Application of Adapted Tracer Gas Test for Ventilation Assessment in Two Locations

Sarah L. Paralovo [a,b], *Marianne* Stranger [b], *Borislav* Lazarov [b], *Maarten* Spruyt [b], *Jelle* Laverge [a].

[a] Research Group Building Physics, Department of Architecture and Urban Planning, Ghent University, Ghent, Belgium, sarah.limaparalovo@vito.be.

[b] Unit HEALTH, Flemish Institute for Technological Research, Mol, Belgium.

Abstract. In the wake of the current worldwide COVID crisis, the vital role of ventilation in keeping healthy indoor environments has become increasingly clear. But even before that, researchers have been pointing out how crucial ventilation is in avoiding the accumulation of pollutants in indoor spaces and in interpreting indoor air quality (IAQ) data. Given the importance of ventilation, especially in estimating pollutant sources' strength and proposing remediation actions, it is imperative that IAQ assessments quantify the actual building ventilation rates. However, many IAQ field studies found in the literature do not report ventilation rates adequately. This paper describes the application of an alternative method to passively measure the average ventilation in two different locations. This alternative method consists of an adaptation of the traditional tracer gas test (TGT) used for long-term average air change rates (ACH) measurement. This adapted TGT employs an alternative tracer gas (decane-D_{22}) that is more adequate than the currently employed SF_6 and perfluorocarbons. The selected tracer can be co-captured and co-analysed with commonly assessed VOCs by commercial passive IAQ-sampling. A passive source design of decane-D_{22}, optimized in lab, provides stable and repeatable emission rates unaffected by varying RH and ACH. The actual source emission rate is determined from the average room temperature via an exponential prediction curve derived in lab. Results from the two field experiments described in this paper show the satisfactory applicability of the proposed adapted TGT in different types of environments and settings. The ultimate research goal is to provide an accessible enough method to quantify ventilation that it may encourage researchers, contractors and building owners to perform appropriate ventilation assessments more often and with a good degree of accurateness.

Keywords. Ventilation, passive sampling, tracer gas test, air change rate.
DOI: https://doi.org/10.34641/clima.2022.255

1. Introduction

The quality of the air present in indoor spaces has an undeniable influence over the health and well-being of occupants, and one of the key factors impacting indoor air quality (IAQ) is ventilation [1][2][3][4]. In the wake of the COVID-19 pandemic, the vital role of ventilation in controlling the spread of airborne diseases became clearer than ever before [5]. But even disregarding SARS-CoV-2, a myriad of other different pollutants of concern is ubiquitous to most buildings [2][3]. Therefore, assessing the contamination level in the air of all indoor spaces designed for human occupancy is crucial to assure its quality is enough to promote a healthy environment. For such assessments to be significant, measurements of ventilation rates must be included. Ventilation data is crucial in interpreting IAQ, studying pollutant sources, evaluating the performance of ventilation systems and proposing remediation actions if needed [6]. Especially in energy-efficient, more airtight buildings, it is of utmost importance to monitor the ventilation rates of the occupied spaces to make sure that a healthy level of ventilation is kept.

Despite the vital role ventilation plays in the field of IAQ, however, many IAQ assessments found in the literature do not report ventilation rates. Even when they do, in many cases the measurement approaches are not described in sufficient detail to evaluate their quality or applicability to the study design [7]. Among the many possible reasons for such a lack of adequate reporting on ventilation, it can be pointed out that the current methods available to measure ventilation rates are limited. While some are not suitable for application in the presence of occupants, others require the use of expensive and complex equipment and/or environmentally-unsafe substances. Moreover, the existing ventilation measurement methods are generally disconnected from the indoor pollutants' concentration measurements, hindering the inter-comparison and co-interpretation between the ventilation and IAQ data.

In this this paper, an alternative method to quantify ventilation is applied in two different locations. This alternative method consists of an adaptation of one of the most common methods used to measure ventilation rates, the tracer gas test (TGT). In the TGT technique, an easily identifiable substance (tracer gas) is injected by a source to the indoor air, and then the total air change rate (ACH) in the space is inferred from the tracer air concentration and injection rate. This technique is the only one capable of directly measuring the actual total ACH in a room (i.e. from natural and mechanical ventilation, either intentional or from infiltration) [8]. Furthermore, TGTs in general are inherently simpler and more convenient than other ACH measurement methods.

