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Ventilation and Indoor Air Quality in Part F 2006 Homes

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Department for Communities and Local Government

The findings and recommendations in this report are those of the authors and do not necessarily represent the views of the Department for Communities and Local Government.

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Executive summary

Introduction

1. This study was commissioned by Communities and Local Government to inform and provide evidence for the amendments to the Part F regulations and guidance documents that are due to come into force in October 2010.

2. The study has assessed whether the guidance in the 2006 edition of Approved Document F (ADF) is effective at providing adequate ventilation and good indoor air quality in new dwellings, thereby minimising the risks to health of the occupants. It has also investigated how well dwellings comply with Part F 2006 standards. The focus has been on more airtight dwellings which are naturally ventilated.

3. This report presents the results from a sample of 22 occupied homes built to Parts L and F 2006 standards. The project involved carrying out measurements of airtightness, whole house air exchange rates, mechanical extract flow rates, relative humidity (RH) levels and other indoor pollutant concentrations. All homes were occupied with, where possible, the ventilation system set up at full capacity to test whether the ventilation guidance in ADF is adequate. Diary records of occupant activities and questionnaires on the dwellings and their indoor environments were also collected.

4. The results have been analysed to assess the significance of dwelling characteristics, ventilation factors and indoor sources in determining concentrations of indoor pollutants. They have also been analysed to determine whether the design recommendations in ADF 2006 are being met within the dwellings.

Approved Document F 2006

5. ADF 2006 provides guidance for new dwellings built to an air permeability down to 3 to 4 $m^3.h^{-1}.m^{-2}$ at 50 Pa. ADF accounts for the contribution made by air infiltration when determining the purpose-provided ventilation necessary to provide good indoor air quality. It suggests that additional ventilation may be required for more airtight homes where there is less air infiltration, but no additional guidance is provided.

6. Since ADF 2006 was published, new evidence has emerged to suggest that there has been a significant improvement in the airtightness of new dwellings. Approximately 5% of around 3000 new dwellings that have been pressure tested achieve results better than 3 $m^3.h^{-1}.m^{-2}$ and 30% achieve better than 5 $m^3.h^{-1}.m^{-2}$.

Aims

7. The primary aim of this study was to establish whether additional ventilation is required in more airtight dwellings with an air permeability equal to or better than 5 $m^3.h^{-1}.m^{-2}$. The study focused on ADF ventilation system 1: "Background ventilators with intermittent extract fans" because:

- This ventilation system type is the one most commonly used in new dwellings.
- Greater concern has been expressed by stakeholders on the use of natural ventilation in airtight properties, and in particular the reliance on natural driving forces (wind and temperature stack effects) to provide the background ventilation through trickle ventilation.
- Given the sample size and the difficulty of finding dwellings with an air permeability equal to or better than 5 $m^3.h^{-1}.m^{-2}$, the analysis would be more meaningful if it focused on just one ventilation system type.

8. There were a number of secondary aims:

- *Compliance with Part F:* We wished to investigate whether the installed ventilation systems complied with Part F guidance. There is both objective and anecdotal evidence to suggest that ventilation systems are designed to comply with ADF 2006 standards but do not achieve this on construction due to inadequate installation and inspection.
- *Air pressure testing for Part L:* For Part L compliance, air pressure testing is undertaken to BS EN 13829: Method A (all mechanical ventilation systems sealed, all natural ventilation openings closed). The proposed amendments to ADL1A would change the test method to BS EN 13829: Method B (all mechanical ventilation systems sealed, all natural ventilation openings closed and sealed). We wished to investigate the impact and need for this change.
- *Air pressure testing for Part F:* We wished to investigate if an air pressure test with all natural ventilation systems fully open would provide an estimate of the equivalent area of the installed background (trickle) ventilation.

Results

9. The key results from this study are:

- We have monitored 22 dwellings built to Parts F and L 2006 standards, with trickle ventilation and intermittent extract. Ten of the 22 dwellings tested (46% of total sample including pilot homes, 50% of main sample) achieved an air permeability of less than 5 $m^3.h^{-1}.m^{-2}$.

- Nearly three-quarters of the dwellings (72% of sample) did not have sufficient trickle ventilation installed to meet ADF 2006 guidance. In the worst case, only just over half (57%) of the recommended trickle ventilation was installed.
- 52% of the internal doors failed to achieve the 10 mm gap under the doors recommended in ADF 2006.
- Less than half of the kitchen or bathroom fans achieved the flow rates recommended in ADF 2006. Furthermore, none of the fans located away from the cooker achieved the recommended flow rates in the kitchen.
- All relative humidity levels monitored over a week-long period were within the new daily and weekly relative humidity guideline levels proposed in the consultation version of ADF 2010. However, making reasonable assumptions, it would be expected that approximately four homes would have monthly relative humidity levels that would exceed the newly proposed monthly relative humidity guideline level.
- Four homes had levels of nitrogen dioxide in the kitchen that exceeded that recommended in ADF 2006. A key issue in these cases was insufficient installed flow where fans are located away from the cooker.
- All homes had acceptable levels of formaldehyde.
- Over half of the homes with TVOC measurements had levels exceeding that recommended in ADF 2006. It is important to note that in developing ADF 2006, TVOCs were chosen to represent organic compounds. A review of indoor air quality results suggested that if the TVOC guideline level of 300 $\mu g.m^{-3}$ was met, then individual chemical health-based guideline levels (eg benzene, toluene, formaldehyde) should also be met.

Conclusions

10. The key conclusions are:

- It is difficult to make a conclusive judgement as to whether or not the current recommended natural ventilation provisions in ADF 2006 are sufficient for airtight homes. The study is relatively small and the conclusions should only be treated as indicative. Furthermore, in all cases, the capacity of the ventilation system did not meet that recommended in ADF 2006.
- The intermittent extract rates appear to be sufficient. It is important to ensure that they are installed correctly to provide the capacity recommended in ADF 2006. There is no evidence from this study that with correct installation, the extract rates should be increased for more airtight dwellings.
- The trickle ventilator sizes appear to be insufficient. Even allowing for installation issues for the ventilation system as a whole, at least a significant minority of TVOC levels would be expected to exceed the recommended guideline level,

particularly for the more airtight homes. VOCs are produced by building products and the activities of the occupants such as smoking, use of personal hygiene products and interior decorating. It may seem pedantic to change the design of a ventilation system just to better control one pollutant, but the long term effects on health due to exposure to VOCs are not well documented, and it seems prudent to err on the side of caution. Furthermore, the TVOC criterion was selected as a sensitive marker for individual organic chemical compounds (ie if TVOC levels are below the criterion, previous research suggest that individual organic chemical compounds would also be below recognised indoor or outdoor health-based levels for these pollutants). There are also other hazards to health that are affected by ventilation, such as house dust mites, which are associated with respiratory illnesses including asthma. We do not currently attempt to control these under Part F because their breeding success is influenced by heating and hygiene practice as much as ventilation. Improving ventilation would be step in the right direction to limit this risk.

- Better guidance needs to be provided for the natural ventilation of flats. While the flats had two façades, and were ventilated as 'multi-sided façades' according to ADF 2006, they were effectively single façades as the second façade was limited. The ventilation and indoor air quality results suggest that these homes were under-ventilated.
- It is important to note that in practice, occupants do not use their ventilation system to full capacity (trickle vents are not always open and fans are not always used). Hence, the actual pollutant levels in dwellings will likely be higher than those recorded in this study.

Recommendations

11. The key recommendations are:

- It is important that the ventilation system should be installed correctly and inspected to provide the ventilation capacity as designed.
- Further evidence needs to be obtained to substantiate the indicators from this study. However, there are sufficient grounds to support the proposal to increase trickle ventilators in dwellings having an air permeability equal to or tighter than 4 $m^3.h^{-1}.m^{-2}$. This is based on the levels of TVOCs observed, and the implications for individual organic compounds. This could also have benefits in controlling other hazards to health, but this is difficult to quantify.
- This was a relatively small study. A larger study is necessary, building on the findings of this study, to better determine indoor air quality levels achieved in airtight dwellings in which the ventilation system is installed correctly.
- Given the relatively high level of TVOCs, greater consideration should be given to reducing source strength by product controls.

