Energy-led retrofitting of solid wall dwellings: technical and user perspectives on airtightness

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Purpose – Mechanical ventilation with heat recovery (MVHR) is increasingly being promoted in the UK as a means of reducing the CO2 emissions from dwellings, and installers report growing activity in the retrofit market. However, the airtightness of a dwelling is a crucially important factor governing the achievement of CO2 reductions, and the purpose of this paper is to understand the technical implications of airtightness levels in an experimental dwelling, purpose built to typical 1930s standards, at the same time as gaining the users' perspectives on airtightness and ventilation in their homes.
Design/methodology/approach – In-depth interviews were carried out with 20 households to collect information on their retrofit and improvement strategies, attitudes to energy saving and their living practices as they impinge on ventilation. The experimental house was sealed in a series of interventions, leading to successive reductions in the air permeability as measured by a 50 Pa pressurisation test. The behaviour of a whole-house MVHR system installed in the experimental house, was simulated using IES Virtual Environment, using a range of air permeability values corresponding to those achieved in the retrofit upgrading process.
Findings – In the house considered, air permeability must be reduced below 5m3/m2h for MVHR to make an overall energy and CO2 saving. However, to achieve this required a level of disruption that, on the basis of the views expressed, would be unlikely to be tolerated by owners of solid wall dwellings.
Originality/value – The paper is the first to combine results from a user-centred approach to exploring the existing practices of householders with a simulation of the energy and CO2 performance at different levels of airtightness of an experimental house in which MVHR has been installed.
Keywords Housing, Buildings, Heating and ventilation services, Energy consumption, Airtightness, Dwellings, Householders attitudes, Mechanical ventilation
Paper type Research paper

1 Introduction

The UK has the oldest housing stock in the developed world (Energy Saving Trust, 2003). Of 25 million dwellings in the UK, 34% have solid walls and are responsible for 50% of the total UK domestic sector CO_2 emissions. In a typical unimproved UK solid wall dwelling the ventilation heat loss rate is approximately equal to the heat loss rate through the fabric (walls, roof and ground floor) so, in the context of Government targets of reducing CO_2 emissions from buildings, reducing this ventilation heat loss is attractive and the Energy Saving Trust (2005) emphasises the importance of improving the airtightness of dwellings. Since mechanical ventilation with heat recovery (MVHR) is an established contributor to achieving the zero carbon homes standard required by UK legislation for all new homes by 2016, including those reaching Passivhaus standards, there is an emerging market for MVHR in retrofit installations. However, it is much more difficult to achieve the required low levels of air permeability by retrofitting an existing dwelling than when building a new one, and it is not clear to what extent users and specifiers of retrofit MVHR systems realise how important the building's airtightness is in achieving the anticipated savings. Understanding the technical implications and the user perspectives on airtightness is therefore necessary to prevent inappropriate advice, potentially leading to undesirable disruption and expensive mistakes, being given.

This paper describes some of the work in progress as part of a consortium project entitled *Consumer appealing low energy technologies for building retrofitting* (CALEBRE - www.calebre.org.uk), which aims to establish a validated, comprehensive refurbishment package for reducing UK domestic carbon emissions, that is acceptable and appealing to householders, and specifically targeted at UK owner occupied solid wall properties (classified as 'hard-to-treat'). It is investigating a selection of technologies, informed by the reality of the user perspective, addressing such questions as the degree of disturbance that householders are prepared to tolerate during a refurbishment programme. Some of the retrofit solutions have been installed and are being evaluated in a newly-constructed test house (the E.ON 2016 House, Figure 1), specially built in 2008 to 1930s standards at Nottingham University. This house has cavity walls which are assumed to have similar performance, when the cavity is filled, to solid walls with external insulation, and there is no reason to expect the air permeability to be different in the two cases. This paper describes results in two main areas, (i) the importance (and difficulty) of achieving airtightness in reducing heat losses and CO_2 emissions from dwellings and (ii) homeowners' perspectives on this aspect of the retrofitting of their homes.