However, the TGTs currently employed by IAQ researchers and practitioners have important limitations that are often overlooked. The method applied in this paper incorporates a few key adaptations to the classic TGT method in order to address some important limitations identified in the literature. Ultimately, the research goal is to propose a ventilation quantification method as simple, accurate and accessible as possible, so that it may encourage researchers, contractors and building owners to perform appropriate ventilation assessments more often in the future.

2. Materials and methods

2.1 the adapted TGT employed for ACH measurement

The three most important shortcoming commonly related to TGTs in the literature are: 1) Limited comparability between IAQ and ventilation data, as most TGTs provide short-term results while the concentrations of indoor pollutants are commonly measured using long-term sampling techniques that report time-averaged results; 2) Use of inadequate substances as tracer gases, e.g. sulphur hexafluoride (SF_6) or perfluorocarbons (PFTs), which are potent greenhouse gases with very long lifetimes in the atmosphere [9]; 3) Potential bias in the measurements arising from indiscriminate perfect-mixing assumption (i.e. if the air mixing is limited, the tracer distribution will be spatially heterogeneous across the assessed room; thus the placement of sources and samplers may bias the measurements of tracer concentration and, consequently, the calculated ACH) [8][10].

Therefore, the adaptations proposed for the new TGT applied in this research focus in 1) exclusive use of passive techniques (i.e. based solely on diffusive processes, excluding the use of pumps or any type of forced airflows, either for the injection or sampling of the tracer gas), 2) the use of standard, commercially available passive samplers commonly used in IAQ studies to capture the tracer gas simultaneously with IAQ pollutants of interest (automatically matching the IAQ and ventilation data timescales and rendering them comparable), 3) the employment of an alternative and more adequate substance as tracer gas and 4) the inclusion of a pre-TGT planning phase in which the TGT is simulated beforehand in the space to be assessed. Moreover, considering that the presence of occupants may significantly impact the indoor environment, the adapted TGT also aims for occupancy compatibility.

Based on these guidelines, the adapted TGT utilizes an alternative substance as tracer gas (the solvent decane-D_{22}) and an adapted passive tracer source design to measure long-term average ventilation rates. These proposed adaptations have previously been extensively tested in lab conditions and successfully validated in a controlled field test (against an active TGT using artificially-injected CO_2 as tracer). Details on the development and testing of the adapted TGT can be found elsewhere [11]. In summary, the alternative tracer decane-D_{22} is non-reactive, non-toxic, not found naturally in the atmosphere and does not adhere/absorb significantly to common indoor surfaces. The adapted passive source of decane-D_{22} consists of a very simple design that provides stable and repeatable tracer emission rates unaffected by varying RH and ACH (emission tests under varying RH/ACH were performed in previous development stages and are not shown, results were reported elsewhere [11]). The source design is shown in Figure 1; it consists of one single 1ml glass vial filled with ~0,5 ml of liquid decane-D_{22} and capped with a metal cap, with the rubber stop substituted by a PE filter disk (through which the tracer that volatilizes inside the vial diffuses to the air).

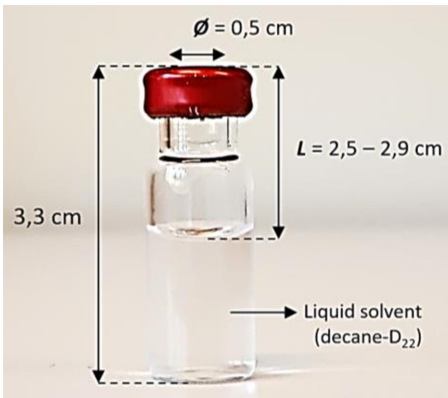

Fig. 1 - Tracer source design employed in the adapted TGT.

The source emits tracer gas at a known rate until the room concentration reaches a steady state (if the ACH is constant), from which the total ACH can be inferred using Equation 1.

$q = \frac{G}{V C_S}$ (1)

where q is the ACH (h^{-1}), G is the source emission rate (mg h^{-1}), V is the total volume of the assessed space (m^3) and C_s is the steady-state tracer concentration (mg m^{-3}). In a normal long-term passive TGT, however, neither q, G nor C_s can be assumed as constant. G and C_s will assume the average values of tracer emission and concentration over the whole sampling period. Thus, Equation (1) is still valid, but in that case the calculated q represents the average ACH over the total period.

