Measuring the ventilation rate in occupied buildings and adapting the CO_2 tracer gas technique

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ABSTRACT

Measuring ventilation rates in occupied dwellings is challenging but represents the conditions that occupants experience. This paper explores the constraints of existing methods when measuring the ventilation rate of occupied buildings and proposes a new method addressing some of them.

Ventilation rates in occupied buildings can change over short time scales due to changes in weather or window and door positions. PFT based methods measure average ventilation over an extended period. Similarly, an annualised ventilation rate based on the '20th rule of thumb' can be approximated using pressurisation tests. It is unclear how the results relate to the ventilation rate under any specific conditions. Conversely, measurement periods of less than an hour are possible with tracer gas techniques.

The spatial scale over which ventilation is measured is important. Whole dwelling estimates are obtained from pressurisation tests and tracer gas methods if the whole dwelling is dosed. In both cases internal doors must be open, affecting the airflow, which may or may not reflect the occupied configuration. Differences between whole dwelling and in-use ventilation could be important for IAQ and heat loss. Single zone tracer gas techniques have been applied to one room and assumed to represent the whole dwelling. Multi-zone methods using several different gases are not usually applied in occupied buildings because of the complexity of the experimental set-up.

Measurement techniques must be acceptable to occupants. Pressurisation tests are minimally disruptive, taking less than an hour. PFT measurements are unobtrusive, only requiring small sources and sorption tubes. Injection of tracer gases, such as SF_6, and concentration measurement can require pumped gas sampling which is noisy and bulky, causing inconvenience to the occupants. Metabolic CO_2 based methods do not require the injection of gas or pumped sampling and may be more acceptable to occupants.

CO_2 decay techniques require knowledge of occupancy; historically this has relied on occupant reports, assumed hours of occupancy, or hand-picked sections of data. Similarly, CO_2 equilibrium or accumulation techniques require knowledge of the CO_2 generation rate and occupant activities.

A new approach has been developed to address some of these issues, based on metabolic CO_2 tracer gas decay. An algorithm for identifying when a dwelling is occupied has been developed, agreeing with reported occupancy in 87% of cases, meaning that large volumes of data can be analysed automatically. CO_2 is measured in each room every 5 minutes, meaning that sub-hourly variations in ventilation rate, and variation between rooms, can be explored. Proximity sensors are used to monitor windows and doors, so that ventilation can be calculated during periods with constant conditions, and variation due to different configurations can be investigated. The proposed method represents a step towards appropriate measurement of ventilation and its variation in occupied buildings.

KEYWORDS

Ventilation, ventilation measurement, tracer gas, occupancy, occupied buildings

1 INTRODUCTION

Through the Paris Agreement, 185 countries have agreed to make efforts to tackle climate change (UNFCCC, 2015). Limiting excess ventilation improves the thermal efficiency of buildings; ventilation can account for 50% of the primary energy used in a UK dwelling (CIBSE, 2015). However, sufficient ventilation is required to maintain adequate indoor air quality (IAQ) in occupied buildings (Persily, 2006). Poor IAQ has been associated with various health implications, including: asthma, allergies, cancers, 'sick building syndrome' and respiratory tract infections (Sundell *et al.*, 2011). Fisk (2018) reviewed the literature and concluded that there is likely to be an association between low ventilation rates and poor health outcomes. Additionally, the ventilation rate that the occupant experiences is likely to affect their thermal comfort and use of air conditioners (Iwashita and Akasaka, 1997).

Occupants can significantly influence the ventilation rate in their homes through their practices of window and door opening (external and internal) and use of mechanical ventilation (Kvisgaard and Collet, 1990). However, characterising the ventilation occupants experience is challenging due to the spatial and temporal variability of ventilation rate and the acceptability of the technique to the occupants. This can mean that it is difficult to understand the ventilation rates that the occupants are likely to experience.

This paper explores some of the challenges of measuring ventilation in occupied buildings, and suggests a method which addresses some of them. The following section reviews some of the issues with current ventilation measurement methods when used in occupied buildings, Section 3 introduces the proposed method, and describes the algorithm that has been developed to determine when a building is occupied, and the results of combining the measurement method and the occupancy algorithm. Section 4 discusses the strengths and weaknesses of the proposed method. Finally, Section 5 provides the conclusions and implications.