Chapter 1

Introduction

This study was commissioned by Communities and Local Government (CLG) to assess whether the guidance in the 2006 revision of Approved Document F (ADF) is effective at providing adequate ventilation and good indoor air quality in new dwellings, thereby minimising the risks to health of the occupants. A key secondary aim was to investigate how well dwellings complied with Part F 2006. The study particularly focused on more airtight dwellings which are naturally ventilated. It is intended that the results from this study will help inform the 2010 amendments to Parts F and L of the Building Regulations.

This report presents the results from a sample of 22 occupied homes built to Parts L and F 2006. The project involved carrying out measurements of airtightness, whole house air exchange rates, mechanical extract flow rates, relative humidity (RH) levels and other indoor pollutant concentrations. All homes were occupied with, where possible, the ventilation system set up at full capacity to test whether the ventilation guidance in ADF is adequate. Diary records of occupant activities and questionnaires on the dwellings and their indoor environments were also collected.

Analysis of the results was used to assess the significance of dwelling characteristics, ventilation factors and indoor sources in determining concentrations of indoor pollutants. The results were also analysed to determine whether the design recommendations in ADF 2006 were being met within the dwellings.

Chapter 2

Background

2.1 Introduction

This study was undertaken to provide evidence for the proposed amendments to Part F 2010. In particular, it reviews the necessity of increasing ventilation provisions for more airtight dwellings. It also addresses other issues such as compliance with Part F.

2.2 Primary aim

ADF 2006 provides guidance for new dwellings built down to an air permeability of 3–4 $m^3.h^{-1}.m^{-2}$ at 50 Pa. It accounts for the contribution of air infiltration in determining the purpose-provided ventilation necessary. It suggests that additional ventilation provisions may be required for more airtight homes, due to less air infiltration. As it was expected that in the near future relatively few dwellings would approach or be tighter than this level of air permeability, no additional guidance was provided for these dwellings at that time. Approved Documents are intended to provide guidance for some of the more common building situations.

Since ADF 2006 was developed, new evidence suggests that there has been a significant improvement in the airtightness of new dwellings. Approximately 5% of new dwellings pressure tested achieve results better than 3 $m^3.h^{-1}.m^{-2}$ and 30% achieve better than 5 $m^3.h^{-1}.m^{-2}$. This is based on a total sample of approximately 3000 new dwellings and arises from two sources which agree with one another: a confidential industry analysis and Building Sciences Ltd (BSL) air pressure testing results.

Hence additional guidance is proposed in the consultation version of ADF 2010 for the more airtight homes. In the main, the ventilation system specifications are not amended for dwellings designed to an air permeability leakier than 5 $m^3.h^{-1}.m^{-2}$. However, increased ventilation provisions are recommended for dwellings designed to be tighter than this.

The primary aim of this study is to provide evidence to determine whether additional ventilation provisions are required for those more airtight dwellings, with air permeability equal to or better than 5 $m^3.h^{-1}.m^{-2}$. Furthermore, it particularly focuses on ADF ventilation system 1: background ventilators with intermittent extract fans. There are three key reasons for this focus:

- This ventilation system type is the one most commonly used in new dwellings.
- Greater concern has been expressed by stakeholders on the use of natural ventilation in airtight properties. In particular, the reliance on natural driving forces (wind and temperature stack effects) to provide the background ventilation through trickle ventilation.
- Given the sample size, and practical difficulties in achieving only dwellings with an air permeability equal to or better than 5 $m^3.h^{-1}.m^{-2}$ as described later, better analysis could be undertaken by focusing on just one ventilation system type – with the expectation that inferences could be made to other system types.

2.3 Secondary aims

There were a number of secondary aims to this study.

Review compliance with Part F: We wished to investigate whether the installed ventilation systems complied with Part F. There was a mix of objective and anecdotal evidence to suggest that the ventilation systems were designed to ADF 2006 but did not achieve this on construction due to inadequate installation and inspection.

Air pressure testing for Part L: For Part L compliance, air pressure testing is undertaken as per BS EN 13829: Method A (all mechanical ventilation systems sealed, all natural ventilation openings closed). The consultation version of ADL1A proposes changing the test method to BS EN 13829: Method B (all mechanical ventilation systems sealed, all natural ventilation openings closed and sealed). We wished to investigate the impact and need for this change.

Air pressure testing for Part F: We wished to investigate the use of a further air pressure test for Part F. This would be undertaken similarly to the testing above but with all natural ventilation systems fully open. The proposal was that by comparing these results with those of Method B (with natural ventilation systems fully sealed), it could provide an estimate of the equivalent area of background (trickle) ventilation installed in dwellings to confirm installed capacity met design intentions.

Chapter 3

Study design

3.1 Dwelling selection and recruitment

The initial selection criteria for dwellings were as follows.

- Constructed to Parts F and L 2006
- Mixture of types (flat, detached house, terraced house, bungalow, etc)
- Air permeability equal to or better than 5 $m^3.h^{-1}.m^{-2}$
- Occupied at least six months prior to sampling to reduce the initial impact of high indoor pollutant emissions from, for example, the building drying-out, new construction materials and furnishings, and painting and decorating. No specific occupancy levels were selected – although we looked to obtain the sample from both private and social housing to provide a mix.
- Within a reasonable distance (150 miles) of Oxford where Building Sciences Limited, who were carrying out the testing, are located.

These initial criteria proved challenging for three principal reasons.

- While house-builders were interested in this study, there were limits to the help they could give in finding these homes given the current economic climate.
- Relatively few dwellings had been constructed to 2006 Building Regulations and lived in for six months. Many dwellings constructed since 2006 had planning permission to pre-2006 Building Regulations.
- Where dwellings were identified that met the above criteria, if the initial contact was with the householder, in a majority of the cases they did not have details of the airtightness of their dwelling to determine if it was equal to or better than 5 $m^3.h^{-1}.m^{-2}$.

As a result, we modified the criteria to monitor any dwelling constructed to Part F/L 2006 (air permeability should be better than 10 $m^3.h^{-1}.m^{-2}$). This in itself is a valuable study as we are assessing the performance of newly introduced regulations.

To meet the primary aim of the study, we would aim to gain data on the performance in the most airtight homes through:

- biasing the sample where possible to those more airtight dwellings with an air permeability better than or equal to 5 $m^3.h^{-1}.m^{-2}$
- analysing both the sub-set of more airtight dwellings as well as investigating the trend in performance from leakier to more airtight dwellings.

We decided to focus only on ADF ventilation system 1 (trickle ventilation with intermittent extract). This should allow us to better determine the trend line in performance as airtightness varies (*ie* removes variation due to different ventilation system types). Additional reasons for focusing on this ventilation system were discussed in Section 2.

The sample was obtained through a combination of the following routes:

- an invitation to AECOM staff via the intranet
- Building Sciences air pressure testing database
- industry contacts
- mailing households on new developments
- leaflet drop on new developments.

A disturbance payment of £100 was paid to the householder to take part in the study. Information about the nature of the testing was provided in advance.

3.2 Sample size

An initial pilot study of two dwellings was undertaken. The aim of the pilot study was to assess the protocol developed for this project in terms of practicality, reliability and variability, to confirm the techniques for measurements and to check the suitability of the household questionnaires and diaries that had been developed for the study.

The sample size for the main study was 20 dwellings with the intention of at least half having an air permeability of better than 5 $m^3.h^{-1}.m^{-2}$. While the total sample number was relatively small, it was considered that it should give a good indication if issues of poor indoor air quality or poor compliance with Part F were common.

3.3 Monitoring period

The intention was to undertake the main sampling in March and April 2009.

- Natural ventilation is dependent on wind and stack driving forces. During this period, the difference between internal and external temperatures would be reduced and thus the stack driving forces lower.
- Internal RH levels would likely be higher as the external moisture levels are high and there is less warming of the outside air (and reduction in RH) as the air enters the home. (It is noted that the actual risk of condensation should also take account of the internal surface temperatures, which would be lowest during the coldest winter periods. However, this methodology provides the reasonably worst case internal RH levels.)
- It would still be during the heating season and so the dwelling would be fairly 'closed-up', i.e. relatively little use of windows, etc.

In practice, this aim was broadly met with the main study taking place between March and mid-May. The initial pilot study took place in January/February 2009.