In this newly proposed TGT, the average tracer emission rate from the passive source (G) is either determined gravimetrically in lab or estimated from the average room temperature measured during the TGT via an exponential prediction curve (Figure 2), derived after several controlled lab tests.

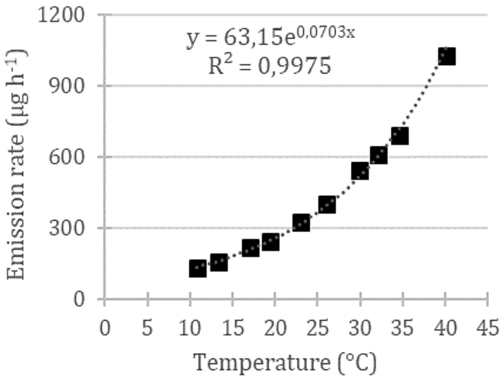

Fig. 2 - Tracer source emission rate as a function of room temperature for sources with 2,9 cm > L > 2,5 cm. Regression equation and linearity are also presented.

During the application of the TGT, the decane-D_{22} concentration in the indoor air is measured passively with Radiello® VOC samplers (for chemical desorption). Samplers and source(s) are left in the studied space for the pre-defined sampling period (usually 7 consecutive days), and then retrieved for analysis in lab. The passive samples obtained in the test are analysed by means of gas chromatography coupled to mass spectrometry detection (GC-MS), after extraction using carbon disulphide (CS_2) as solvent. All samples, calibration solutions and blanks are spiked with the same amount of internal standard (2-fluortoluene) to improve the precision and accuracy of the results.

Another adaptation proposed in the TGT employed in this paper is the addition of a simulation-based planning phase before the actual application of the TGT onsite. This is intended mostly to evaluate the air mixing in the space to be assessed and thus aid in the positioning of sources and samplers to avoid bias in the final ACH calculations. However, the field test previously performed for validation of the adapted TGT suggested that the air in indoor spaces can be in fact very well-mixed, and thus satisfactorily simulated using simple multizone software tools like CONTAM (as opposed to more computationally-demanding CFD tools) [11]. Therefore, the field tests described in this paper have also the aim of evaluating the adequateness of using perfect-mixing assumption to simulate different field settings.

2.2 sampling sites and testing setups

Unoccupied building: The first of the two tests described in this paper was performed in an unoccupied low-energy building located in Ostend (Belgium), the so-called E-Cube. The E-Cube is a zero-energy house of 265 m^3 that has been designed by team of students from UGent in 2011, during their participation in the U.S. Department of Energy Solar Decathlon 2011 competition [12]. After the competition, the structure was rebuilt in the Greenbridge Science Park in Ostend (Belgium), where it is currently used as a testing facility. All characteristics and HVAC systems of this building are well-known [13] and, as it is subject to real environmental conditions, the E-cube is ideal for measurements providing data for validation of simulation models and methods in general. Due to the open-plan design, the building behaves as a single-zone even though it has a ground and first floor. Figure 3 shows a picture of the exterior façade of the E-Cube as well as an interior view of the building.

Fig. 3 - Exterior (top) and interior (bottom) view of the E-Cube (Source: [14]).

The E-Cube was ventilated continuously during the experiment by the installed mechanical ventilation system, set to "low ventilation" configuration (design airflow rate = 110 m^3 h^{-1}[13]). The building's thermal and ventilation behaviour over one year had been thoroughly simulated in CONTAM as part of a previous experiment [12], and therefore no new simulation was performed during this field test. The previous simulation was executed to study the effect of varying outdoor environmental conditions over the indoor environmental conditions via leakage and uncontrollable exchanges through the building envelope, i.e. without any forced air flow. From the results of that simulation, the ACH in the E-Cube ranges between 0,1 and 0,5 h^{-1} without the aid of the mechanical ventilation system, with the lowest ventilation rates during summer months and the highest during the winter months. The experiment was executed in April, when an intermediate unintentional ACH of 0,2 h^{-1} is expected. Adding the (intentional) contribution of the mechanical ventilation system (which, from the design ventilation and the internal building volume, should be of approx. 0,4 h^{-1}), the total ACH during the experiment was expected to be around 0,6 h^{-1}.

The ventilation assessment was executed alongside a parallel experiment by Ghent University, intended to study aldehydes emissions from the building materials (reported elsewhere [12]). Since it was known from previous experiments that the indoor conditions of the E-Cube were highly influenced by sunlight, a minimum indoor temperature of 30°C was set and a fixed schedule of air humidification was deployed in order to minimize the fluctuations of indoor temperature and relative humidity.

