Airtightness and non-uniformity of ventilation rates in a naturally ventilated building with trickle vents

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ABSTRACT

Infiltration is an uncontrolled contribution to ventilation in a building and can contribute significantly to the total ventilation rate, particularly in older, leaky, dwellings which can rely on infiltration to provide adequate indoor air quality. However, as explored in this paper, using a whole house airtightness metric to characterise ventilation rates can fail to identify low ventilation rates in specific rooms.

Measurements were undertaken in autumn and winter for a dwelling with an airtightness (by blower door) of 15.1 $m^3/hr/m^2$@50Pa. The dwelling was built in the 1930's: semi-detached, suspended timber floors, cavity walls and retrofitted throughout with double glazing incorporating trickle vents.

The whole dwelling ventilation rate (by CO_2 tracer gas decay) with the trickle vents closed was 0.7 ach, and 0.8 ach with the trickle vents open. However, the ventilation rate (by CO_2 tracer gas decay) in a single room with its internal door closed under different weather conditions was only 0.17 ach (standard deviation = 0.06 ach, number of measurements = 34), and with trickle vents open 0.32 ach (standard deviation = 0.13 ach, number of measurements = 40). This is below the 0.5 ach required for good indoor air quality. This is likely related to the closed internal door reducing cross-ventilation and the non-uniformity of air leakage paths in the dwelling. The leakage paths were investigated using smoke pens during a pressurisation test and significant air leakage paths were observed in other rooms: through the under stairs cupboard, around services in the kitchen and bathroom, and through the ceiling into the loft.

Low air change rates have been observed in a building with very low airtightness, typical of older stock in the UK. The dwelling was retrofitted with double glazing, which is likely to have significantly affected the airflow, but still left the dwelling with low total airtightness. The double glazing had trickle vents, but these did not provide adequate ventilation. Inclusion of trickle vents in replacement windows is 'good practice' according to English building regulations, but not compulsory if there were no vents in the previous windows. Similarly, undercuts are required for doors in new dwellings, but are only required for existing buildings in new wet rooms; the tested dwelling had undercuts half the size required for ventilation regulations in new buildings.

The difference in ventilation rates at different spatial scales is rarely discussed, but this research shows that there can be major discrepancies. This paper discusses the implications of this for appropriate measurement of ventilation, and the implications for ventilation regulations and guidance as well as the need for further research into the complexity of the manifestation of ventilation in occupied buildings.

KEYWORDS

Ventilation, airtightness, measurement, indoor air quality, building regulations.

1 INTRODUCTION

The Climate Change Act (2008) commits the UK to reducing carbon dioxide emissions to 80% of 1990 levels by 2050. In 2015, the domestic sector accounted for 29% of final energy consumption in the UK; space and water heating made up 80% of this energy use (BEIS, 2016). CIBSE (2015) state that heat loss through ventilation can account for up to 50% of the primary energy used in a building in the UK, so reducing heat lost through ventilation in dwellings is important. However, sufficient ventilation is required for good indoor air quality (IAQ). Fisk (2018) reviewed the literature and found that lower ventilation rates are likely to be associated with poor health outcomes, although the evidence is complicated by confounding factors and associations are not universally observed. A ventilation rate of 0.5 ach is often considered to be sufficient for IAQ (Sundell *et al.*, 2011; Dimitroulopoulou, 2012; Fisk, 2018).

UK Building Regulations require that there ‘shall be adequate means of ventilation provided for people in the building’ (HMG, 2013b). The Approved Document to the UK Building Regulations Part F (ADF) specifies whole dwelling ventilation rates, dependent upon floor area and number of bedrooms, which should be achieved in new dwellings and details of ventilation systems which will be assumed to meet the requirements (HMG, 2013b).

The total ventilation in a building includes purpose-provided ventilation and ventilation through infiltration. Infiltration is uncontrolled airflow through unplanned breaks in the air barrier of the building (HMG, 2013b). Air permeability gives the average volumetric airflow through each unit area of the building envelope and characterises the infiltration.