Each dwelling was monitored for one week. It was thought sufficient to provide the information required for that dwelling. Furthermore, as highlighted below, the study made requirements of the occupants and based on experience it was considered that the necessary occupant behaviour may not have been reliably met over longer periods.

3.4 Ventilation conditions

To assess whether ADF 2006 recommendations were adequate, it was necessary for the ventilation system to be used to its full capacity. Hence the following steps were undertaken:

- all trickle ventilators (or other ventilation inlets) were fully opened and the occupants asked to keep them open
- occupants were asked to use bathroom/WC mechanical extracts at full capacity during all bathing occasions
- occupants were asked to use their kitchen extract on its highest setting during cooking times
- occupants were asked not to open windows.

A daily diary was given to the occupants to complete during the monitoring period to confirm that the above instructions were followed and, if not, why they needed to make changes.

3.5 Monitoring

3.5.1 Introduction

The strategy of the study was based on previous research experience of measuring airtightness, ventilation and indoor air quality in homes and used as far as possible well proven, validated techniques and methods of investigation in order to provide reliable, quality assured data. A summary of the parameters measured in this study is provided in Table 1. The parameters selected are further discussed below and the next section provides more detail of the individual measurement techniques.

3.5.2 Airtightness

The following airtightness tests were carried out on the first visit to each dwelling:

- BS EN 13829: Method A (all mechanical ventilation systems sealed, all natural ventilation openings closed)
- BS EN 13829: Method B (all mechanical ventilation systems sealed, all natural ventilation openings closed and sealed)
- BS EN 832 with all mechanical ventilation systems sealed, all natural ventilation openings opened.

Comparison of the first two tests will allow an evaluation of the advantage of including Method B instead of Method A[1] as the means for compliance testing for dwellings.

Comparison of the latter two tests provides a means of estimating the equivalent area of trickle ventilation in the dwelling to compare against what appears to have been installed.

3.5.3 Ventilation

The perfluorocarbon (PFT) technique was used to provide an estimate of the ventilation rate in the dwelling over the one week sampling period.

3.5.4 Extract flow rates

A rotating vane anemometer with an aircone hood attachment was used to determine the air flow rate of each extract fan and cooker hood in the dwellings at its highest setting.

[1] Technical Standard 1 (TS1), published by the Air Tightness Testing and Measurement Association (ATTMA), currently refers to BS EN 13829 Method B as the compliance testing method. However, Method B is specifically amended in TS1 to remove the requirement to temporarily seal trickle ventilators. Hence, for the purpose of this report, the method referenced for Building Regulations compliance is Method A.

3.5.5 Indoor air quality

The following indoor pollutants were monitored:

- Relative humidity (RH)
- Nitrogen dioxide (NO_2)
- Total volatile organic compounds (TVOCs) and some individual VOCs
- Formaldehyde (HCHO).

All of these pollutants, with the exception of formaldehyde, are covered by performance criteria in ADF Appendix A. Formaldehyde was also measured as there have been suggestions to introduce formaldehyde into the Appendix A performance standards.

3.5.6 Questionnaires/diaries

Each occupant who participated in the study answered a questionnaire concerning his/her home, their normal ventilation behaviour and the activities in the home during the sampling period. In addition, the occupant completed a diary regarding gas cooking activity, use of extract fans and window opening.

During the initial visit to the property, the research team recorded:

- the sizes of trickle ventilators in each room
- whether trickle ventilators were open or closed
- the size of the internal door undercuts (between the bottom of the door and the top of the floor finish)
- the setting found on the cooker hood or extract fan in the kitchen
- the position of the isolator switches (ie on or off) for bathroom, en-suite and WCs
- over-run times for all fans.

This was undertaken to provide information about how the occupants would normally operate their ventilation system, without being biased from later stages of the study, after we had informed them of the appropriate utilisation of the ventilation system and reasons for doing so.

Table 1 Summary of the IAQ and ventilation monitoring during the pilot and main study

	Pilot study	**Main study**
Sampling period	29 Jan to 5 Feb 2009	2 March to 15 May 2009
No. of homes	2	20
IAQ parameters and locations monitored	NO_2 (kitchen and outside) TVOCs (living room, master bedroom and outside) Temperature and humidity (living room, master bedroom, and outside) HCHO (living room, master bedroom and outside)	NO_2 (kitchen and outside) TVOCs (living room, master bedroom and outside) Temperature and humidity (living room, master bedroom, kitchen, bathroom and outside) HCHO (living room, master bedroom and outside)
Ventilation rate measurements	Air permeability measurements (three types) PFT technique for whole house ventilation Internal door undercuts Mechanical extract fan flow rates (bathroom, en-suites, WC and kitchen)	Air permeability measurements (three types) PFT technique for whole house ventilation Trickle ventilator area noted (not measured) in each room Internal door undercuts Mechanical extract fan flow rates (bathroom, en-suites, WC and kitchen)

Chapter 4

Methodology

4.1 Air permeability

The dwellings were air permeability tested using the following three methodologies:

- As per BS EN 13829: Method A. All mechanical ventilation systems sealed, all natural ventilation openings closed.
- As per BS EN 13829: Method B. As above but with natural ventilation openings closed and sealed.
- As per BS EN 832: As Method A but with all natural ventilation inlets fully open.

Each of the above test methods was performed using pressurisation and depressurisation procedures, ie six tests per dwelling, using UKAS calibrated domestic standard 'blower door' fan and micromanometers and associated equipment. The final air permeability results for each method are determined as the average of the pressurisation and depressurisation results with an overall uncertainty of less than ±10%.

4.2 Ventilation capacity

4.2.1 Natural

Approved Document F (ADF) recommends that the equivalent area is marked on the trickle ventilator in any easily visible location where practical. Where available, the equivalent areas were recorded. In the few cases where this information was not visible, a geometric area measurement of the trickle ventilator was made. The total equivalent area for each dwelling and associated dwelling floor areas were referenced to the recommended equivalent areas published in Table 1.2a of ADF.

Door undercuts to internal doors were measured to confirm adequacy of cross ventilation provision, ie 10 mm clear gap.

4.2.2 Mechanical

The volumetric flow through all intermittent extract fans and cooker hoods was measured within each dwelling using a UKAS calibrated Airflow AV-2 rotating vane anemometer with an aircone hood attachment to encompass the fan, or ceiling/wall terminal. The readings were all taken with the fans and hoods at their highest flow setting over a 30 second averaging time. The overall uncertainty with this measurement technique for the flow rates measured is less than ±5%.

4.3 Air exchange rates

The PFT technique is a passive sampling technique for measuring ventilation rates in buildings, which is described in ISO-standard 16000-8. In this technique, a perfluorocarbon compound is passively emitted from small tracer sources, with a known constant emission rate, and passively collected on adsorption tubes. The amount of tracer adsorbed depends mainly on the emission rate from the source tubes and the dilution of it by ventilation air. The PFT technique is based on the fact that the average air infiltration rate is approximately equal to the reciprocal of the time averaged indoor tracer gas concentration and, using this technique, the time averaged indoor tracer gas concentration is determined.

PFT sources were set out in all rooms in each house, including hallways and stairwells, but not in small or wet rooms (e.g. store cupboards and bathrooms). The total number of sources in each room (source strength) was arranged to give an approximately uniform source rate per unit volume throughout the house. The samplers were placed in the living rooms, kitchen and all bedrooms.

The PFT sources and samplers were obtained from PentIAQ, Sweden. Following the sampling, they were then returned to PentIAQ for analysis. The results for the effective air exchange rate for the houses are derived from the emission rate per volume (room) and the local mean age of air.

The overall uncertainty of this technique is a combination of the source emission rate, the sampling rate, site limitations and number of sources/samplers, and the laboratory analysis, which combined, provides an accuracy of ± 10%.

4.4 TVOCs

Passive automatic thermal desorption (ATD) tubes, pre-conditioned with Tenax® TA at the analytical laboratory (Scientifics), were installed in each house for a period of seven days. Three ATD tubes were installed at each house: the master bedroom, living room and garden. After the sampling period, the tubes were analysed at the laboratory by automatic thermal desorption–gas chromatography (ATD–GC). Chemical compounds were then identified via a mass spectrometric (MS) detection library. The concentration of total volatile organic compounds (TVOCs) was determined by the total ion current response of the individual compounds, quantified using the calibrated response factor of toluene.