2 VENTILATION MEASUREMENT IN OCCUPIED BUILDINGS

Measurement of ventilation in occupied buildings can be complicated by factors including the weather, its spatial variability and the influence of occupants. These aspects are reviewed in relation to the most common methods used to characterise ventilation in this section.

2.1 Time Scale of Measurement

The ventilation rate estimated from a measurement is specific to the time for which the measurement took place. However, the weather conditions and building configuration will vary in occupied dwellings, thus the estimated ventilation rate only holds for the conditions during which the measurement took place (Persily, 2016). For example, changes in window or internal door position may alter the ventilation rate significantly, weather conditions particularly affect naturally ventilated buildings. Measurements taken in a specific configuration cannot easily be extrapolated to different conditions.

Methods to estimate ventilation may be broadly categorised as those which provide an average rate over a long duration (days to months), and those that provide a shorter-term 'snapshot' of the ventilation rate. Those methods estimating a long term ventilation rate are valuable in estimating the overall conditions in the space, but cannot distinguish the impact of factors such as door and window opening. This combined with the intermittent occupation of specific spaces by occupants means it can be challenging to interpret occupant exposure to pollutants using these methods. The physical interpretation of the calculated rate is also unclear in using these methods (Sherman, 1990). Perflourocarbon tracer gas methods (PFT) are commonly used to measure the average tracer gas concentration over varying time scales, examples range from two days (Bornehag *et al.*, 2005) to a month (Bekö *et al.*, 2016). In analysis of this data a constant ventilation rate over the period of measurement is assumed.

Another common method for estimating the average ventilation of a building is the 'rule of thumb' that the air change rate measured at 50 Pa divided by 20 is a rough estimate of the annualised air change rate under 'normal' conditions. Sherman (1998) stresses the limitations of this given the influence of variations in weather conditions and dwelling characteristics. Liddament (1996) suggests this can be particularly problematic for naturally ventilated buildings as the instantaneous ventilation rate can deviate significantly from the average.

Other methods provide a 'snapshot' of the ventilation rate in a space and specific configuration over a limited duration (minutes or hours). These may be useful to identify exposure to pollutants under specific conditions, but give relatively little information about general ventilation in a building. They are challenging to interpret if information about the weather, doors and windows is missing (Persily, 2006). Tracer gas methods may be used to estimate the ventilation rate from the rate of release required to produce constant concentration, from its rate of accumulation given a known rate of release, or from its rate of decay. Tracer gas concentration is usually monitored over approximately 1-2 hours, assuming the ventilation rate to be constant over this period. Compared to the long term techniques above, the ventilation rate is much more likely to be stable on this shorter time scale. However, changes in doors, windows or operation of a ventilation system could still alter the ventilation rate significantly during the measurement period and the contextual information required to interpret such ventilation rates is considerable. Additionally, the relation of such estimated ventilation rates to those in different building configurations and weather conditions is not clear and may require extensive measurement and analysis to understand.

The number of measurement repeats carried out under different conditions varies considerably in the literature. Wallace, Emmerich and Howard-Reed (2002) carried out ventilation measurements every 2 to 4 hours in an occupied house over a year. They recorded weather conditions and fan use, but window use was inconsistently recorded and internal doors were not mentioned. A measurement period this long is extremely unusual, most measurements of ventilation rates using non-PFT tracer gas methods last less than a week (Guo and Lewis, 2007; Sharpe *et al.*, 2015; Keig, Hyde and McGill, 2016). Apart from Wallace, Emmerich and Howard-Reed's extremely extended study (whose method is unlikely to be acceptable to many building occupants, see section 2.3), little research has been published addressing the variation in ventilation rates of buildings, which may only be investigated using techniques requiring a short measurement duration.

2.2 Spatial Scale of Measurement

Air flows within buildings may be complex; dependent on the configuration of walls, the opening of internal doors and furniture. In addition, the air exchange with outdoors may be through both planned and unplanned ventilation paths. As a result, ventilation rates of different spaces within the building can be variable, due to the changes in door and window opening, amongst other factors. The IAQ may therefore vary substantially across the spaces that are occupied, resulting in an exposure to pollutants in individual spaces that may not reflect the whole house ventilation, or that in different rooms (Persily, 2006). It can also impact the thermal comfort of occupants and their consequent actions, for example in particularly still parts of a building occupants may increase their use of cooling in the summer (Iwashita and Akasaka, 1997), or in particularly draughty parts of the building may increase their use of space heating in the winter.