The results of air permeability tests can be used to estimate the ventilation rate using the n/20 ‘rule of thumb’ which states that the annualised whole dwelling ventilation rate is equal to the air change rate at 50 Pa divided by 20 (Sherman, 1987). In the UK, the Standard Assessment Procedure (SAP) – a method for estimating the energy efficiency of a building – uses a form of this rule to estimate the ventilation rate due to infiltration (BRE, 2014). The SAP method uses the air permeability rather than the air change at 50 Pa as the numerator. Sherman (1998) stresses the limitations of this approximation given variations in weather conditions and dwelling characteristics. Liddament (1996) suggests that this can be particularly problematic for naturally ventilated buildings as the instantaneous ventilation rate can deviate significantly from the average.

Air leakage paths are not evenly distributed throughout buildings (Johnston *et al.*, 2011). Breaks in the air barrier around services in kitchens and bathrooms, into roof voids or around poorly fitting windows or doors are common. So whole dwelling ventilation rates are unlikely to be evenly distributed and will depend on which doors are open or closed. However, little research has addressed the difference in ventilation rate measured on different spatial scales; for example Bekö *et al.* (2010) and Sharpe *et al.* (2015) measured only bedrooms, while Oreszczyn *et al.* (2005) and Keig, Hyde and McGill (2016) all characterised only the whole house ventilation rate, Johnston and Stafford (2017) compared the n/20 rule to the ventilation rate in two rooms, but did not discuss the different spatial scales of the measurement.

Differences in ventilation rate at different spatial scales could affect the occupants exposure to pollutants or their use of space heating, or both. This paper report on a case study dwelling that has been investigated to explore the ventilation rate in different spaces, and the research illustrates the possibility that occupants experience different ventilation rates depending on how they use internal spaces. The results are used to consider how guidance for providing adequate ventilation can be improved given spatial variation in ventilation rates.

This paper also considers the performance of trickle vents (background ventilators). Trickle vents are intended to ensure that buildings are adequately ventilated. They are an element in three of the four ADF approved systems for ventilation, and are recommended in existing buildings when windows are replaced (HMG, 2013b). Despite the prevalence of trickle vents there are limited studies on their performance. Low ventilation rates have been observed in naturally ventilated dwellings with trickle vents (Crump *et al.*, 2005; Sharpe *et al.*, 2014) and many occupants keep them closed (Sharpe *et al.*, 2015). This research gap is addressed here by investigating the effect of opening and closing trickle vents on the whole house and individual room ventilation rate.

The following section describes the case study building and the methods used to characterise the ventilation rates at different spatial scales using tracer gas analysis, then Section 3 presents the results. Section 4 discusses the implications for research and the need for further work to understand the implications of spatial variability in ventilation, as well as implications for ventilation regulations and the interacting factors at work in designing for adequate ventilation in occupied dwellings. Finally Section 5 provides the main conclusions and implications.

Figure 1. Photograph of the test dwelling.

2 METHODS AND CASE STUDY

2.1 Description of the test house

A single case study dwelling was studied: built in the 1930's, semi-detached, with suspended timber floors, cavity walls and retrofitted throughout with double glazing and trickle vents. Figure 1 shows the outside of the building.

ADF gives whole house ventilation rates which should be achieved only in newly built dwellings only. If this building were newly built, a ventilation rate of 28 L/s would be required, 0.4 ach assuming the whole house volume takes part in the ventilation. Since there will be dead-zones, the effective volume will be smaller than the physical volume and this would increase the required ach value.

The dwelling is naturally ventilated with no mechanical ventilation. The total geometric area of the trickle vents was 32,000 mm^2 for the whole house, 6,400 mm^2 for the single room studied in detail. The geometric area is provided because the slots inside the trickle vents were cut smaller than the manufacturer recommends, so the equivalent area is not known. If the dwelling were newly built, background ventilators with equivalent area of at least 5,000 mm^2 would be required in the single room, and 45,000 mm^2 in the whole house.

2.2 Pressurisation tests and smoke survey

Pressurisation tests use the flow rate required to maintain a given pressure difference between indoors and outdoors to measure air permeability. Pressurisation tests were conducted in line with the ATTMA protocol (ATTMA, 2016). Measurements were taken with a Minneapolis Model 3 and a Retrotec 6000 blower door on calm weather days in August 2018 and February 2019 respectively; one pressurisation and depressurisation test was carried out in each case and the mean value is reported below.

Additionally, while the house was pressurised, a qualitative survey of the dwelling was carried out using a smoke pen to visualise the air leakage paths.

