.90 ± 0.14 h^{-1} for kitchen & living room, and from 0.16 ± 0.03 h^{-1} and 0.96 ± 0.13 h^{-1} for double bedroom. The effect of the wind direction and velocity is clearly recognizable in Fig. 2 where the air exchange rates measured in the different rooms (and the corresponding expanded uncertainties) as a function of the wind velocity component (u) perpendicular to the window are reported. The trend shows an exponential increase of the ventilation (in particular for test c1 and c2) as the face velocity of the wind on the windows increase. The uncertainty of the n values obtained through the tracer gas decay test according to the approach described in section 2.3.2 ranged from 10% to 21%; such variability is mainly due to the different CO_2 concentrations levels measured during the decay tests, as clearly stated by eq. (7), indeed, as expected, for lower $CO_{2\text{-peak}}$ and $CO_{2\text{-final}}$ concentrations higher uncertainties were obtained [61]. A detailed discussion of the uncertainty results of each tracer gas decay test is not reported for the sake of brevity.

The ratio between the n_{50} values obtained through the blower door test and the actual air exchange rates here presented clearly demonstrates that the "rule of thumb" reported in the scientific literature to estimate the annual average air exchange rate (i.e. dividing the n_{50} by a factor $N = 20$) [53-55] would fail by a large amount in the specific case study here presented. Indeed, the n_{50}/n ratio resulted in the ranges 19.7 ± 4.7 ÷ 100.6 ± 27.4 for hall & studio, 17.7 ± 5.4 ÷ 71.4 ± 22.6 for kitchen & living room, and 16.0 ± 3.6 ÷ 94.7 ± 25.0 for double bedroom. The suggested value of 20 doesn't even fall within the uncertainties of the n_{50}/n ratios, despite such uncertainty is quite high (20% to 32%).

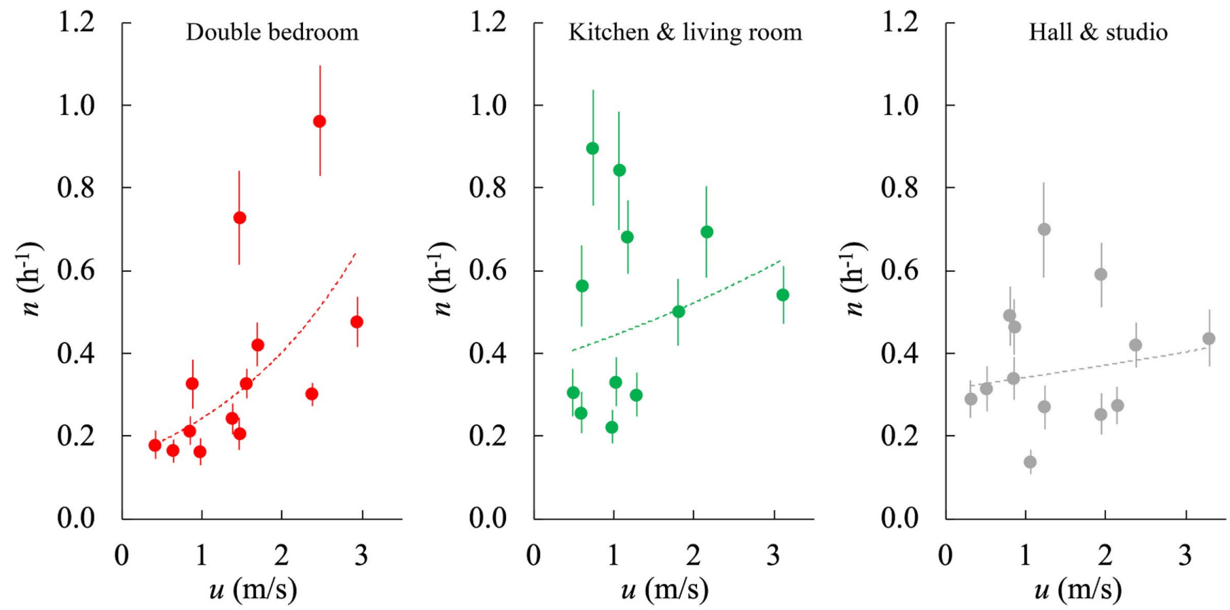

Fig. 2. – Air exchange rates measured for test c3 in the double bedroom as a function of the wind velocity component (u) perpendicular to the window. Expanded uncertainties of the air exchange rates are also reported.