4.5 HCHO

Passive formaldehyde (HCHO) badges were installed for three days consecutive sampling using SKC UNME 00 samplers using 2,4dinitrophenyl-hydrazone (DNPH) as the adsorbent packing material. The HCHO badges were supplied and analysed by the analytical laboratory (Scientifics), and were installed in the master bedroom, living room and garden of each house. Desorption and analysis of the diffuse samplers was performed using a diffuse high Performance liquid chromatography (HPLC) using UV absorption between 230 and 370 nm. Limit of detection (LOD) was 1.0 µg.m^{-3} with an accuracy of ±15%. The concentration of HCHO in the air was determined by subtraction of HCHO adsorbed onto the blank (correction) tape from that adsorbed onto the exposed sample tape.

4.6 Nitrogen dioxide

The average mean concentration of NO_2 was measured using passive diffusion (Palmes) tubes over the 7-day sampling period. The Palmes tubes were supplied and analysed by the analytical laboratory (Scientifics) and were installed in the kitchen and garden of each property, at least 1 metre from vertical surfaces. This method relies on the transfer of NO_2 by diffusion to a collector at one end of the tube, which contains a mesh treated with 50% triethanolamine (TEA) and 50% acetone that adsorbs NO_2. At the end of the sampling period, the mean NO_2 concentration was quantified using a segmented flow autoanalyser with ultraviolet detection. The reported accuracy is ±10%.

4.7 Temperature and relative humidity

Hygrothermal conditions were recorded using combined temperature and relative humidity USB data loggers located in the master bedroom, living room, kitchen, main bathroom and garden of each property. The loggers were set to record at 5-minute intervals during the 7-day monitoring period and were generally placed between 1000–1500 mm above floor level to minimise variations induced by thermal stratification. At the end of the monitoring, the data were downloaded for later analysis. The typical accuracy of the loggers used was ±0.3% and ±2% for temperature and relative humidity, respectively.

Chapter 5

Pilot study

5.1 Results and lessons learnt

The aim of the pilot study was to assess the protocol, measurement techniques and questionnaires and diaries. Overall, everything worked as intended and as a result we have included the pilot study results with the main study results (see Section 7). RH was not measured in the kitchen and the bathroom in the pilot homes but was in the main study. In addition, the pilot study only recorded the number of trickle vents whereas in the main study we also recorded the equivalent area.

The main lesson learnt was the difficulty in obtaining the sample group (discussed previously in Sections 2 and 3). This resulted in modifications to the study design, in particular the criteria for recruitment.

Chapter 6

Results

6.1 Summary of dwellings monitored

The sample of 22 homes (including the pilot study), comprised the following dwelling types all built to Parts F and L 2006.

- five flats
- six terraced houses (three mid and three end)
- five semi-detached houses
- six detached houses.

6.2 Measurements of air permeability

6.2.1 Introduction

This section provides a summary of the results of the air permeability tests undertaken at all 22 homes. The individual test results for each dwelling are presented in Table A.1 of the Appendix.

6.2.2 Air pressure testing with trickle vents closed (Method A)

As referred to in Section 4.1, air pressure test Method A is the current test method used for Part L compliance purposes. All mechanical ventilation systems are sealed and all natural ventilation openings are closed but not sealed.

Figure 1 shows the distribution of the air permeability for each dwelling. Ten of the 22 dwellings tested (46% of total sample including pilot homes; 50% of main sample) achieved an air permeability of less than 5 $m^3.h^{-1}.m^{-2}$. Two homes exceeded the maximum level of 10 $m^3.h^{-1}.m^{-2}$ required by ADL 2006 for dwellings sampled. This is discussed further in Section 7.

Figure 2 shows how the air permeability varies by dwelling type (P1–P2 are the pilot homes and H1–H20 are the main study homes). Overall, the flats were the most airtight dwelling type in this sample – all achieving an air permeability of less than 5 $m^3.h^{-1}.m^{-2}$, with a mean of 3.7 $m^3.h^{-1}.m^{-2}$. The mean air permeability of the remainder of the dwellings (houses) was 6.9 $m^3.h^{-1}.m^{-2}$. Each dwelling type had at least one dwelling with an air permeability of better than 5 $m^3.h^{-1}.m^{-2}$. Note that while we looked to bias this sample towards more airtight dwellings, the overall mean value of 6.2 m^3.h^{-1}.m^{-2} is similar to the mean value of approximately 6.5 m^3.h^{-1}.m^{-2} obtained from a sample of approximately 3000 new dwellings combined from two sources: a confidential industry analysis and Building Sciences Ltd (BSL) unpublished air pressure testing results (from their air pressure testing services).

Figure 1 Air permeability distribution (Method A)

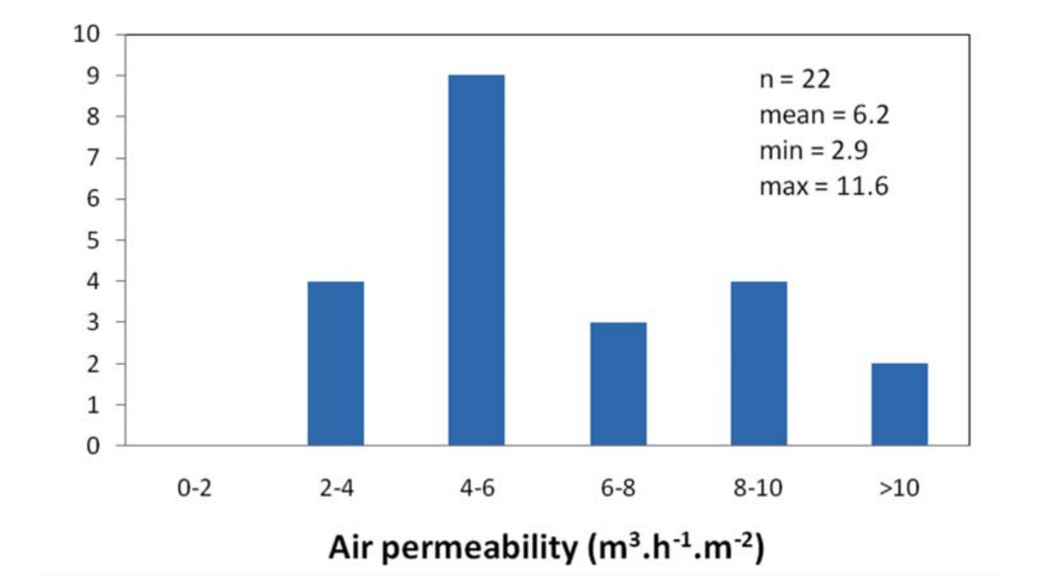
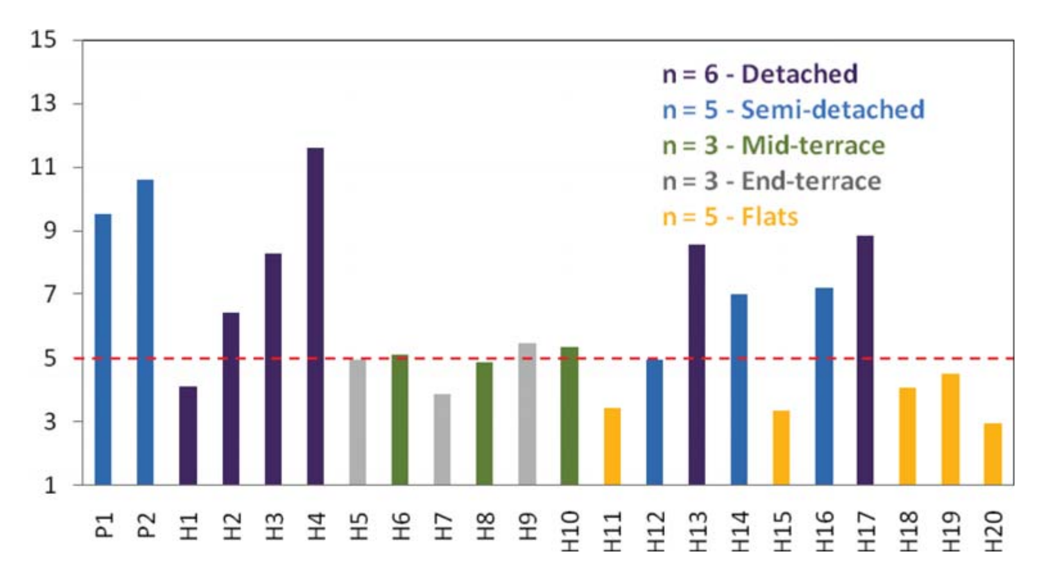