2.3 Tracer gas tests

Tracer gas methods use a gas to 'tag' airflow and are based on the conservation of mass of tracer gas and air. The tracer gas concentration decay method was used with CO_2. Measurements were performed according to ASTM (2012) guidance.

The air change rate was calculated using the following equation (ASTM, 2012), and the analysis was carried out using a least squares curve fitting algorithm (curve_fit from SciPy):

$$CO_{2,Diff}(t) = CO_{2,Diff}(t = 0)\exp(-A.t) \quad (3)$$

Where $CO_{2,Diff}(t)$ is the difference between the indoor CO_2 concentration minus 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 2 shows a floor plan and locations of the CO_2 sensors in the test dwelling. The diamond in the corner of the back room represents three sensors: at floor level, at ceiling level and 1.2 m above floor; the diamond in the corner of bedroom 2 represents two sensors: at 1.2m above floor and ceiling level. All other sensors were all between 1.1 m and 1.3m above the floor. The CO_2 concentration was recorded every 5 minutes with Eltek GD-47 (NDIR) sensors. The outdoor CO_2 concentration for each sensor was taken to be the mean concentration during a

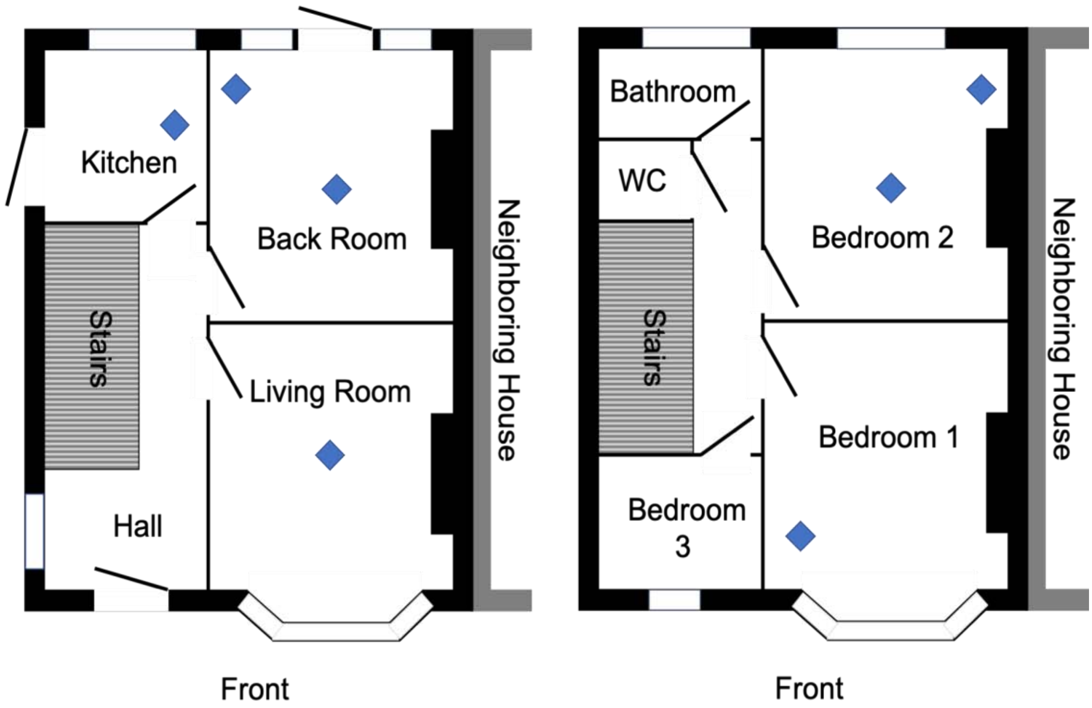

Figure 2. Layout of the test dwelling, ground floor on the left hand side, first floor on the right hand side. The CO_2 sensors are indicated by the blue diamonds. The single room tests took place in the downstairs 'back room'.

three-day period in which the dwelling was continuously unoccupied. Variation between sensors was less than 50 ppm and the mean of all sensors was 430 ppm during this time.

The tracer gas tests were carried out on two spatial scales: the whole house and a single room. These are described in more detail in the subsections below.