Some ventilation measurement methods are applied to the whole dwelling, such as the n/20 rule of thumb, which assumes that the building can be adequately described as a single zone (Sherman, 1998). Multiple blower doors can be used to characterise different parts of buildings, but this is uncommon and air leakage between internal spaces is challenging to characterise.

Single-zone tracer gas experiments can also be used to estimate whole building ventilation rates. A uniform concentration of tracer gas throughout the building is required (ASTM, 2011), meaning that internal doors are opened, which may alter the conditions compared to those experienced when the building is in use (Keig, Hyde and McGill, 2016). Fans are often used to ensure that uniform concentrations are achieved. However, Liddament (1996) suggests that fans should not be used if the aim of the measurement is to understand air quality, since areas of poor mixing are important in this context.

Multi-zonal tracer gas analysis can be used to investigate the effect of interzonal flows (e.g. Penman and Rashid, 1982; Smith, 1988; Harrje *et al.*, 1990). However, the analysis and experimental set-up is much more complex than for single zone measurements and this method is rarely carried out (Persily, 2006).

The ventilation rate of single rooms is often used to provide insight into IAQ and the exposure of occupants to pollutants. For example, Guo and Lewis (2007) and Sharpe *et al.* (2015)

measured a single room and assumed this to be representative of the whole building. However, in such cases the airflow between internal spaces has not been accounted for and the resultant estimate of the ventilation rate does not represent the indoor-outdoor ventilation (Persily, 2006). The complexity of airflow through and between spaces in buildings, and the resultant limitations in estimating and interpreting a ventilation rate to provide insight into the conditions experienced by occupants, is challenging and depends on the desired insights of the study. Averaging the ventilation over an entire building means that the ventilation the occupant experiences is unlikely to be understood, given that occupants will tend to move around rooms and close doors. However, it is technically challenging to adequately account for interzonal flows such that measurements can be taken in the building configuration that the occupant experiences.

2.3 Invasiveness of Equipment

The inconvenience associated with a measurement technique will likely influence how long people will tolerate its presence in their building. This section briefly reviews the invasiveness of different methods to estimate the ventilation rates of properties.

Pressurization tests can usually be completed in less than an hour and do not require any equipment to be left in a building. During testing occupants cannot use an external door and the test is noisy; however, they have been used in many studies of occupied buildings (e.g. Oreszczyn *et al.*, 2005).

Tracer gas methods are likely to vary in their acceptability to occupants. PFT equipment is small and silent so may be acceptable to occupants. Use of a safe tracer gas is essential, and using CO_2 (particularly metabolically generated) is likely to be more acceptable than other gases as it is naturally present in the air and does not involve the release of any gas for the purpose of measurements – a key motivation for the development of this method by Penman and Rashid (1982). CO_2 can be measured using NIR sensors, these are not excessively large and are silent so may be acceptable to occupants. By contrast pumped gas sampling requires tubes to be distributed around the building, increasing the spatial and visual burden to the occupant, as well as being noisy. Wallace, Emmerich and Howard-Reed (2002) used pumped gas sampling for a year, but this research took place in the home of one of the authors; recruitment of non-researcher participants may be challenging for an extended campaign with this method.

In order to ethically conduct ventilation measurements in occupied buildings, participants must be aware of any disruption likely to be caused, and must find this acceptable for the duration of the research. Less invasive techniques may be acceptable to a greater proportion of people, for example pressure testing may be more widely accepted than tracer gas experiments, but the insights gained may be reduced.

2.4 Knowledge of Periods of Occupancy

It is often important for the interpretation and analysis of measurements to know the times a building is occupied, this is essential for CO_2 based methods. However, methods to determine the occupancy status of dwellings during ventilation measurements have not been widely published. Guo and Lewis (2007) suggest that the difficulty in accurately determining when a dwelling is occupied is one of the reasons that there are few examples in the literature of the use of metabolic CO_2 as a tracer gas. In Guo and Lewis' study decay periods identified using an occupant-reported daily log-sheet; occupant diaries may not always be accurate and they increase the burden of the occupant participating in the research (Bryman, 2004). Roulet and Foradini (2002) monitored a single office-room and manually identified periods of decaying CO_2, implying that prolonged periods of decreasing CO_2 can be interpreted as indicating that there were no occupants present. However, this does not account for the possibility of leakage between zones and manual identification of unoccupied periods is a laborious process for long monitoring campaigns.