Figure 2 Air permeability distribution by dwelling type



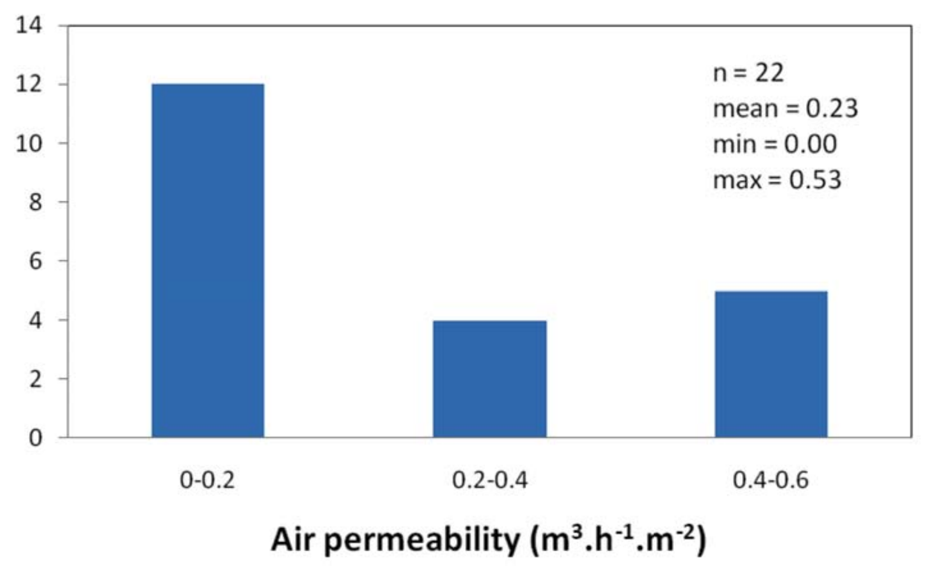
6.2.3 Air pressure testing with trickle vents sealed (Method B)

As referred to in Section 4.1, air pressure test Method B was similar to Method A with the addition of all natural ventilation openings (in this case trickle ventilation) being sealed instead of simply closed. This test method is proposed in the consultation version of Part L 2010 to replace Method A.

The results show a small reduction in air permeability with trickle ventilation sealed. Figure 3 shows this reduction in air permeability. The mean reduction was 3.3% or 0.2 $m^3.h^{-1}.m^{-2}$ @ 50 Pa.

The relative merits of Methods A and B are discussed in Section 7.

Figure 3 Reduction in air permeability with vents sealed

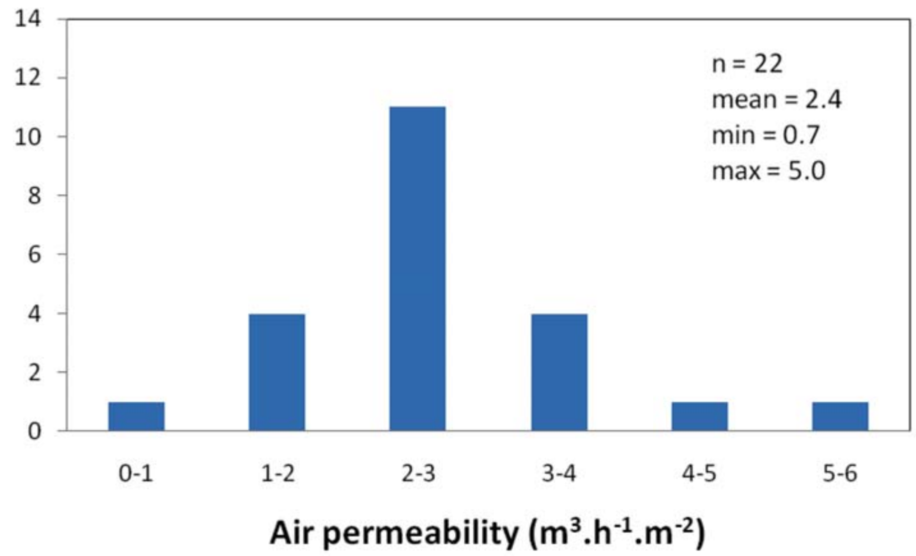


6.2.4 Air pressure testing with trickle vents open

As referred to in Section 4.1, these tests were similar to Methods A and B. The exception is that all natural ventilation openings (in this case trickle ventilation) are fully open.

The results show a smaller than expected difference compared to the results with trickle vents sealed (Method B). The results are shown in Figure 4. They show an increase of only 2.6 $m^3.h^{-1}.m^{-2}$ @ 50 Pa on average on fully opening the trickle ventilators. In the development of ADF 2006, and using the 1/20th rule-of-thumb conversion between air permeability and infiltration, we would have expected a value perhaps twice this value. Causes for these low readings are discussed further in this and the next section.

Figure 4 Increase in air permeability with trickle ventilators open



6.3 Natural ventilation opening areas

6.3.1 Introduction

This section provides a summary of the results of the ventilation provisions installed. For results of individual dwellings see Table A.2 in the Appendix.

6.3.2 Recorded trickle ventilation equivalent areas

Figure 5 shows the provision of trickle ventilation in the dwellings compared to that recommended in ADF (2006) Table 1.2a. Of the sample of 22 dwellings, data were not recorded in the pilot study and only 18 of the 20 homes in the main study had the equivalent area visible on the trickle ventilator and are reported here.

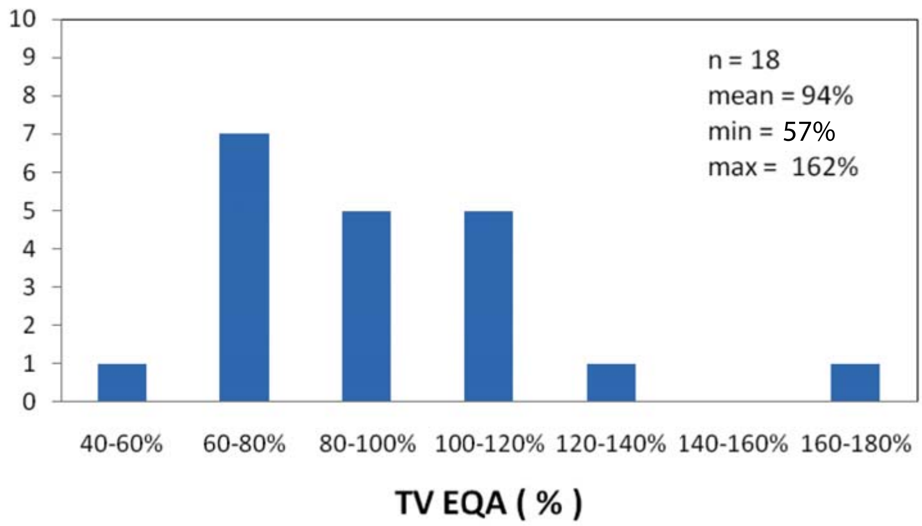
Nearly three-quarters of the dwellings (72% of sample) did not have sufficient trickle ventilation installed to meet ADF (2006). At worst, just over half (57%) of the recommended trickle ventilation was installed. In contrast, the maximum provision of trickle ventilation was 162% of that required in a home with a high window to façade ratio.

Further review of the data suggests that the provision of trickle ventilation in many homes was based on one trickle ventilator per window installed rather than reviewing the overall requirement of the dwelling. This may be insufficient, depending on the size of trickle ventilator installed.

This under-provision of trickle ventilation will partially explain the lower than expected readings for air pressure test Method C (see Section 6.2). However, this is not expected to be the full explanation. The results from the air pressure tests suggest that we are only installing 50% of the required trickle ventilator area on average. The area of trickle ventilation recorded provides a possible explanation for 6% (ie one-tenth) of this.