2.3.1 Whole house tests. Two whole house tests were carried out in February 2019: one with trickle vents open, the other with trickle vents closed. The temperature differences were 13 ºC and 15 ºC, the wind speeds were 10 mph and 14 mph for the measurement with the vents open and closed respectively. The wind direction was South-West in both cases.

CO_2 was released in each of the rooms and fans were used to encourage good mixing. However, it was not possible to maintain the CO_2 difference within 10% of each other in all the spaces as recommended by ASTM (2012). The downstairs sensors remained within 10% of each other, as did the upstairs sensors. There were differences of up to 30% between upstairs and downstairs. The volume-weighted average CO_2 concentration was used in the analysis.

2.3.2 Single room tests. The single room was on the ground floor and is identified as the 'back room' in Figure 2. The measurements took place between September and December 2018. Temperature differences ranged from -3 ºC to 18 ºC, the wind direction was predominantly North West to North East, and ranged from 3 mph to 23 mph. There were 34 tests with trickle vents closed and 40 with trickle vents open.

There were four CO_2 sensors in the single measurement room. These remained within 10% of each other throughout the single room tests and the mean concentration was used to calculate the air change rate. The sensors in adjacent rooms recorded CO_2 rises, suggesting inter-zone flows, but the concentration never exceeded the CO_2 concentration in the single room.

3 RESULTS

Table 1 summarises the results from each of the methods described above. The dwelling is leaky compared to modern properties, but is fairly typical of older dwellings - Perera and Parkins (1992). The qualitative smoke pen investigation revealed several significant air leakage

Figure 3. Photograph of the smoke pen survey, showing significant air leakage behind the kitchen cupboard.

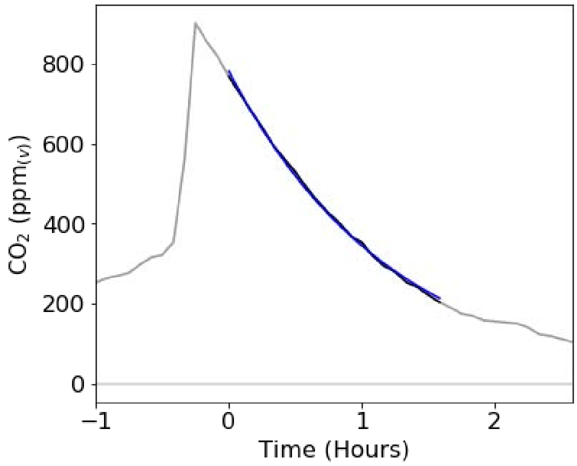

Figure 4. The whole house CO_2 decay with trickle vents open. The y-axis shows the volume weighted CO_2 difference. The black line shows the decay period, and the exponential model is shown in blue.

paths in the under stairs cupboard, around the services in the kitchen and bathroom, through several cracks in the walls and around the front door. The windows were well sealed. Figure 3 shows an example of the smoke being pulled into the space behind the kitchen cupboard, while the house is pressurised by blower door.

The whole house ventilation rate found using CO_2 decay is above the threshold of 0.5 ach with trickle vents open and closed, and the dwelling is therefore well ventilated from an IAQ perspective, but excessively inefficient to heat. Figure 4 shows an example of the CO_2 decay and log-linear fit of the data for the whole house measurement with the trickle vents open.

In contrast, the single room ventilation rate is below 0.5 ach with trickle vents open and closed. This suggests this individual room could have issues with poor IAQ when the door is closed. Figure 5 shows a histogram of the air change rates calculated for tests when the trickle vents are opened and closed. The ventilation in both configurations varies considerably because of the variety of weather conditions during the experiments, however none of the trickle vent closed rates are above 0.5 ach, and very few of the trickle vent open rates exceed this figure.

4 DISCUSSION

4.1 Limitations of the techniques

As with all methods to estimate ventilation rates, several limitation apply to this study. In particular, results from this case study may not be generalised to the wider stock. However, this building is of typical construction for a house built during the 1930s, and the available evidence suggests that the dwelling is not abnormal: the airtightness is typical of older stock (Perera and Parkins, 1992) and similar leakage paths locations have been found in other dwellings (Stephen, 2000). This study therefore identifies issues are that are likely to occur more widely in the stock, with unknown prevalence and highlights issues of policy and practice that may form the basis of further study.