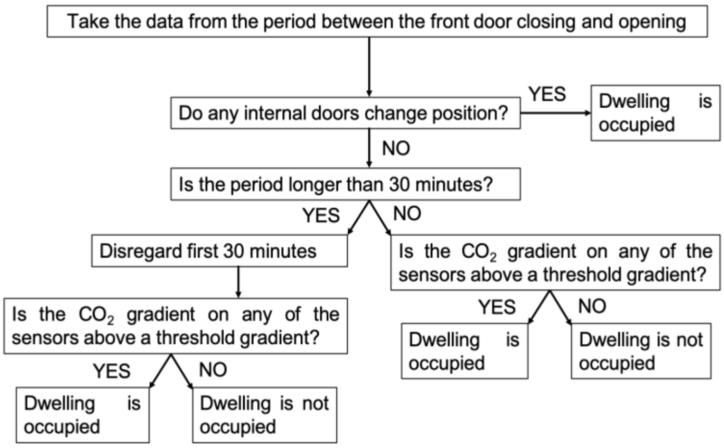

Figure 1. Flow chart of the decision making of the occupancy algorithm.

3 DEVELOPING A NEW TECHNIQUE TO ESTIMATE VENTILATION RATE

A new method has been developed, which refines the application of the CO_2 tracer gas decay method using metabolically generated CO_2. It is essential that the periods when the building is unoccupied are reliably known with this method; to achieve this state sensing of doors and windows is combined with an algorithm to determine the occupancy state.

The state of doors and windows was measured using binary magnetic contact sensors which record when a door or window is open or closed. Not only are these data required to determine occupancy, they also aid understanding of the configuration of the building during the unoccupied measurement. Additionally, measurements of the weather conditions and internal temperatures support the interpretation of the results.

3.1 Developing an algorithm for determining building occupancy

As discussed in Section 2.4, the ventilation literature has relatively few examples of methods for determining when a building is occupied. Where building occupancy has been recorded this has tended to be through occupant diaries, or by hand-picking sections of data for analysis.

Chen, Jiang and Xie (2018) reviewed the literature on determining occupancy in buildings, finding that different sensors have different results are often obtained when different sensors are combined. Dedesko *et al.* (2015) used beam-break sensors in an attempt to count the number of people passing in or out of the room. They also measured CO_2 concentrations and used estimated CO_2 generation rates to determine whether a beam-break event was associated with someone entering or leaving the room.

The algorithm developed in this research can be used to filter the data collected from the occupied buildings so that only those times which are identified as unoccupied are used in ventilation rate calculations; it is based on similar principles to the Dedesko method. The algorithm is based on the logic that if any of the internal doors or windows change state between the front door closing and the next time it opens, then the building must be occupied during that period. If none of the doors or windows change position, then the CO_2 concentration gradient is tested on the basis that if the CO_2 rises significantly then the building is highly likely to be occupied (or another significant source of CO_2 is present, which precludes use of the decay method). The first 30 minutes of data after the front door closes are disregarded if the period under investigation is sufficiently long to allow some stabilisation of the airflow. This ensures that if the door to a room with a high concentration of CO_2 is opened shortly before the building becomes unoccupied and causes the concentration of CO_2 to rise in adjacent rooms, this period isn’t falsely identified as occupied. The flow chart in Figure 1 shows the decision making process used by the algorithm.