The newly proposed TGT was performed simultaneously with an active, constant-emission TGT, employing artificially-injected CO_2 as tracer gas. The complete duration of the two tests was 4 consecutive days. One pressurized CO_2 cylinder was placed outside the E-Cube, and a long flexible tube connected it to the interior of the building, with the end of the tube at a 1,3 m height. A pressure nozzle and a mass flow controller kept the CO_2 emission rate tightly at 0,5 l min^{-1}. One decane-D_{22} source was weighed uncapped with the microbalance in lab one day before and one day after the test for determination of the average emission rate (0,8 mg h^{-1}). Four CO_2 automatic loggers and four Radiello® passive samplers were distributed in the interior of the E-Cube (centre of the ground floor, next the window close to the backdoor and on the first floor) to check the indoor air mixing, and one sampler for each tracer was placed outdoors. Due to time and logistics constraints, the passive decane-D_{22} source was placed (with PE filter cap) in the E-Cube only 30min before the placement of the passive samplers. During these 30min, the CO_2 source and sensors were also placed.

Occupied apartment: The second experiment described in this paper was performed in a 1st-floor residential apartment occupied by one couple and one cat. The apartment is 52 m^2 and has no mechanical ventilation system, except for one extraction hood in the kitchen and another one in the bathroom, both of which manually activated by the occupants. Except for these local on-demand extraction points, the ventilation on the dwelling relies on natural ventilation through the openable windows (and ventilation grills over the windows). The TGT was applied in the part of the dwelling most intensively occupied by the dwellers: the living room/kitchen. In this apartment, there is no physical limit between the living room and the kitchen, and the open space acts like a single-zone. This space is also fully merged to the entrance hall/corridor. The TGT was performed employing two decane-D_{22} sources and three passive samplers scattered around the room to evaluate the air mixing. The sources were placed 3h before the samplers. Two sensor boxes for CO_2 and T active monitoring were also placed in the room. Figure 4 shows a sketch of the studied space and the test setup.

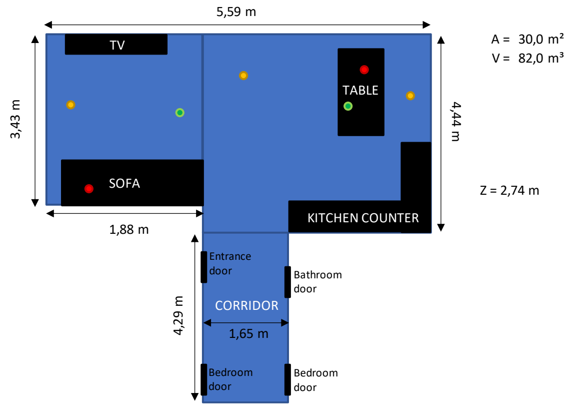

Fig. 4 - Sketch of the test space, along with the TGT setup in the occupied apartment. Green dots represent the decane-D_{22} sources, the yellow dots represent the passive samplers and the red dots represent the CO_2/T loggers. Distances in figure not to scale.

Before the application of the TGT, the test space was modelled in CONTAM (Figure 5). Since the space would be normally occupied and the occupancy-dependent patterns (e.g. presence/absence of occupants, windows opening, activation of extraction hoods) were unpredictable, the model was then intended to predict the lowest ventilation in the space, resulting from infiltration and exchanges through closed doors and windows. From the previous simulations performed until this point, the same simplifications were applied (closed doors and windows modelled as forced flow openings of 6 and 5 m^3 h^{-1}, respectively).

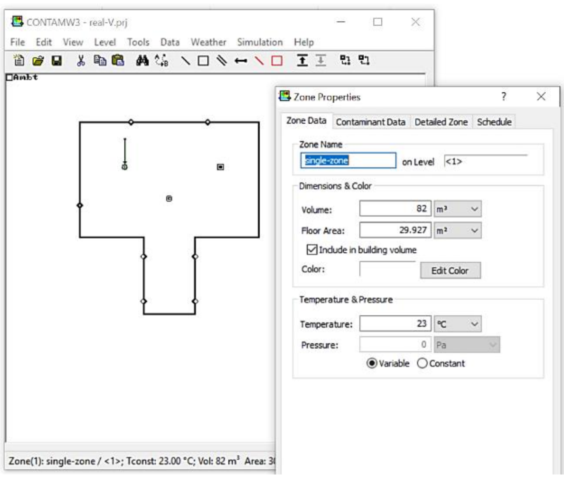

Fig. 5 - The apartment assessed during the TGT, as modelled in CONTAM.