Table 1: Summary of results characterising the case study dwelling from the pressurisation and CO_2 decay tests

	Trickle Vents Open	**Trickle Vents Closed**
Air Permeability	-	15.1 $m^3/hr/m^2$
ACH_{50}	-	15.1 ach
$N_{50}/20$	-	0.8 ach
Whole house CO_2 decay	0.8 ach	0.7 ach
Single room CO_2 decay (mean)	0.3 ach	0.2 ach

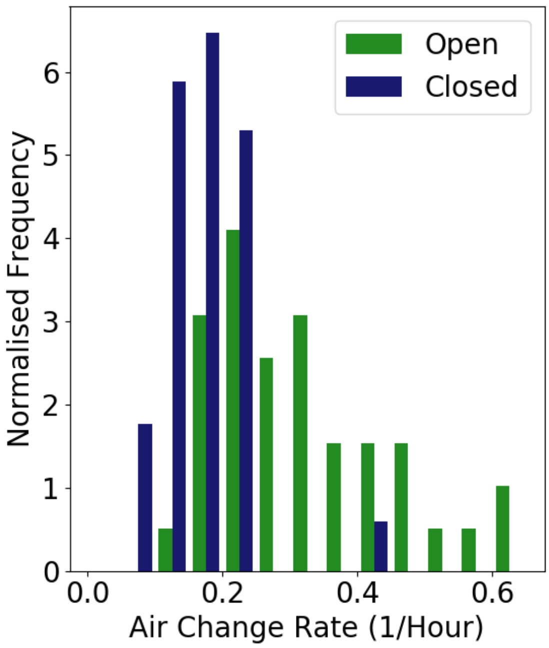

Figure 3. Normalised histogram of the measurement of air change rate measured in the single measurement room with the trickle vents opened and closed.

In application of the whole house tracer gas method it was not possible to maintain the CO_2 concentrations to within 10% between upstairs and downstairs. Analysis of the upstairs sensors resulted in a decay constant of 0.7 ach for trickle vents open and 0.5 ach for trickle vents closed. These values are systematically biased towards low values because the stack effect caused CO_2 to flow from downstairs to upstairs due to buoyancy effects. Given that these values are at or above the threshold of 0.5 ach, the finding that the whole dwelling is over-ventilated holds despite the inability to maintain uniform concentration.

The single zone approximation was used for the single room, neglecting flow between rooms. The CO_2 concentration in adjacent rooms was always below the measurement room, so any airflow to other internal spaces will have systematically biased the result towards higher values. The true indoor-outdoor ventilation rate is likely lower and therefore the IAQ worse.

Whole house tests were conducted once, while multiple tests were conducted in the single room. The distributions therefore cannot be compared, but since the whole house measurements took place with neither the highest temperature difference nor the highest wind speeds, the difference in ventilation rates between different scales is not due to more extreme weather conditions.

4.2 Difference in ventilation rate measured at different spatial scales

The results show that measurements of ventilation on different spatial scales can differ significantly. The whole dwelling value suggests that the dwelling is over-ventilated, while the single room with the door closed suggests poor IAQ due to a low ventilation rate. Whether this affects occupants would depend on how long occupants spend in a specific room, the ventilation rate and pollutant sources. For example: the use of candles, cleaning products, drying of clothes or simply the presence of several people are all events that could take place in a room with the door closed which could lead to poor IAQ (Satish *et al.*, 2012; Porteous *et al.*, 2014; Dimitroulopoulou *et al.*, 2015).

The difference in ventilation rates is likely to be caused by a range of factors, including the non-uniformity of air leakage paths and limited air exchange between spaces with closed doors. Inter-zone air flow may be encouraged by door undercuts; ADF requires undercuts of 7600 mm^2 in new buildings. However, the measured room had undercuts approximately half this size, which will have significantly reduced the airflow to the rest of the building.

4.3 Implications for research

It has been shown that the spatial scale on which ventilation is measured, and the closing of internal doors, can have a substantial effect on the ventilation rate that is calculated and consequently whether the ventilation appears to be adequate. This highlights the need to determine the purpose of ventilation measurements in study design, and identify the limitations to the values estimated in different ways.