3.2 Testing the occupancy algorithm

A case study monitoring campaign was set-up in an occupied flat to provide data for developing the occupancy detection algorithm. The flat was monitored between February and July 2018. Three adults lived in the flat and it was unoccupied for several hours most days as all of the occupants worked full-time. CO_2 sensors were placed in every room except the bathroom. Door

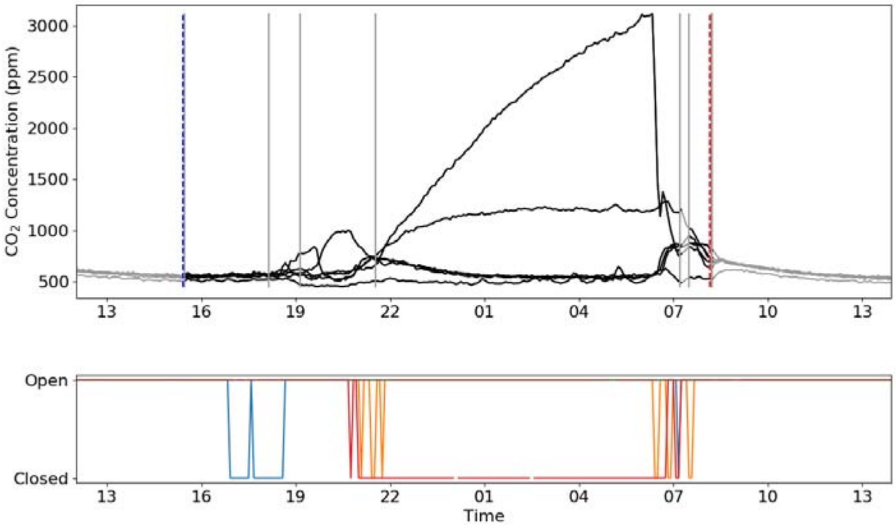

Figure 2. Example of the occupancy algorithm identifying the time at which the dwelling became occupied and unoccupied. The top part of the graph shows the measured CO_2 concentrations in each of the rooms, with the black sections of the CO_2 data indicate that the space has been identified as occupied. The grey vertical lines indicate the front door opening and closing. The blue (red) dashed vertical line indicates that the occupant reported the beginning (end) of the occupancy. The bottom part of the graph shows the internal doors changing between open and closed.

sensors were placed on all doors. The internal door sensors recorded the state (open or closed) every 5 minutes (state monitoring), whereas the front door sensor recorded every time the door opened or closed (event monitoring). The occupants were asked to record when the last person left the dwelling (occupancy ends) and when the first person entered the dwelling (occupancy begins). There were 62 reported start or end of occupancy times. Figure 2 shows an example of a reported occupancy start and end time with the door opening data and CO_2 concentrations in the dwelling.

The occupant records were compared to the results from the algorithm and these were in agreement in 87% of cases. To calculate this agreement the following logic was used: when the period before the occupant reported a start of occupancy event was identified by the algorithm as unoccupied this counted as one event of the algorithm correctly estimating the occupancy. Similarly, when the period after the occupant reported start of occupancy was identified by the algorithm as occupied this counted as another event of the algorithm correctly estimating the occupancy (and vice versa for end of occupancy data). The percentage of agreement was then calculated.

Disagreements between the occupant records and algorithm were investigated through detailed study of all the measured parameters. In some cases it is likely that the disagreement was due to window opening – the temperature rapidly dropped but the CO_2 did not rise. This highlights the need for window sensors to improve the algorithm performance. In other cases, the front door was in frequent use (likely because the occupants were arriving or leaving for work at similar times), in 10 of the 16 cases of disagreement the front door was opened with a frequency of more than 30 minutes. Since the door and window state was recorded every five minutes, the algorithm was sometimes unable to identify these periods as occupied; use of event logging equipment will resolve this issue. By recording windows and using event logging, the agreement would likely have been at or above 95%.

3.3 Measuring the ventilation rate

Calculation of the ventilation rate is based on the single zone approximation of the continuity equation in which no sources are present (Sherman, 1990):