The temperature was set to the average expected inside the apartment during the experiment. One source of decane-D_{22} was modelled with a constant emission rate of 0,72 mg h^{-1}, corresponding to twice the emission rate expected from a tarcer source at 23°C (according to the prediction curve from Figure 2). From the simulation results, the minimum ACH in the studied space should be 0,44 h^{-1} and the steady state decane-D_{22} concentration should be 20,0 µg m^{-3}. According to the simulation, 90% of the steady-state concentration would be reached in the space after 5h of source placement.

In an occupied setting such as the apartment in this experiment, the application of an active CO_2 constant-emission TGT is hindered both for technical and for practical reasons. Since the occupants act like mobile CO_2 sources of unknown (and hardly calculable) emission rate, neither CO_2 emission rate nor concentration can be kept at a minimally constant level during the test, and thus the average ACH cannot be calculated. Moreover, the transportation and installation of a pressurized cylinder (plus the necessary flow controllers) and the potential noise arising from the gas injection would cause great disturbance to the daily-routine of the occupants. Nevertheless, the CO_2 concentration was monitored throughout the experiment. In combination with specific activities annotations from the occupants, short periods in which the occupants were absent from the test space (e.g. left the apartment or went to bed with closed door) and the ventilation conditions were clearly stated could be carefully selected for applying a decay test calculation to the CO_2 concentration to determine the ACH in that short period. In a decay testing, there is no emission/injection of tracer into the space, thus the tracer concentration decays exponentially. The ACH in the space is thus derived from plotting the natural logarithm (ln) of the concentration difference between the CO_2 concentration and the background versus time. The coefficient of the linear regression obtained is equal to ACH in the space.

3. Results and discussion

3.1 Unoccupied building

Figure 6 shows the concentration of CO_2 measured over the 4-days test at the 4 indoor and 1 outdoor locations in the E-Cube, together with the temperature measured indoors.

The graph in Figure 6 shows that the air inside the E-Cube was well-mixed all throughout the experiment, with the 4 indoor sensors recording very similar CO_2 concentrations between themselves the whole time. Although a stark temperature difference can be noted between the indoor and outdoor environments during the experiment, the strategy adopted to minimize indoor temperature variation worked, as it did vary much less than the outdoor temperature, even with a very sunny weather over the whole week (75th-percentile global horizontal irradiation = 623 W m^{-2}). It is noticeable that there was an inverse correlation between the CO_2 concentration and the recorded outdoor temperature, indicating that the leakage was inversely proportional to the temperature difference, differently from what would be expected.

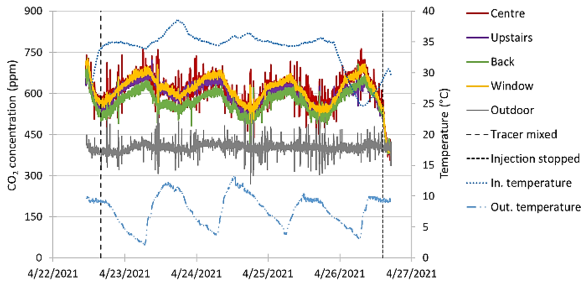

Fig. 6 - CO_2 concentration and temperature recorded over the 4-days experiment in the E-Cube.

Regarding the passive sampling results, the average decane-D_{22} concentration measured by the 4 samplers was 3,8 µg m^{-3} with an RSD = 3,7%, once again indicating an excellent level of air mixing in the E-Cube during the experiment. This result is another good indication that most indoor spaces are in fact well-mixed, regardless of size (the E-Cube is approx. 7 times larger in internal volume than the office assessed in by Paralovo et al. [11]) and occupancy status (researchers tend to assume that occupancy is one of the driving forces of air mixing, but it was not a factor in this experiment). Figure 7 shows the ACH calculated from both the active and passive TGTs (ACH calculation method described in greater detail in Paralovo et al. [11]).