To date there has been relatively little empirical work exploring how internal spaces are divided and used by occupants. Banfill *et al.* (2012) found that particular doors were opened and closed at regular times each day, while particular rooms were almost permanently closed off due to adult children moving away. McDermott, Haslam and Gibb (2010) found several reasons people opened or closed doors including: watching children in next door rooms, letting light in, and blocking sounds. Sharpe *et al.* (2015) found that bedroom doors often closed overnight and doors were more likely to be open when a child is present.

Further work on how spaces and doors within buildings are used would support a better appreciation of the conditions that occupants experience, and their relation to whole house air change rates, or those in specific rooms. Such research would also support the application of appropriate techniques to estimate ventilation rates, according to the purpose of the measurement, in assessing whether spaces are under- or over-ventilated and the implication of this. For example, studies investigating the link between ventilation rate and health may be confounded if a whole building ventilation rate is measured, while occupants experience a very different rate (affecting their exposure to pollutants) in the spaces they use. Sundell *et al.*, (2011) and Fisk (2018) reviewed the literature and concluded that it is more likely than not that there is a detriment to health associated with low ventilation rates. Whilst neither author discusses the spatial scale of the measurements, Fisk suggested that greater clarity and uniformity in measurement of ventilation rate would be helpful for understanding and comparing results.

4.4 Implications for policy

At present, ADF specifies ventilation strategies for new buildings which will be assumed to meet the requirements for adequate ventilation. These provisions differ depending on the planned air permeability of the building. The results presented here suggest that this could be inappropriate, since the air permeability and subsequent ventilation through infiltration are unlikely to be evenly distributed around the building – a higher air permeability does not necessarily mean that more ventilation is provided in the places in which it is needed.

ADF recommends but does not require that trickle vents are installed when windows are replaced in existing buildings. The trickle vents improved the ventilation in the single room in this case study (though were unable to raise it to adequate levels). The installation of replacement UPVC glazing units is likely to increase the airtightness of a room and may result in reduced IAQ (Oreszczyn *et al.*, 2005). Requiring that all rooms contain adequate background ventilation whenever any change is made that could influence the air change rate in a space could mitigate this issue.

The trickle vents in this dwelling were unable to raise the single room ventilation rate to an adequate level. Further work is required to determine if this issue is widespread, but this result is in line with previous authors (Crump *et al.*, 2005; Sharpe *et al.*, 2015). Whilst increasing the number or size of trickle vents would improve the ventilation rate with the internal door closed, it would contribute to increased excess ventilation with the door open. Additionally, the ventilation rate for properties with natural ventilation through trickle vents is variable, depending on the weather conditions. This presents a challenge in devising appropriate policies and practice guidelines: appropriate ventilation depends on whether internal doors are open or closed. The problem is exacerbated by the findings of several authors that trickle vents are frequently closed in occupied dwellings (Crump *et al.*, 2005; Sharpe *et al.*, 2015), despite the stated intention in ADF that they are permanently open. The role of occupants on ventilation rate is therefore highly significant and measures designed to provide adequate ventilation must account for occupant behaviour. Strategies could include improving the design of trickle vents or raising public awareness such that occupants more readily understand their intended purpose, or providing trickle vents which cannot be closed.

This research has highlighted that the current building regulations are not designed to take into account differences between the behaviour of the whole building and individual rooms. Two measures that may address the observed disparity for naturally ventilated buildings are the use of undercuts for doors and vents between rooms. Undercuts with an area of 7600 mm^2 are required by ADF for new buildings and may improve flow between rooms with closed doors. However, there are no requirements for undercuts for existing buildings, except where a new wet room is added. Whilst the magnitude and scale of this issue is not known, requiring either undercuts or between room vents when doors are replaced, or when major building work is completed on a property, could improve the single room ventilation rate without increasing the whole building ventilation rate with internal doors open.

Potential occupant acceptability issues arise for undercuts or vents: they allow cool draughts which may decrease thermal comfort, and they allow noise to travel between rooms. ADJ recommends noise attenuating vents when they are installed to provide adequate combustion air for flued appliances (HMG, 2013c), this may provide a partial solution.