2 Indoor air quality, ventilation and airtightness

2.1 Technical background

Ventilation is needed to dilute and remove pollutants produced indoors, such as moisture, body odours, cooking smells and volatile organic compounds, as well as to supply fresh outdoor air (Awbi, 2003). If moist air comes into contact with a cool surface, the local relative humidity increases, and when it exceeds 80% the risk of mould growth increases rapidly (Roulet, 2001). Any surfaces below the dew-point temperature will permit condensation to form, a serious problem with uninsulated external walls. The development of damp, mould and fungi can result in health and comfort issues for occupants, therefore it is important for the ventilation strategy to maintain RH levels between 30-70% (Carrer et al, 2001). This means that in general the ventilation rate is greater than that required merely to supply fresh air (Energy Saving Trust, 2003). For dwelling renovation, therefore, it is important to consider the ventilation strategy when implementing measures to improve the building airtightness to ensure there is no detrimental effect on occupant comfort or the building fabric.

The UK's relatively mild climate means dwellings predominantly rely on uncontrolled natural ventilation. This does not guarantee a sufficient air change rate to maintain indoor air quality all year round, but allows excessive ventilation and heat loss in windy conditions. Until the recent drive towards low carbon housing, the airtightness of UK dwellings showed little improvement. In a survey of 471 dwellings (Stephen, 1998) those constructed between 1900-1930 had a mean air permeability just over 10 air changes per hour (ach^{-1}) at 50 Pa, measured by the pressure test (CIBSE, 2000). For a sample of houses built 1930-1960, it exceeded 15 ach^{-1}, while in the most recently constructed properties it had returned to 10 ach^{-1}. In other parts of Europe dwellings are much more airtight and mechanical ventilation (with or without heat recovery) is universal. It should be noted that the 50 Pa value, specified in standards, is different from the unpressurised infiltration rate that should be used in thermal energy calculations. Kronvall (1978) derived a 'rule of thumb' method in which the natural infiltration rate is 0.05 times the tested air change rate. In this paper, all measured air change rates and permeabilities are 50 Pa pressure test values.

Passivhaus standards (2011) specify 0.6 ach^{-1} at 50 Pa and were developed to enable the design and construction of dwellings with annual heating or cooling energy consumption below 15 kWh/m^2 treated floor area. At this level, the ventilation system can address the space heating needs and a whole house MVHR system is an essential component of this strategy. Although strictly these standards apply only to new buildings, they are increasingly being implemented in refurbishment projects, and the first certified Passivhaus retrofit in the UK was recently achieved for a terraced Victorian property (Octavia Housing, 2011).

The heat recovered from the ventilation air by MVHR offers a modest contribution to CO_2 emissions savings. As a result the market for MVHR systems in the UK has been stimulated and in 2009 was estimated at 15000 units annually, worth £30million. Of this the retrofit sector accounts for a small but growing share of about 5% (Waddell, 2010). Since the effectiveness of an MVHR system depends on the correct balance between heat recovery efficiency, fan efficiency, air flow rate and building airtightness there is a technical challenge in using MVHR for retrofit. Since there was no prior information on this, the technical objective of this investigation was to establish the airtightness level that must be achieved in order for MVHR to have a significant effect on the CO_2 emissions, using both modelling and monitoring.

Macintosh and Steemers (2005) found differences between the expectations and reality for an MVHR system in housing in four areas:

1. Noise – disturbance from external noise and pollution should be improved, but residents in the study reported noise from inlet vents which was unwanted.
2. Perceived freshness – ventilated air may not be perceived as fresh as it is not at external temperature and no direct connection to the outside (for example via a window) was made by residents.
3. Perceived control – residents opened/closed windows much more frequently than they made adjustments to the MVHR controls.
4. Misunderstanding – residents misunderstood what the ventilation was for and when it should be used.

In light of this, the behavioural objective of the investigation in this paper was to compare the technical findings with user perspectives in order to identify acceptable ways forward.

2.2 User centred design background

For any new technology to be successful, it must be accepted by the end users and meet their needs. These needs include their social, emotional, practical and economic needs. For a technology such as MVHR, it is critical that it is considered in context of the built environment and the end users, that is householders. By taking a user centred design approach, it should be possible to explore the existing ventilation practices of householders and identify requirements for the technology that will meet these requirements in context. The principles of user centred design are generally accepted to be an early focus on users and tasks, empirical measurement and iterative design (Gould and Lewis 1985), leading to the design of useful, useable and desirable products. Preece et al. (2002) propose that providing "an easily accessible collection of gathered data" will help designers remain focused on user needs. Clear communication of requirements to designers and technologists in a way that is meaningful and relevant is therefore a crucial component of user centred design. To this end, CALEBRE is taking a user led approach to understanding householders with the intention of ensuring that the resulting technologies are designed to be acceptable and appealing.