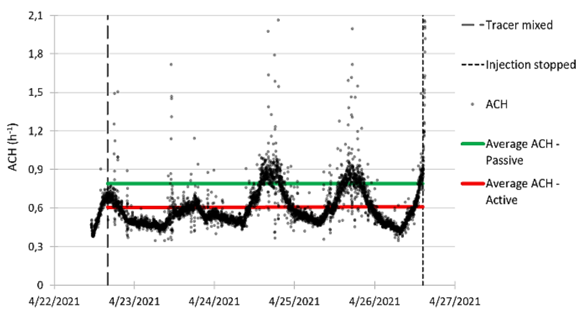

Fig. 7 - ACH calculated from the measured concentrations of CO_2 (active) and decane-D_{22} (passive).

The results displayed in Figure 7 show that the ACH in the E-Cube fluctuated mostly between 0,3 and 0,9 h^{-1} over the 4-days experiment. The average calculated from the active CO_2 measurements (black dots, represented by the straight red line) was 0,61 h^{-1}, almost exactly the same value that was expected from the theoretical evaluation, indicating that the previous model of the building leakage [12] is adequate and that the design flow rate of the ventilation system at "low ventilation" configuration is satisfactorily maintained in practice.

On the other hand, the average ACH calculated from the passive decane-D_{22} measurements (0,79 h^{-1}) was

22,9% higher than the value calculated from the active CO_2 measurements. Considering the intrinsic passive sampler uncertainty (10,5%) and the error arising from imperfect air mixing in this experiment (3,7%), the decane-D_{22} average concentrations measured in the E-Cube experiment had a global uncertainty of 14,2%. Thus, the 22,9% difference between the active and passive results, although low, is significant. There are two potential explanations for this ACH overestimation: 1) the underestimation of the true decane-D_{22} average concentration in the studied space and 2) the overestimation of the actual source emission rate. The likelihood of (1) is small but considerable, as it is known that passive samplers can be sensitive to concentration peaks (they need more time to be able to capture enough analyte mass to reflect the actual concentration increase — time by which the concentration peak itself is already decreasing), i.e. they have a natural tendency to underestimate the actual averages when the target contaminant concentration fluctuates significantly during the sampling time. Besides, in this particular experiment, the total sampling time (4 days) was shorter than the recommended by the manufacturer (1 week), which can also influence the accuracy of the analysis when the average concentration is overall low. Thus, it is recommended that the minimum sampling time of 7 consecutive days is respected in future TGTs and, especially in larger spaces, that multiple tracer sources are employed to reach higher levels of tracer concentration.

On the other hand, the likelihood of (2) is a bit more prominent. While it is preferable to measure the emission rate of the source gravimetrically using a micro-balance, potential losses of tracer from inside the source during transportation cannot be ruled out. For the E-cube experiments, the source had to be weighed one day before the start of the experiment and then one day after its finish, as its transportation between the lab and the E-Cube site took 3h. During the 6h in the car rides (for the complete round-trip), the source position could not be controlled, and the liquid tracer in the source was subject to the car movement and vibrations, getting into full contact with the rubber-septum in the vial cap. It is possible that small amounts of liquid tracer were adsorbed in the rubber septum, and therefore lost when the cap was substituted by a new one with a PE filter disk (and also when the second rubber-cap for the trip back was removed for the final weighing). Therefore, not all the weight difference measured can be attributed to the actual tracer volatilization during the TGT.

Another potential evidence of (2) is the fact that the emission rate measured gravimetrically was around 12% higher than the value predicted by the Figure 2 prediction curve (0,70 mg h^{-1}) from the average temperature measured in the E-Cube. That prediction curve was derived from more than 20 separate experiments using several replicate sources simultaneously, and applying different environmental conditions. Even when the conditions to which the sources were subjected varied during the experiment, the final gravimetric measurements still showed excellent agreement with the prediction curve (considering the average temperature). If the predicted source emission rate is used for the ACH calculation in the E-cube test instead of the gravimetrically measured one, the calculated ACH (0,70 h^{-1}) becomes then only 13% different than the ACH calculated from the active CO_2 measurements, a value below the global uncertainty of the passive sampling for this experiment (14%), i.e. with this method of calculation, the new TGT can be considered validated also in a larger space. Therefore, the recommendation for future applications of this new TGT is to determine the source emission rate either via the prediction curve shown in Figure 2 or gravimetrically with an on-site scale (minimum accuracy of 0,1 mg), to avoid potential tracer losses during transportation.