Finally, in considering how to improve airflow through dwellings the need for buildings to be firesafe must be considered. Fire doors are tested for fire safety compliance with a particular undercut, up to a maximum of 25 mm (BSI, 2008). Any adjustment to the undercuts would require re-testing doors for their fire safety with a new undercut depth. Similarly, in order to comply with Approved Document B (HMG, 2013a), vents between rooms should not be used in fire-resisting walls and vents should be placed at low level to reduce the spread of smoke, this prevents placement of vents at high level to improve thermal comfort.

The above discussion has demonstrated the complexities involved in the design and regulations for adequate ventilation in occupied dwellings, especially those which are naturally ventilated. The research has shown that differences between individual rooms and whole house ventilation rates can affect whether the ventilation is adequate; research on the use of internal doors and the effect on internal environments is lacking. Neither is this difference adequately accounted for in current regulations. Trickle vents have been shown to be an unsatisfactory solution as the whole house became more over-ventilated and the individual room remained under-ventilated, compounding this, trickle vents are known to be shut in many occupied homes. Door undercuts and through-wall vents may mitigate this issue, though occupant concerns and fire regulations must be observed. The manifestation of ventilation in occupied buildings requires further research given that the way occupants use a building is influential yet challenging to account for when designing adequate, robust and safe guidance and regulations for ventilation.

5 CONCLUSIONS

Adequate ventilation is required to maintain good indoor IAQ, while excessive ventilation reduces the thermal efficiency of a building: a ventilation rate of 0.5 ach is considered to balance these issues (Sundell *et al.*, 2011; Dimitroulopoulou, 2012; Fisk, 2018). This paper addressed the differences in ventilation rates measured on different spatial scales in the same building. A case study building was measured with an air permeability of 15.1 $m^3/hr/m^2$@50Pa, the whole dwelling ventilation rate was 0.8 ach, while the ventilation rate was 0.3 ach in one room with the door closed (both ventilation rates with trickle vents open). The building is over-ventilated with all doors are open, but inadequate IAQ may be experienced in the single room when the door is closed. Although the dwelling has high air permeability, it cannot be assumed that the ventilation is adequate in the rooms with the door closed.

The differences in ventilation rates on different scales identified here are likely to be replicated in other dwellings in the stock as the locations of air leakage paths were not unusual (Stephen, 2000) and the air permeability was typical for a building of this age (Perera and Parkins, 1992), but the incidence and magnitude of the difference is unknown. More modern dwellings are built with a lower total air permeability and this issue may become more acute in these buildings as the ventilation through infiltration will be smaller so the single room ventilation rate could be even lower leading to a corresponding increase in indoor pollutant exposure.

Opening the trickle vents increased the whole dwelling ventilation rate in the case study property, worsening the heating efficiency, but did not provide adequate ventilation in the individual room with closed door, potentially leading to inadequate IAQ in this space. Additionally, previous research has shown that trickle vents often closed in occupied homes (Crump *et al.*, 2005; Sharpe *et al.*, 2015), despite permanently open trickle vents being the stated intention in ADF (HMG, 2013b). This shows that occupant actions have a significant

impact on the ventilation rate experienced and highlights the challenge of designing ventilation strategies and guidance which ensure appropriate ventilation in occupied dwellings.
The current building regulations do not adequately account for the differences between whole house and individual room ventilation rates. Strategies which may improve individual room ventilation rates, without increasing whole house ventilation, include increased undercuts beneath doors and vents between rooms. Undercuts are required for new buildings, but are only required in existing buildings when new wet rooms are fitted. Amending the regulations such that undercuts and vents between rooms are required when doors are replaced or major building work takes place may improve individual room ventilation rates. There are potential occupant acceptability issues with these measures: they may increase cold draughts and increase noise transmission around the dwelling. Noise attenuating vents provide a partial solution this issue. Fire safety concerns must also be addressed: between wall vents should not be placed in fire-resisting walls and should only be placed at low levels to reduce smoke transmission in the event of a fire; additionally, fire doors are rated for a particular depth of undercut so these may need to be retested if undercuts are adjusted.
This paper has shown that the spatial scale over which ventilation is measured can influence whether the ventilation appears to be adequate. This highlights the need to identify the purpose and limitations of a ventilation measurement when designing research. Further work on how occupants interact with buildings, including internal door opening behaviours, would support a better understanding of the appropriate scale over which to measure ventilation and appropriate measurement techniques for different purposes.

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