$$CO_{2,\mathrm{Diff}}(t) = CO_{2,\mathrm{Diff}}(t = 0)\ \exp(-A.t) \tag{1}$$

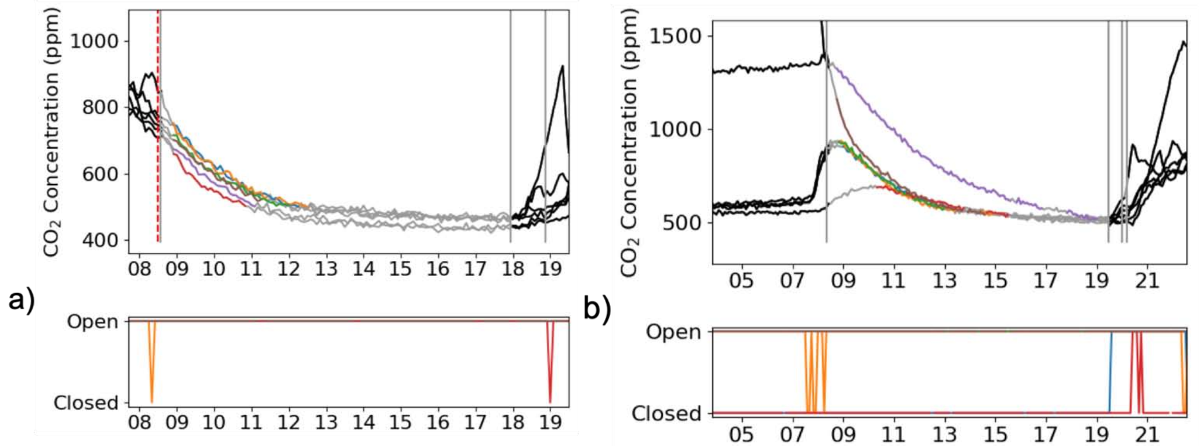

Figure 3. Examples of data collected in the test dwelling. The top part of each figure shows the CO_2 concentration against time of day in each room: occupied periods are shown in black, data suitable for decay analysis are shown in colour. The grey vertical lines show when the front door opened and closed. The bottom part of each graph shows the internal door states. In part a) all the internal doors are open and in figure b) some doors are closed.

Where $CO_{2,Diff}(t) = CO_{2,int}(t) - CO_{2,ext}(t)$, $CO_{2,int}(t)$ is the indoor CO_2 concentration, $CO_{2,ext}(t)$ is the outdoor CO_2 concentration, $CO_{2,Diff}(t = 0)$ is the concentration difference at the start of the decay period, A is the air change rate, and t is the time since the start of the decay.

Figure 3a shows an example of the data collected to test the occupancy algorithm: the transition from occupied to unoccupied and subsequent decay in CO_2 concentration can be seen. In this case, all internal doors were open and the CO_2 concentrations are closely matched in all rooms. In this case, $CO_{2,int}(t)$ would be the mean of the internal concentrations, as dwelling is behaving as a single zone.

Figure 3b shows a second example in which two of the rooms have their door closed. The CO_2 concentration decay is clearly different in different rooms. In this case, the dwelling does not behave as a single zone, so a single ventilation rate does not adequately describe the internal conditions, and the mean internal concentration should not be used in estimating the ventilation rate. However, the CO_2 concentration decay in different rooms can be used to estimate the ventilation rate in those rooms, with a systematic bias in a known direction. This is a significant advantage over measurements in which only a single room is measured, or in which the whole house is treated as homogenous. In this example, one room has higher CO_2 concentration throughout the decay (shown in purple). This room has a lower ventilation rate than the other rooms. To estimate the ventilation rate in this room $CO_{2,int}(t)$ would be the CO_2 concentration in this room only. The single room ventilation rate calculated would systematically larger than the 'true' indoor-outdoor ventilation rate of this room, because some of the reduction in CO_2 is likely due to air exchange with the other areas of the building.

Conversely, any ventilation rate calculated for the rest of the building using the concentration recorded in other rooms would be systematically higher than the 'true' indoor-outdoor ventilation rate of this space. This is because the rate of CO_2 decay would be reduced by any leakage of CO_2 from the first room. However, it is possible to see that the rest of the building eventually becomes well mixed, and then decays at the same rate throughout.

Figure 3b highlights the importance of the internal doors, in addition to ventilation to the outside, in determining the airflow in a dwelling. The implications of such issues on the data analysis and interpretation are discussed in the following section.

4 DISCUSSION

The method developed in this work may be used to estimate the ventilation rate in intermittently occupied properties. It does not account for interzonal flows as it uses the single zone approximation. However, collecting CO_2 and door opening data from each room supports appropriate analysis and interpretation of the results. If the whole dwelling behaves as a single zone (Figure 3a) this technique gives the outdoor ventilation rate of the space in that configuration. When the building does not behave as a single zone (as in Figure 3b), the calculated ventilation rate of any particular room (using the concentration from that room only as $CO_{2,int}(t)$) is that assuming the decay in CO_2 is entirely due to exchange of air with outdoors (Mumovic *et al.*, 2009). By recording the concentration in all rooms, the direction of the systematic bias that the single zone assumption introduces to the ventilation rate calculated for particular rooms is known.