3.2 Occupied apartment

Figure 8 shows the CO_2 concentration monitored during the 7 days in the occupied apartment, along with three periods selected for the decay test calculations and the ACH calculated for each period.

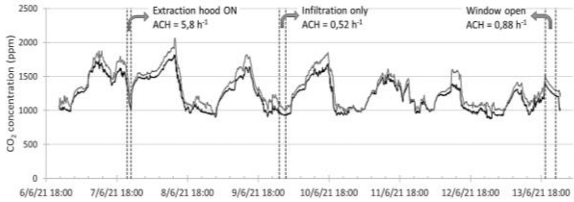

Fig. 8 - CO_2 concentration measured by two active logging sensors during the TGT in the occupied apartment. The straight dashed lines mark 3 short periods right after the occupants exited the test space, and when distinct ventilation characteristics were in place.

Figure 8 shows that the CO_2 concentration in the apartment oscillated greatly during the experiment, mostly between 900 and 2000 ppm, reflecting both the ventilation variations and the CO_2 sources (i.e. occupants) movement. Hence why an accurate CO_2-based TGT would be impractical in this setting. Despite this issue, the three well-characterized periods highlighted in Figure 8 provide a few insights for further analysis of the decane-D_{22} TGT results. According to Figure 8, the infiltration-only portion of the ventilation in the studied space amounts to an ACH = 0,52 h^{-1}, a value only 15% higher than the predicted by the CONTAM simulation. The ventilation in the space is increased tenfold (ACH = 5,8 h^{-1}) when the extraction hood over the kitchen counter is activated on full-power. An intermediate ventilation level (ACH = 0,88 h^{-1}) is achieved when one of the windows is open. Since it is not possible to know with certainty the actual weight the ventilation strategies held during the experiment, any passively-calculated average ACH between 0,5 and 5 h^{-1} should be considered at least realistic in this case.

The average decane-D_{22} concentration measured by the three passive samplers was 13,4 μg m^{-3} with a very low RSD between them (1,6%), indicating that the studied space was very well-mixed during the experiment period. As was observed during the E-Cube experiments, the sources' emission rates measured gravimetrically (509 mg h^{-1}) were higher than the value predicted with the Figure 2 curve by the same factor of 12%. This suggests that, when the liquid tracer gets in contact with the vial cap during transportation, a specific minimum amount of tracer is adsorbed by it, leading to an overestimation of the average emission rate by at least 12%. Thus, the value theoretically predicted by the curve from the average temperature measured during the TGT (26°C) was applied to both sources (450 mg h^{-1}).

Therefore, by applying these measured and estimated values to Equation 1, the average ACH calculated from the passive TGT is of 0,82 h^{-1}. This value is in line with the predictions based on the CO_2 concentration, and in fact very close to the ACH calculated from the CO_2 decay when the window was open. Therefore, it can be considered that the TGT can provide realistic estimations of ACH in occupied naturally-ventilated spaces as well.

4. Conclusion

This paper presented two successful applications of a newly proposed TGT to measure average ventilation rates over long-term periods in varied types of buildings. The proposed test is passive, more affordable and practical than commonly applied active pressurization tests, e.g. the blowerdoor test. Moreover, it is also more environment-friendly when compared to the currently employed long-term passive TGTs, which use known potent greenhouse gases (PFTs) as tracers. The first application reported in this paper took place in an unoccupied building, and the second one in an occupied apartment. Results from both experiments showed reasonable agreement with predictions previously done with CONTAM multizone simulations, indicating a good level of air mixing inside both studied buildings. Additionally, results yielded by the newly proposed TGT in both settings demonstrated the accuracy of the tracer emission rates estimated with the lab-derived prediction curve (Figure 2). More applications of this proposed TGT are recommended to further evaluate its appropriateness to different and more complex settings in the future, so that the main goal of providing a reliable, accessible and accurate alternative to researchers, contractors and buildings owners to assess ventilation in a wide range of buildings is achieved.

5. Acknowledgement

The authors would like to acknowledge the support of colleagues from VITO who, although not directly involved in this project, assisted and facilitated our work immensely. Special thanks to the UGent colleague Klaas De Jonge for the partnership developed during the E-Cube experiments. No potential competing interest is reported by the authors.

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Data Statement

The datasets generated and analysed during the current study are not publicly available because they are owned by VITO, but can be shared on an individual basis via direct contact with the authors.