It is also worth noting that only 40% of the trickle ventilators were open when the monitoring team arrived at the property (see Table A.3 in the appendix). For the purpose of this study, the trickle ventilators were all left in the open position.

Figure 5 Installed trickle ventilation versus ADF Table 1.2a requirement



6.3.3 Measured trickle ventilation equivalent areas

An alternative method was used to determine the equivalent area, using Methods B and C pressure testing results. This was to assess whether it was possible to measure simply on-site whether the equivalent area written on the trickle ventilator area was accurate. Two sources of errors in the laboratory testing were considered possible. This may provide a further explanation of the lower than expected readings for air pressure test Method C (see Section 6.2).

- The trickle ventilator should be installed in the laboratory tests in similar surroundings to the actual installation and this may not be the case.
- The general accuracy of the testing procedure.

Three steps were undertaken in analysis:

Step 1: The total equivalent area at 1 Pa was determined for each dwelling using Method B (trickle vents sealed) and Method C (trickle vents open), using the following equation:

$$A=1000.Q_{50}.(P_1/P_{50})^n.(1/C_d).(r/2P_1)^{0.5}$$

where:

A = the background ventilator equivalent area (mm^2)

Q_{50} = the air supply rate at 50 Pa (l/s)

C_d = the discharge coefficient, taken as 0.61

r = air density (kg/m^2), taken as 1.2

P_1, P_{50} = the pressure across the vent at 1 and 50 Pa

n = flow rate exponent for the air pressure test.

Step 2: For each of the two methods, the equivalent area was calculated using 'n' from pressurisation and 'n' from depressurisation fan tests and an average taken.

Step 3: The equivalent area from Method B was subtracted from Method C. This should give the equivalent area for the trickle ventilators only at 1 Pa. The equivalent area reported on a trickle ventilator is also the equivalent area at 1 Pa.

The results were generally smaller than the total equivalent areas recorded on the trickle ventilators. However, it is considered that the results from this analysis are not sufficiently reliable. The air pressure testing results were at 35 Pa and above. Within the equation, the flow rate exponent ('n') is used to extrapolate down to 1 Pa. The evaluation of 'n' is not sufficiently accurate to do so in a robust manner. It would be necessary to undertake fan flow rate tests at lower pressures to improve this accuracy.

6.3.4 Door undercuts

Natural ventilation relies on air flow between rooms – cross ventilation across the dwelling and/or stack ventilation up through the dwelling. When internal doors are closed, there needs to be sufficient gap around the doors to maintain adequate air flow. To achieve this, ADF (2006) recommends that doors have a minimum undercut of 10 mm above the floor finish.

Figure 6 summarises the door undercut in the sampled dwellings. Of the 127 doors measured, 52% of all doors failed to achieve this 10 mm gap. Hence, these rooms may well be under-ventilated when their door is closed as well as the ventilation for the whole house being lower as the contribution of the trickle ventilation in that room to the whole house ventilation will be reduced (e.g. less contribution to cross ventilation within the house). While some doors had larger gaps this will not make up for smaller gaps – the increase in air flow as the gap becomes larger follows a law of diminishing returns.

Table 2 shows that there is some variation in door undercut depending on the room. Within this relatively small sample, it appears that the bedrooms have the largest undercuts. It is unclear why this may be the case and how representative this is of the building stock.

Only one dwelling had at least a 10 mm gap for all rooms measured. All others had at least one room with a gap of less than 10 mm.

Figure 6 Size of door undercuts

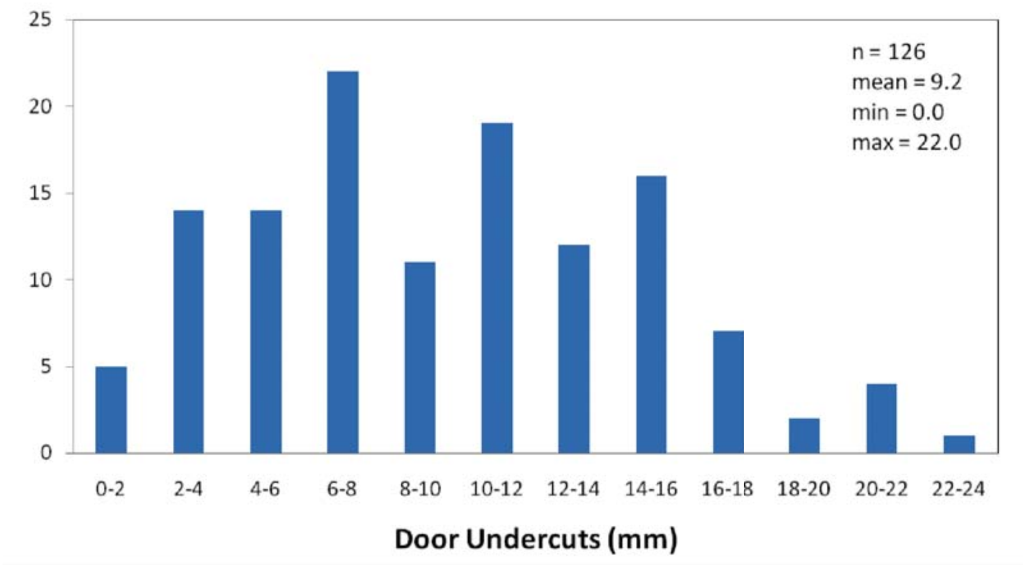


Table 2 Distribution of door undercuts for different rooms

	Lounge	Kitchen	Master bedroom	Other bedrooms	Bathroom	En-suite	WC
Number	19	17	20	33	18	6	13
Mean (mm)	6.2	7.7	12.2	11.3	7.4	8.0	8.6
Min (mm)	1	1	4	2	0	5	2
Max (mm)	10	21	20	22	20	13	15
St Dev (mm)	3.4	5.6	4.6	4.6	5.5	2.8	4.5

6.4 Whole house air exchange rates

6.4.1 Introduction

This section provides a summary of the results of the air exchange rates. For results of individual dwellings see Table A.4 in the Appendix.

6.4.2 PFT measurements

Figure 7 shows the distribution of air exchange rates measured in the dwellings using the PFT technique. Figure 8 shows the air exchange rates for both flats and other dwellings. The mean air exchange rate for the flats was 0.28 ach whereas it was 0.51 ach for houses.

Figure 9 compares the ventilation rate monitored for each dwelling against the background ventilation rates recommended in ADF Table 1.1b. This analysis takes into account that the recommended background ventilation rate depends on the size of the dwelling and its intended occupancy. None of the flats achieved the ADF recommended background ventilation rates while 60% of the other dwellings did.

A number of factors have been identified to help explain these low results:

i. The trickle ventilator areas are sized in ADF 2006 for the winter period. ADF highlights that due to lower temperature differences between inside and outside during the spring and autumn periods, thereby lowering the natural ventilation driving forces through the trickle ventilators, window opening may be required.

ii. Overall, as shown in Section 6.3, there is under-installation of trickle ventilator area in these dwellings. On average, only 94% of the required area is installed, based on the equivalent area marked on the trickle ventilators. Further checking is also required as to how well this marked equivalent area (based on laboratory tests) represents the actual equivalent area in practice.

iii. Half of the door undercuts are below the recommended size. This will have particular significance if the occupant closes their internal doors.

iv. Many of the flats were classed as multi-sided ventilation but, in fact, most of the ventilation was on one side of the dwelling and limited ventilation along a second side. Hence, effectively they were single-sided properties and ADF 2006 recommends additional ventilation for such properties.

v. The PFT approximates the air exchange rate. If the ventilation rate varies much during the measurement period, the approach will tend to under-read the true air exchange rate. This variation depends on the natural ventilation driving forces and occupant ventilation behavior. Based on some computational modeling work undertaken for this study, it is estimated that the air exchange rates may have under-read by between 5–15%, with the former for two-storey dwellings and the latter for flats. The results suggest that there should be greater variation in ventilation rates for flats as they are reliant on just wind for ventilation whereas for two-storey dwellings they are reliant on both wind and stack forces which smoothes out variations in the ventilation rate.

This is further discussed in the next section when the results are all considered together.