3 Research Methodology

3.1 Summary of the CALEBRE project

The CALEBRE project aims to develop a number of technologies suitable for retrofitting to solid wall dwellings. These are at various stages of completion and will be tested either in the laboratory or in service in the E.ON 2016 house. In addition to the work described in this paper, there are a number of technological workpackages, which can be summarised as follows:

- Develop an electric air-source heat pump, able to deliver hot enough water to make it suitable for replacing the boiler in an existing central heating system.
- Develop a gas-fired air-source heat pump, able to deliver hot enough water to make it suitable for replacing the boiler in an existing central heating system.
- Develop vacuum double and triple glazing units, able to achieve U-values of 0.33 W/m^2.Kor less, suitable for use in conventional windows.
- Develop advanced surface treatments for internal walls, with hygrothermal properties able to smooth the changes in air temperature and relative humidity.

In addition, the project will explore the market development issues associated with mass production of these novel technologies and develop a prototype selection tool, informed by the identified needs of homeowners. The project has a strong consumer focus and a group of householders has been recruited to participate in the evaluation of the technologies and their implications for user behaviour and performance in service.

3.2 Airtightness measures

Air permeability tests using the 50 Pa fan pressurisation technique (CIBSE, 2000) were carried out on the E.ON 2016 house in its initial state and following each stage of the application of a series of retrofit solutions (Table 1), installed over several months with the aim of reducing the level of uncontrolled ventilation. This provided a series of measured permeability values which could inform the infiltration value used in a dynamic thermal model of the house to assess the impact on the annual energy consumption and CO_2 emissions. Some of the upgrades to the external fabric and glazing have multiple benefits in that they contribute to reduced infiltration rates as well as conduction losses. Measuring the changes in the building's air permeability allows the combined effect of these improvements to be assessed as a series of retrofit measures by updating these properties simultaneously in the thermal model.

3.3 Dynamic Thermal Modelling

Dynamic thermal modelling software (IES Virtual Environment) was used to build a model of the E.ON 2016 house (Figure 1) to simulate a year's operation and calculate the annual energy consumption and CO_2 emissions. Details of the building geometry and orientation were input using the architectural drawings to create zones corresponding to each room and represent the building. The Nottingham Test Reference Year weather file (CIBSE, 2008) was used to simulate local climatic data.

Figure 1 E.ON 2016 house at The University of Nottingham and the IES VE Dynamic Thermal Model

The operational parameters for each room type were derived from the National Calculation Methodology database (NCM, 2010) to develop a set of templates representing the occupied house, specifying heating set-points, domestic hot water consumption and internal gains (lighting, equipment and occupancy), as well as diversity profiles set up to represent daily and weekly variations in these values.

These parameters were consistent for all the analyses so that the variations in energy performance would be attributable to the ventilation strategy and the thermal properties of the building. The thermal modelling assumes that there are no changes in the internal conditions before or after the application of the retrofit measures, and that occupants do not take the benefit of higher living temperatures. This may be wrong, as research into this 'rebound effect' shows (e.g. Sorrell, 2009), but will not be considered further here.

Construction templates were created defining both the internal and external constructions, and performance characteristics. This allowed the changes in U-value between the initial base case house, as built to 1930s construction standards, and the thermally upgraded construction, as per the improvement work carried out as part of the retrofit process, to be replicated in the E.ON 2016 dynamic thermal model. This would simulate the differences in conduction losses associated with the improved glazing and building fabric.

3.4 Understanding of User Requirements

To understand the requirements of the users in context, twenty households (with 66 permanent occupants) were recruited to take part in a series of data collection activities. Each household lived in an owner occupied, solid wall house in the East Midlands region of the UK. A purposive sampling approach was taken, to ensure inclusion of a range of house types (detached, semi-detached, link, mid and end terraced), household types (single, couples, families with young, older and grown up children), participant age ranges (28 – 80 years old), income bands (under £10,000pa – over £70,000pa) and location (urban, suburban, rural). While not intended to be a statistically representative sample, it allowed detailed exploration of a snapshot of different domestic situations.