The calculated ventilation rate for a single room will be systematically higher than the indoor-outdoor ventilation rate when the room in question has CO_2 concentration higher than the adjacent spaces. This is because some of the reduction in CO_2 concentration is due to air exchange between indoor spaces rather than exchange with outdoors, so that the 'true' indoor-outdoor ventilation rate is lower than that measured. Conversely, the calculated value for a single room will be systematically lower when the CO_2 concentration in this room is lower than the adjacent spaces. This is because some additional CO_2 may be flowing into the room in question from the adjacent rooms, causing a reduction in the measured rate of CO_2 decay. The closer the indoor spaces to the concentration in the room in question, the closer the measured value will be to the indoor-outdoor ventilation rate. These measured ventilation rates in particular rooms might be considered 'effective' ventilation rates: when the CO_2 source is removed and given the distribution of CO_2 in the building, the capacity of the building to act as a fresh air reservoir and the configuration of the doors and windows, this quantifies how quickly the CO_2 decays to background concentrations.

Since the building is continuously monitored, the similarity of the configuration of the building during occupied times and unoccupied ventilation measurement periods can be assessed. This means it is possible to understand how the occupants use the building when they are present, and whether their use of internal doors means that the building is likely to behave as one single zone or if they are likely to experience different ventilation rates depending which room they are in during occupied times. This provides much more information on the ventilation conditions that occupants are likely to experience, and how this may vary, than is possible using standard single zone methods.

It should be noted that the binary nature of the window and door sensor limits the extent to which the occupied and unoccupied conditions can be compared – there is no record of whether doors or windows are ajar or fully open.

Weather conditions will also affect the ventilation in a building. The sensors required are silent and reasonably small, meaning that participants may be willing to accept the presence of the equipment for an extended period. An extended measurement campaign allows the variation of ventilation under different weather conditions to be explored. However, the cost of the equipment and management of the measurement campaign are important restrictions to the application of this method.

The proposed method allows detailed insights into the ventilation conditions in occupied buildings. The occupancy algorithm may be used to analyse large volumes of data over extended measurement campaigns with much reduced workload compared to manual selection. This method enables the investigation of the varying nature of ventilation rate, and an understanding of how the occupant's use of the building may affect the ventilation rates they experience.

5 CONCLUSIONS

Estimating the ventilation rate in occupied dwellings is challenging, and the method employed depends on the desired insights, occupant acceptance and resource limitations. Issues include the timescale over which estimates are required (e.g. average over a period, or only during occupied hours), the spatial scale (e.g. specific room or whole building), the intrusiveness of measurements and occupant acceptance, and the researcher time required.

The method developed in this paper is based on metabolic CO_2 tracer gas decay, and uses an automated algorithm to detect occupancy. This method enables the variation in ventilation to be explored. The measurements may be acceptable to occupants since CO_2 is naturally present and the sensors can be silent and reasonably small. These sensors are not expensive, and are combined with sensors that determine the open/closed state of windows and doors, to investigate the differences in ventilation rates in different spaces and under different configurations. The window and door sensors also allow investigation into the extent to which different configurations are experienced in occupied and unoccupied times, and the impact that this has on the ventilation rate that the occupant experiences.

The proposed method uses an automatic algorithm for determining when the building is occupied. The algorithm has been shown to be agree with occupant records in over 80% of cases, which will increase with the use of window sensors and event rather than state loggers. This algorithm reduces burden on the researcher and occupant to manually record or interpret data, enabling the analysis of large volumes of data.

The proposed method represents a step towards appropriate measurement of ventilation and its spatial and temporal variation in occupied buildings. It may enable the measurement of buildings over an extended period, supporting ventilation rate estimation in many different configurations and weather conditions. Such results will support insights into the ways that a building is used by occupants and the ventilation rates that they are likely to experience given their use of the building. This will provide insight into the thermal comfort of occupants, as well as the IAQ they experience. The exposure of occupants to contaminants is complex, depending on ventilation rates, source strength, source location and exposure time: this method provides a detailed picture of the ventilation in occupied buildings, and could help to better understand the association between ventilation rates and health.

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