Figure 7 Air exchange rate estimated using the PFT technique

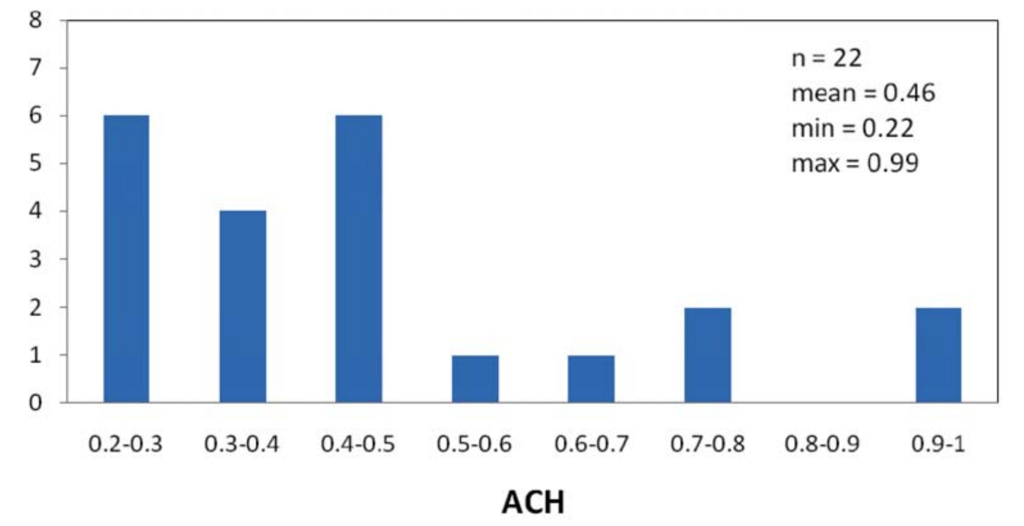


Figure 8 Air exchange rate for individual dwellings

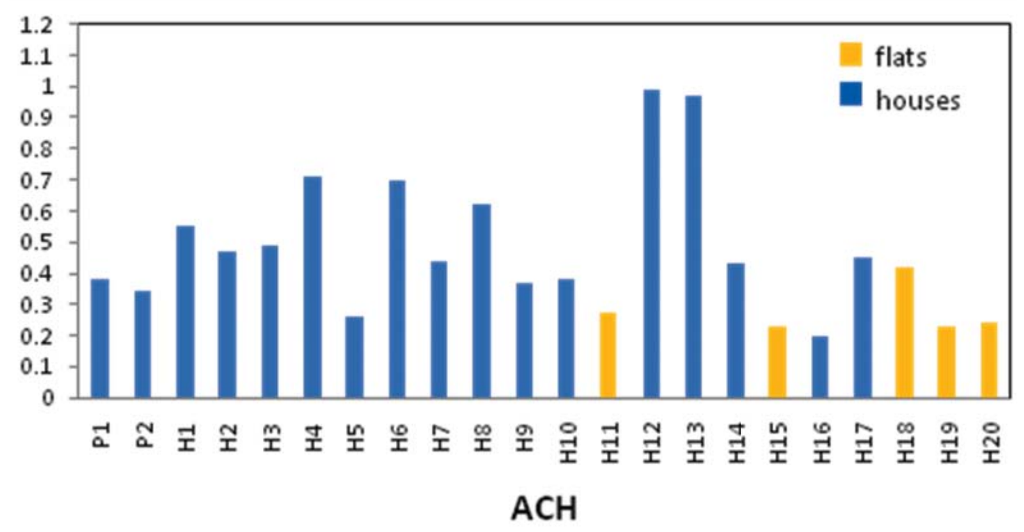
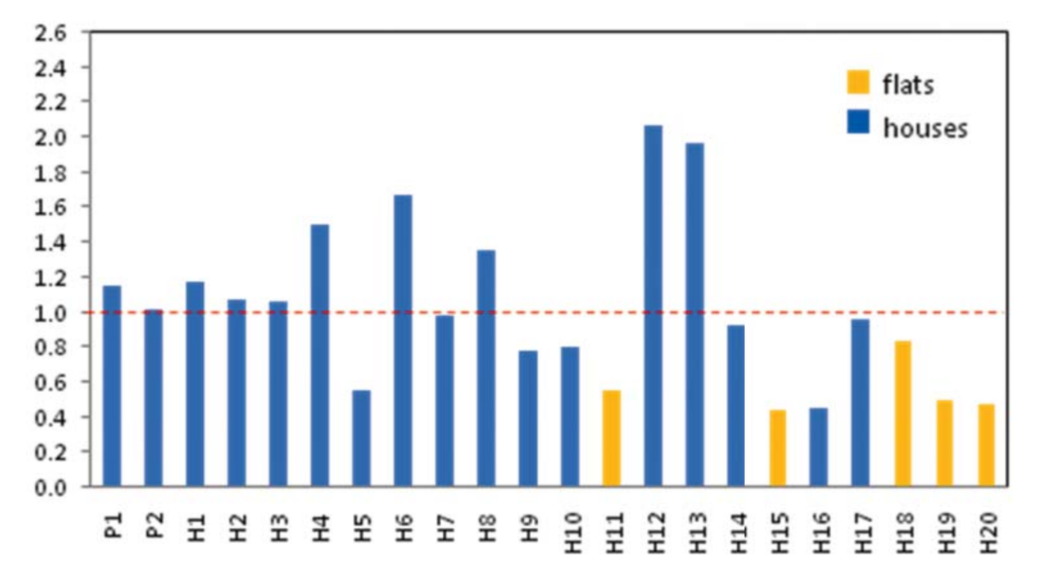


Figure 9 Air exchange rate estimated using the PFT technique vs ADF 2006



6.5 Intermittent extract flow rates

6.5.1 Introduction

Mechanical extract flow rates were measured wherever practically possible. The following is a summary of the findings. A complete set of results is provided in Table A.5 of the Appendix.

6.5.2 Kitchen mechanical extract

Figure 10 shows the distribution of the measured flow rates for the 13 dwellings monitored with an extract over the cooker (all exhausted to the outside). The mean extract flow rate for these fans was 23 l/s, with two achieving the ADF recommended flow rate of 30 l/s. Allowing for a 5% error in the measurement technique (ie pass rate at 28 l/s), six of the 13 dwellings passed.

The minimum flow rate recorded was 9 l/s. In this case, the fan had been replaced with a quieter fan at the occupants' request. The quieter model is likely to have had a lower fan speed and therefore flow rate.

Figure 10 Kitchen extract above the cooker

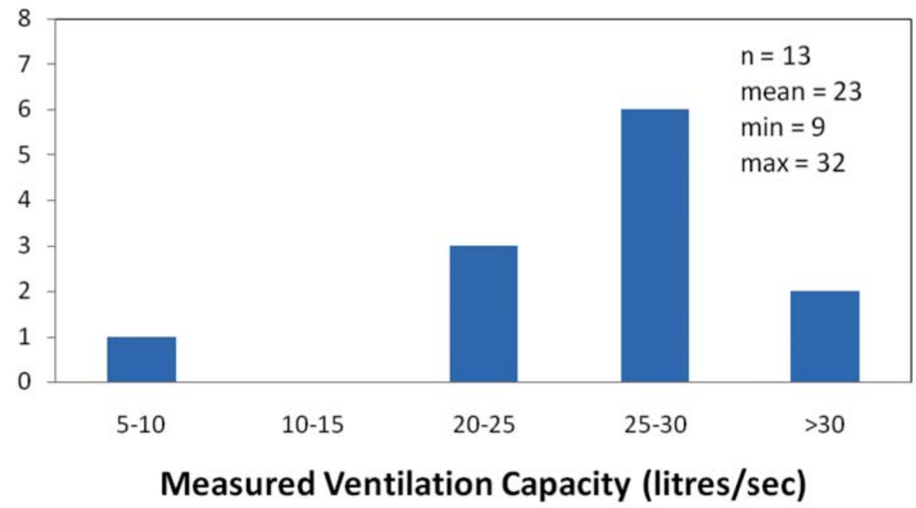
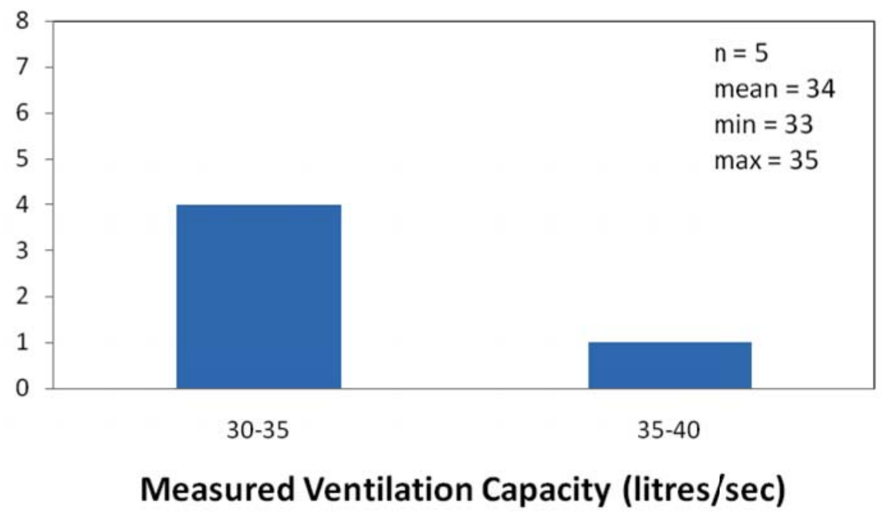