Two in-depth interviews were undertaken with all adult household members wherever possible to ensure a whole household perspective. The first interview explored reasons for buying the property, improvements made to the house and issues relating to these (who did the work, levels of disruption, approximate cost, etc). These were drawn up with the householders using an innovative 'timeline tool', reported in more detail in Haines et al (2010). Issues relating to comfort and home improvement aspirations were also covered. In the second interview, attitudes towards energy saving were explored, the CALEBRE technologies were described to the householders and initial responses obtained. Questions were then asked about the householders' various practices in the home that related to the design of the technologies. These were intentionally focused on the householders and their home lives to ensure a relevant and engaging conversation, rather than a more formal question and answer session. Finally a tour was made of the home to see in detail aspects of the house that had been mentioned in the discussions, as well as to take a photographic record of the various features. Digital audio recordings from these interviews were transcribed and analysed using NVivo 9. Conversational extracts relating to ventilation and related practices were analysed in detail and the key findings are presented in this paper.

4 Results and Discussion

4.1 Air permeability

Each set of improvement measures applied to the E.ON 2016 house contributed to a reduction in the building's air permeability, but with variable success (Table 1). In its original state the house was very leaky and the extensive stage 1 improvements were expected to significantly reduce the measured air permeability but succeeded in reducing it only from 15.57 to 14.31 $m^3/m^2.h$. The relationship between permeability in $m^3/m^2.h$ and air change rate is specific to the geometry of the building: in this case 15.57 $m^3/m^2.h$ = 14.85 ach^{-1}. Noting the inconsistency with air change rates mentioned earlier, we report permeability values here because they are familiar to UK professionals. Inspection revealed that the draught-proofing had been poorly applied to the windows and doors, often with an incomplete seal around the perimeter of the component, and installing the MVHR system had created new gaps in the building envelope and duct connections to the rooms, permitting uncontrolled airflow. In stage 2 the draught-proofing was re-done and extended to the remaining doors and windows, reaching 9.84 $m^3/m^2.h$. The building air permeability was further reduced by the two remaining stages, culminating in the final measure of sealing and insulating the ground floor, which achieved the final building air permeability value of 5 $m^3/m^2.h$ at 50 Pa.

Much effort and cost was needed to reduce the air permeability and the research team were surprised at how poor was the workmanship in the initial stages of draught-proofing, undertaken professionally to current industry standards. Gaps were left around doors and previously installed insulation disturbed by later work. The final stage was especially disruptive and involved lifting floor coverings and furniture before installing a membrane over the timber floor. The total cost of draught-proofing exceeded £12000, and with the MVHR installation costing £6000 this is unlikely to be economic.

While sealing a house is perceived as a simple task, it is in fact much more challenging because of the care and attention to detail needed by the workforce. Air permeability is made up of a myriad of entry points in the fabric, which can be created by oversize holes for pipes and wiring, irregular gaps between new windows and brickwork openings, gaps between walls / floors and walls / ceilings, etc (Energy Saving Trust, 2005). Suspended timber ground floors can be a particular problem and in this case success was achieved by installing a membrane across the boarding, which was dressed up behind the skirting boards.

Table 1. E.ON 2016 house measured air permeability values

Stage	Air permeability at 50Pa ($m^3/m^2.h$)	Description of work
As built	15.57	Single glazed windows Uninsulated walls, floor and roof space No draught-proofing
1	14.31	Double glazing installed Insulation applied to walls and loft Draught-proofing applied to windows (excluding kitchen, bathroom and WC) and doors Installation of whole house MVHR system
2	9.84	Kitchen, bathroom, WC windows and under croft trap-door draught-proofed Draught-proofing throughout house re-installed Window trickle vents blocked up
3	8.60	Service risers sealed Pipework penetrations sealed (radiators, water pipes etc.) Sealing around boiler flue Covers fitted to door locks Kitchen fan removed and bricked up
4	5	Suspended timber ground floor insulated and sealed

4.2 Heat losses, energy consumption and CO_2 emissions

Full details of the dynamic thermal simulation and energy modelling have been reported elsewhere (Banfill et al, 2011) and are summarised here. Figure 2 details the disaggregated loads on the heating system at the time the peak space heating load occurs in the dynamic analyses. Note that, as the final retrofit measure is applied the peak load occurs at a different time of year. The results show the expected significant reduction in energy consumption as a result of the work, but since the focus of this paper is on airtightness, these will not be considered further. Note that measured thermal energy data is not yet available, since performance monitoring is still in progress. Comparing the performance of the building after stage 4 with the base case as built shows an overall 71% reduction in total annual building energy consumption from the base case. This takes into account the energy associated with the space heating, domestic hot water, auxiliary (fans and pumps), lighting and equipment.