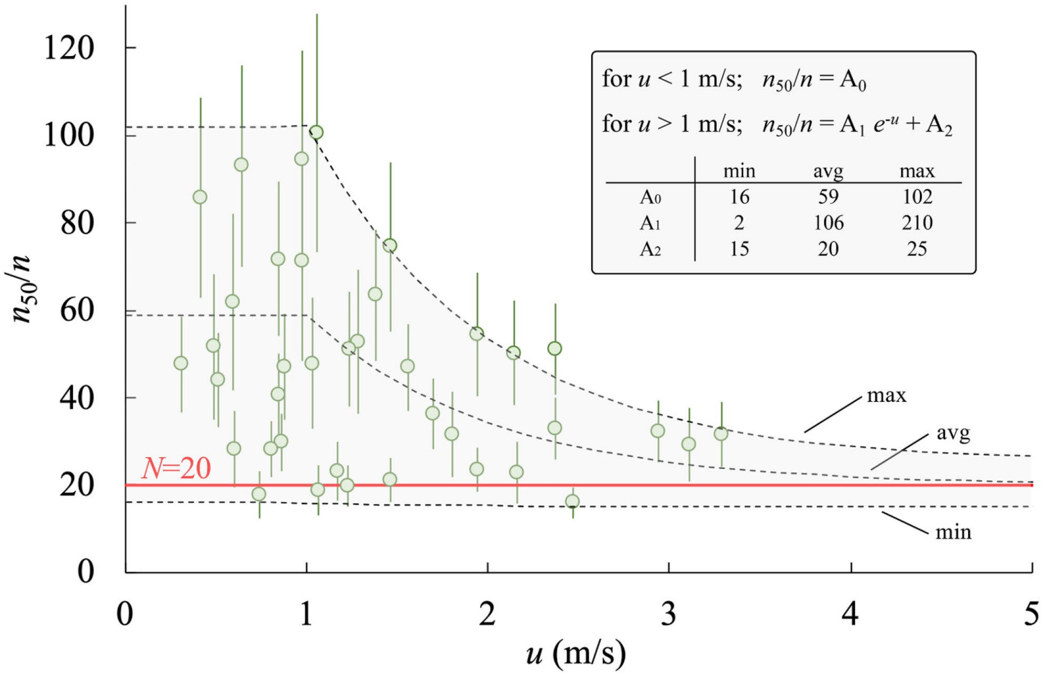

Fig. 3. – Ratios between the n_{50} values obtained through the blower door test and the actual air exchange rates n measured through the tracer gas decay tests (n_{50}/n) as a function of the component of the wind velocity perpendicular to the windows (u). All the tests performed in all the rooms are reported. Minimum (min), maximum (max) and average (avg) fitting curves are also reported.

Thus, the "rule of thumb" relationship would strongly overestimate the actual air exchange rates of the rooms and the exfiltration of indoor-generated pollutants or infectious agents as well, thus, in case of risk assessment, adopting such "rule of thumb" relationship would strongly underestimate the risk of exposed population. Such an overestimate of the air exchange rate is expected to be due to the outdoor microclimatic conditions, in particular wind velocity and direction. To this end in Fig. 3 the n_{50}/n ratios evaluated for the three rooms under investigation (and the corresponding expanded uncertainties) are reported as a function of the wind velocity component (u) perpendicular to the windows (both the those facing east and west). The figure clearly shows that as the wind velocity increases a significative reduction of the n_{50}/n ratio was observed, nonetheless, the expected value of $N = 20$ is not reached also at highest wind velocities occurring during the tests. The n_{50}/n data can be included in area of the graph defined by maximum and minimum fitting curves; in particular, an exponential decrease of the n_{50}/n ratios with respect to the velocity component u is recognizable for u higher than 1 m/s, whereas, a roughly constant trend was recognized at lower u. For the dwelling under investigation, the minimum and maximum constant values for $u < 1$ m/s (named A0 in the figure) were set at 16 and 104, respectively (average value 59); while the minimum and maximum asymptotic values (named A2 in the figure) were set at 15 and 25, respectively (average value 20). The authors point out that such relationship is specific of the dwelling under investigation and that providing a proper and transferable relationship between n_{50}/n and wind velocity and direction is behind the scope of this paper. Nonetheless, future developments of the study should be focused on this aspect, in particular, different dwelling characterized by different types of windows, types of construction, floor level should be considered and analyzed under different wind conditions. This could lead to a more detailed evaluation of the n_{50}/n ratio with respect to that provided by Sherman [54] for the United States. The authors also highlight that the measurements here shown were performed over a limited period of the year (Dec 2018–Feb 2019), thus, the results are specific of the meteo-climatic conditions occurring in that period. Nonetheless, on the basis of the archives of meteo-climatic data recorded by the weather station, the annual average wind velocity component (u) perpendicular to the windows was slightly lower than 2 m/s; thus, the annual average n_{50}/n ratio is expected to be much larger than 20 as well.