To investigate the effect of MVHR alone (i.e. separate from the other measures listed in table 1), a modelling study starting from a naturally ventilated base case of 10 $m^3/m^2.h$ (based on the recommended ventilation rate as advised by BRE Digest 398, where Kronvall's rule of thumb has been used to determine an equivalent air permeability value), simulated its effect on energy and CO_2 emissions at successively reduced air change rates, culminating in the Passivhaus standard of 0.63 $m^3/m^2.h$ (0.6 ach^{-1}) and the results are given in table 2.

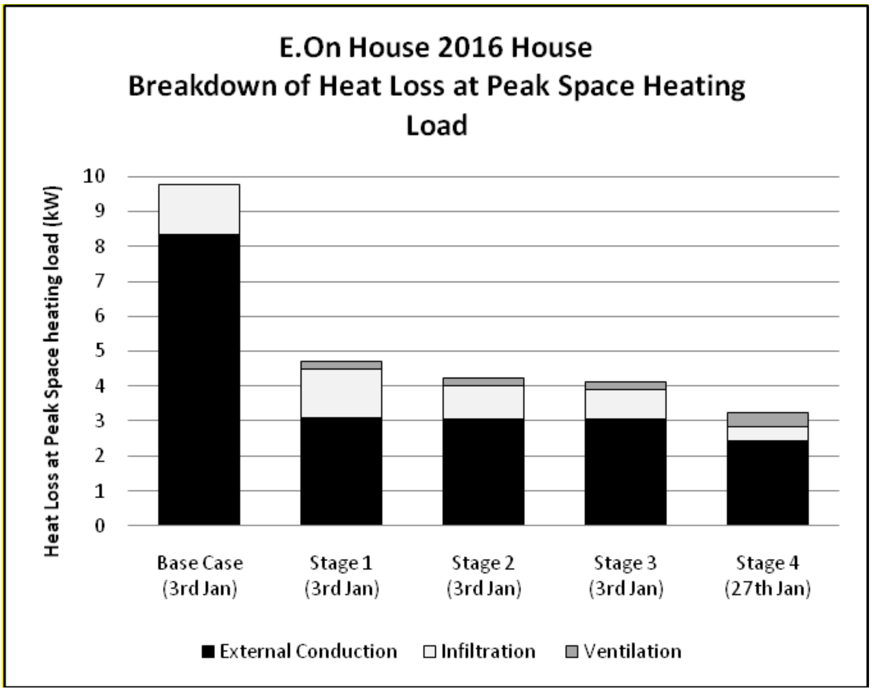

Figure 2 E.ON 2016 House: breakdown of heat loss at peak space heating load

It may be recalled that stage 4 of the retrofitting measures achieved a 50 Pa air permeability of 5 $m^3/m^2.h$. At this level the annual energy consumption is barely reduced and the CO_2 emissions are still above the unimproved house. Further improvements in air permeability would be necessary to effect a significant reduction in energy and CO_2 but even at 0.63 $m^3/m^2.h$, the Passivhaus level, annual energy consumption is only 11.7% lower and CO_2 emissions are only 5.3% lower.

The carbon intensity of the electricity used to operate the MVHR system is about three times that of the gas used for heating and this means that achieving an overall reduction in the building's CO_2 emissions requires the space heating demand to be reduced by three times the electricity consumption of the MVHR system.

4.3 Householder preferences and practices

Achieving an airtight house may be a desirable approach from the perspective of saving heat loss and hence CO_2 but any system, particularly one that will be retrofitted, must meet the householders' requirements or else it will not be appealing nor acceptable. The practices and preferences obtained from the householder interviews uncovered a range of issues that may result in an unappealing system, or one that works sub-optimally. These are discussed below. Whilst many of the homes had some double glazing and loft insulation, none had more advanced energy efficiency measures installed. None had attempted to actively reduce the air permeability of their home (although attempts to reduce draughts had been made through fitting double or secondary glazing, by using carpets and soft furnishings and by blocking up chimneys). None of the houses had an MVHR system.

Table 2. Impact of airtightness on modelled annual energy consumption and CO_2 emissions of the thermally upgraded E.ON 2016 house using an MVHR system specified to best practice standards.

Study	Annual space heating energy (kWh/m^2)	Annual auxiliary energy (kWh/m^2)	Total building annual energy consumption (kWh/m^2)	% change (energy)	Total building annual emissions ($kg.CO_2/m^2$)	% change (CO_2)
10 $m^3/m^2.h$ naturally ventilated	65.7	9.6	126.9	0	44.6	0
10 $m^3/m^2.h$ with MVHR	76.4	10.8	138.8	+9.4%	47.4	+6.2%
7 $m^3/m^2.h$ with MVHR	66.3	10.8	128.8	+1.5%	45.4	+1.7%
5 $m^3/m^2.h$ with MVHR	62.9	11.4	125.9	-0.8%	45.0	+0.9%
3 $m^3/m^2.h$ with MVHR	56.5	11.4	119.5	-5.9%	43.8	-2.0%
1.05 $m^3/m^2.h$ with MVHR	50.3	11.4	113.3	-10.7%	42.6	-4.7%
0.63 $m^3/m^2.h$ with MVHR	49.0	11.4	112.0	-11.7%	42.3	-5.3%

Air flow and freshness

Many householders were keen to maintain air flow within their homes, even if it meant obvious heat loss. Current approaches to controlling air flow included opening and closing doors, windows or vents, or closing curtains to block off draughts. One participant spoke of the more refreshing “natural feeling of a breeze” (Male, age 29) and airtightness was seen as a negative issue: “I like to be able to breathe fresh air. I don’t know if I’d really want an airtight house” (Female, age 61). Associations were made with the environment within an aeroplane, with words such as “recycled”, “stale” and “manky” being used to describe their expectations of a mechanical ventilation system. When an MVHR system was explained to householders in more detail, the idea was more positively received (particularly in relation to some of the other technologies presented) and so there is clearly potential for successful systems once the initial preconceptions are overcome.

Open fireplaces

Of the 20 houses surveyed as part of the project, 15 had some form of open chimney or vent for a wood burning stove. Of these houses, 9 of the householders said they would not be prepared to consider losing the functionality of all their fireplaces (even if they were able to keep the fireplace aesthetics). Some were prepared to lose the functionality of some of the fireplaces, but not all. The majority of households viewed the fireplace as an occasional ‘treat’ rather than the standard method of heating the home. Its use was described by one householder as “High days and holidays – not very often” (Female, age 51). However there were households in the sample that used their fireplaces every day during winter. Although householders may be aware that the fireplace inhibits the airtightness and increases draughts, they were still unwilling to remove its functionality and instead prefer to use temporary blocks for the chimney when it is not in use, as illustrated by this comment: “The only thing that would not be airtight...would be the fire place because there is no balloon in or cap or anything like that, so that can be quite draughty in winter, but we stick a black bag full of newspaper up there don’t we, when we’re not using it” (Male, age 29). Those householders that would be happy to lose the functionality of their chimney expressed a desire to keep the aesthetics of the traditional fireplace in order to maintain the period features of their home. Although some of the houses had fireplaces in upstairs rooms, none were used; when questioned, this was due to safety, and so could easily be made airtight.

Door opening practices

A retrofitted MVHR system is likely to require a good circulation of air within the home (as a more limited venting system will be easier and less disruptive to install) and so internal door opening practices were explored. Householders reported strong habitual practices, for example always closing certain doors at night time, or leaving doors ajar at certain times of the day. Reasons for habitually closing internal doors included to reduce internal noise (from other members of the household, or a striking clock), to stop dust circulating through the house, to keep pets and young children in particular areas of the house, for privacy or to keep light out, or to shut off part of the house, either when a child has grown up and moved away, or when only certain rooms are heated. This final practice was common in houses where householders did not heat their whole house every day (perhaps only doing so when guests were visiting) or to keep the heat from an open fire within a room for the “cosy family stuff” (Female, age 51). Internal doors were sometimes left open by householders as a regular practice, or were so poorly fitting that air would circulate past them easily even if closed: “When they do shut they have got gaps haven’t they” (Female, age 43).

Damp

Many of the householders had damp areas in their homes and used ventilation as a means to control humidity. This may be as a short term measure (e.g. after a shower) or longer term, with the regular use of a de-humidifier. Whilst many householders recognised they had a draughty house, there was a feeling that the draughts kept the house adequately ventilated and healthy. The need for a system to replace what occurred naturally was not recognised. Communicating the benefits of an airtight house with MVHR system is critical to win over these householders.