3.2.2. Entire dwelling

In Table 4 the results of the test d (tracer gas decay test of the entire dwelling through measurements in two different sampling points) are summarized. In particular, the air temperature and the CO_2 peak concentrations measured by the two probes during the test are reported along with the actual air exchange rates determined according to eq. (3). The tests were carried out under homogeneous temperature and CO_2 peak concentrations, indeed the normalized errors of the CO_2 peak concentrations in the two rooms were <1 for each test, moreover the peaks of the two rooms occurred simultaneously as clearly shown in Fig. 4, then confirming the CO_2 uniform distribution in the dwelling.

Table 4 - Air temperatures, wind conditions, CO_2 peak concentrations and actual air exchange rates measured during the test d in the two sampling points considered. Air temperatures are expressed as mean ± standard deviation in order to show the stability during the test, whereas CO_2 peak concentrations and actual air exchange rates are reported as measured value ± expanded uncertainty.

Test	Wind velocity (m/s) and prevalent direction	Air temperature during the test (°C)		$CO_{2\text{-peak}}$ (ppm)		Actual air exchange rate, n (h^{-1})	
		Sampling point 1	Sampling point 2	Sampling point 1	Sampling point 2	Sampling point 1	Sampling point 2
d1	2.06 m/s; S	17.7±0.3	18.0±0.1	2558±176	2319±168	0.33±0.05	0.16±0.03
d2	2.36 m/s; SE	19.4±0.1	19.6±0.2	3349±203	3304±201	0.15±0.02	0.24±0.02
d3	1.56 m/s; N-S	12.7±0.1	12.9±0.1	2297±167	2148±161	0.13±0.03	0.16±0.03

Nonetheless, even if the measurements were carried out under homogeneous temperature and CO_2 conditions, the air exchange rates measured at the two different sampling points may differ significantly. In particular, when the sampling points are placed in two rooms both with windows (tests d1 and d2) the air exchange rates in the two rooms differ more than 1.5-fold (n equals to 0.33 vs. 0.16 h^{-1} for test d1, and 0.15 vs. 0.24 h^{-1} for test d2). On the contrary, the air exchange rates measured during the test d3 in the kitchen & living room and corridor resulted quite similar, this could be due to the fact that the air exchange rate in the corridor is less effected by the windows and, maybe, by the lower wind velocity. The results here obtained point out that even when a uniform concentration in the rooms is achieved, e.g. through appropriate mixing devices as suggested by the standard ISO 12569 [47], air exchange rate gradients within the dwelling can occur. Such gradients can just be recognized using multiple probes, likely as a function of the size and the subdivision of the dwelling;

this aspect is actually not considered in the standard and further scientific investigations should be carried out. Specifically, experimental analyses considering a higher number of measurements, including different outdoor conditions, and with more probes within the dwelling should be designed in order to carry out detailed analyses of the effect of the outdoor conditions on the air exchange rate gradients.