4.4 General discussion

Achieving airtightness is clearly important for reducing heat losses and CO_2 emissions and MVHR can contribute to savings but levels sufficiently low for MVHR to be effective are very difficult to achieve in older properties, as demonstrated by the number of stages needed for sealing the E.ON 2016 house. In addition, people have features in their older homes that mean airtightness is difficult to achieve, in particular open fireplaces that are used regularly in the winter. They may be willing to block these (using a balloon or similar) in the summer but this is not the time when it is needed.

Retrofitting an MVHR system will probably mean a reduced number of vents, because the likely whole house disruption that will be caused by a more integrated system is unwelcome to householders unless they are doing total renovations. However, our study of 20 households suggests that whole house renovation is uncommon other than at the time of purchase (and even then not all householders did this).

Attitudes towards an MVHR system are initially negative: people like fresh air in their home, which they feel is necessary to deal with issues like damp and condensation, as well as a perceived negative effect on health through germs being recirculated. When it was explained to them, householders were more positive about MVHR, appreciating that it could help their damp problems and that the same air was not recirculated, and so the benefits would need to be clearly communicated. However, people have habitual internal door opening / closing practices that mean that air flow within the house may be limited (closing doors for privacy, keeping pets or children contained, etc), which could limit the effectiveness of an MVHR system.

5 Conclusion and Further Research

Airtightness is a crucial factor in achieving energy and CO_2 emissions reductions in dwellings and it is easy to over-estimate the reductions achievable by retrofitting MVHR. Even with equipment specified to best practice standards the air permeability measured at 50 Pa must be reduced to less than 5 $m^3/m^2.h$ to reduce annual building energy and to still lower values to reduce annual CO2 emissions. This difference is due to the CO2 intensity of the electricity used to power the MVHR being higher than the CO2 intensity of the gas saved by reducing the heating energy use. We look forward to being able to compare these modelled predictions with measured data in a future paper, but in the meantime there is clearly potential for over-selling of the merits of MVHR in a retrofit situation. In a context where Green Deal-type incentives are offered for energy-reducing retrofit measures it would be unfortunate if householders used up their credits by installing MVHR early in a sequence of interventions. Other more cost-effective approaches to achieving energy efficiency in dwellings should receive preference, and this point should be considered by those responsible for setting up incentive schemes for householders.

Achieving such low air permeability in existing dwellings appears to be challenging even to experienced installers of draught proofing, because of the high level of care and attention to detail required. In the case of the E.ON 2016 house it was necessary to rigorously seal the entire ground floor, as well as the various penetrations of the building envelope, in order to reduce the permeability to 5m3/m2h. This is an important and worrying finding and suggests that it would be advantageous to set up a competence scheme for installers of draught proofing. The importance of air permeability to energy reduction suggests that airtightness testing should be made a mandatory part of all energy-led retrofit programmes.

Technically, the installation of MVHR in the E.ON 2016 house was carried out with levels of workmanship that fell short of those that would be necessary to achieve the energy savings anticipated. Thermographic imaging showed significant heat loss due to incomplete insulation around ducts and penetrations. Design of a retrofit MVHR installation is likely to be a compromise because of the difficulty of installing supply ductwork in the optimum locations. Air quality measurements in progress to confirm or refute this will be reported in a future paper. All this points to the risk of MVHR underperforming in retrofit applications.

The householder surveys showed that occupants value the very features in their homes that make achieving airtightness difficult, in particular the importance of fireplaces and their availability for use on special occasions or as a focal point for the family. Strong negative perceptions of MVHR were held because of its association with staleness and lack of fresh air whereas, in contrast, it is a source of controlled fresh air which offers the potential for reduction of damp conditions and removal of pollutants. This suggests that there might be situations where positive communication of the benefits of MVHR would change the attitudes of householders.

Finally, achieving the levels of air permeability at which MVHR is of benefit to energy and emissions involved a prolonged and ultimately disruptive process of works. If this were always to be the case, retrofit installation of MVHR would be confined to those occupants who were undertaking a total package of measures, for whom the added disruption would not present a problem. The household survey suggested that such people are in a minority: the majority of householders would not tolerate such disruption.

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