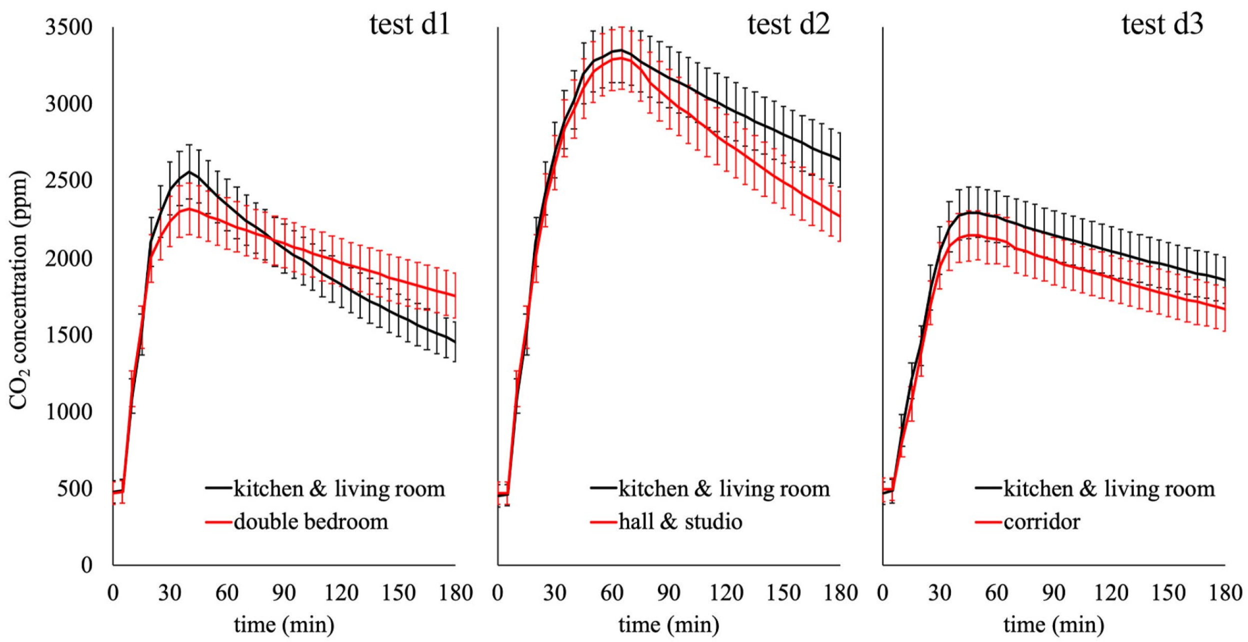

Fig. 4. – CO_2 trends measured during the test d (measurement of the decay rate of the entire dwelling) by the two probes placed in two different sampling points within the dwelling. CO_2 data are here graphed as 5-min average values. The error bars represent the expanded uncertainty of the CO_2 probes.

4. Conclusions

This study was carried out in order to provide an insight into the two main measurement methods of building ventilation-related parameters, i.e. blower door test and tracer gas decay test, and to determine their comparability. To this end an experimental campaign was carried out on a multi-room dwelling in Italy where blower door tests and tracer gas decay tests were performed in the entire dwelling and parts of it (i.e. single rooms). Moreover, to assess the comparability of the tests, uncertainty budgets of the two methods were also carried out. The results of the study demonstrated that, even when the airtightness of the dwelling is uniform (as obtained from the blower door tests performed in each room), the actual air exchange rates of the dwelling present a huge variability (from <0.2 to almost 1 h^{-1}) likely depending on the different outdoor wind conditions. In particular, an exponential increase of the actual air exchange rate was obtained as a function of the face velocity of the wind on the windows. As a consequence, the ratio between the air exchange rates at 50 Pa (n_{50}) provided by the blower door tests and the actual air exchange rates (n) obtained through the tracer gas decay test presented huge variability as well, ranging from <20 up to >100. Thus, the widely accepted "rule of thumb" suggesting a constant conversion factor of 20 could be extremely misleading as it would overestimate the air exchange rate. To this end, the authors strongly suggest avoiding the use of a constant conversion factor to evaluate the actual air exchange rate but rather adopting an exponential relationship as a function of the component of the wind velocity perpendicular to the windows.

Authors' statement

Andrea Frattolillo: Methodology, Conceptualization, Formal analysis, Writing-Reviewing and Editing;
Luca Stabile: (Corresponding Author): Conceptualization, Methodology, Data curation, Formal analysis, Original draft preparation;
Marco Dell'Isola: Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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