Figure 11 shows the distribution of the measured flow rates for the five dwellings monitored with an extract that was not directly above the cooker (all exhausted to the outside). ADF recommends that these fans have a higher flow rate of 60 l/s as they are less effective in removing cooking pollutants (fans above or close to the cooker can remove some cooking pollutants before they become mixed with the room air). All five fans were measured with a flow rate between 33–35 l/s, thus significantly below the value recommended in ADF. It is possible that they were installed to meet the previous 30 l/s criterion.

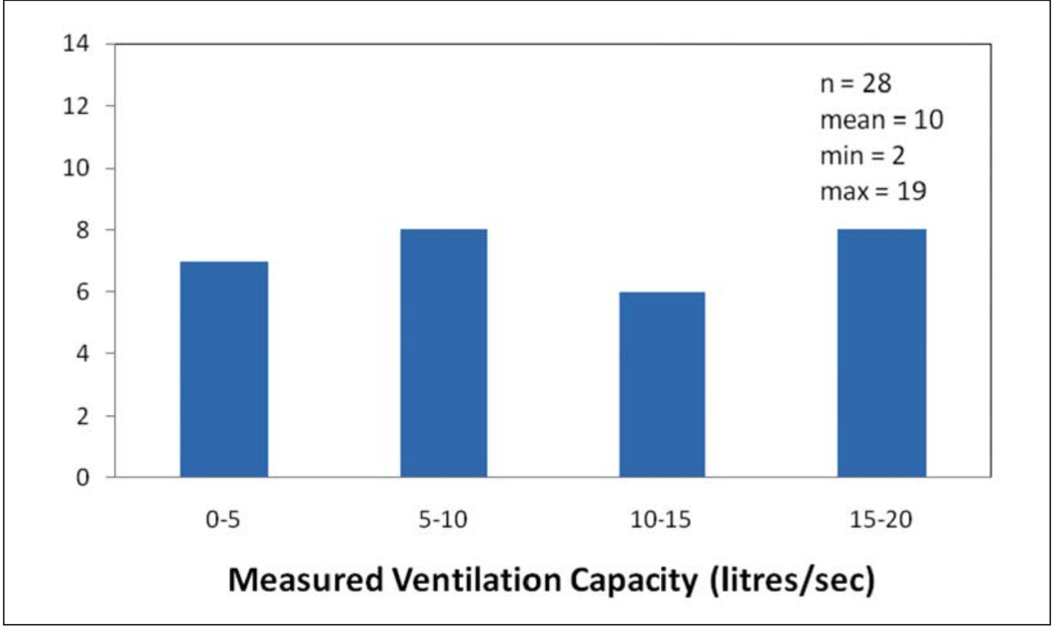
Figure 11 Kitchen extract not above the cooker



6.5.3 Bathroom mechanical extract

Figure 12 shows the distribution of the measured extract rates in the main bathrooms of 21 dwellings (not practical to measure the remaining dwelling) and en-suite bathrooms of eight dwellings. ADF recommends that extract rates should achieve 15 l/s. Only eight (just over one-quarter) of the sample met this criterion. Allowing for a 5% experimental error (pass rate of 14 l/s), allowed a further two fans (10 in total) to pass. There appeared to be no difference between the performance of main and en-suite bathroom fans.

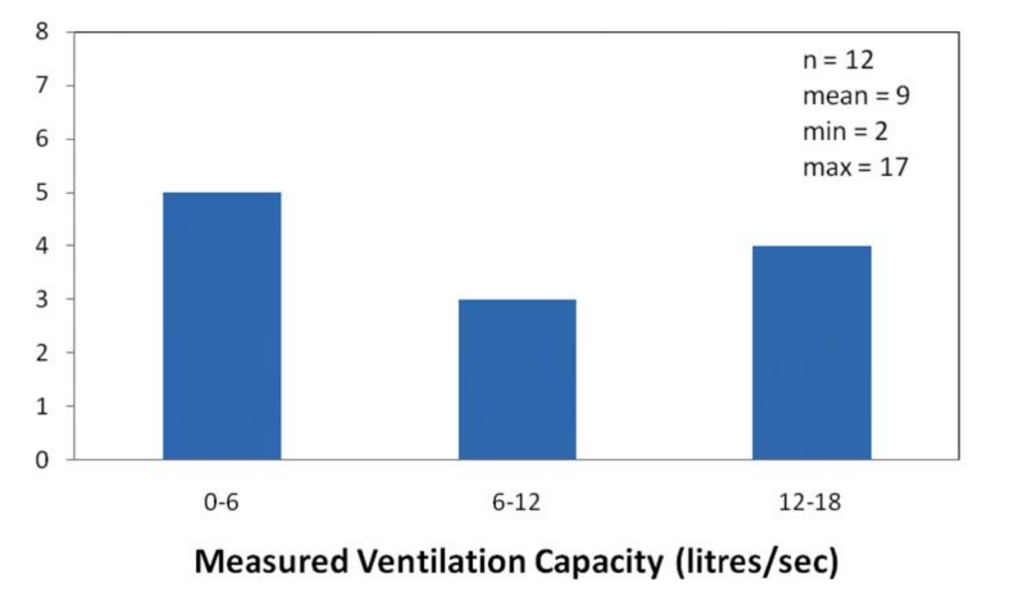
Figure 12 Bathroom extract rates



6.5.4 WC mechanical extract

Figure 13 shows the distribution of the measured flow rates for all 12 dwellings that had a small WC with an extract fan. ADF recommends that extract rate should achieve 6 l/s. Seven of the fans achieved this criterion.

Figure 13 Small WC extract rates



6.5.5 Discussion

A significant number of mechanical extract fans were not providing the recommended flow rates. One possible reason is that the incorrect fan rating may have been installed. Another potential cause is inadequate installation. The study was not focused on investigating installation issues. On several occasions, where the householder had sufficient time and there was easy access, the ducting installation was viewed. Problems noted included unnecessarily long and flexible duct runs and a high number of bends.

6.6 Relative humidity

This section provides a summary of the relative humidity (RH) results measured in living room, kitchen, bathroom and master bedroom for the main sample (RH measurements were not taken in the kitchen and bathroom of pilot study homes). For results of individual dwellings see Table A.6 and Table A.7 in the Appendix.

The consultation version of ADF 2010 proposes new RH criteria to be met during the heating season in each room:

- average monthly RH < 65%
- average weekly RH < 75%
- average daily RH < 85%

Figure 14 shows the distribution of the maximum average weekly RH level monitored in each dwelling. Within each dwelling, the results for each room were determined and the maximum chosen. The maximum average weekly level recorded was 71% which is within the new criterion of 75%.

If it is assumed that the average weekly level is representative of the average monthly level, then four homes recorded RH levels of 65% or greater (H11, H15, H16, H20). Three of these dwellings are flats (H11, H15 and H20), and as previously noted in Section 6.4, none of the flats achieved the ADF recommended background ventilation rate. H16 had the lowest air exchange rate recorded in this study (0.2 ach). It seems reasonable that for these four homes the weekly levels would be similar to the monthly level, as the external levels were close to the average in the sample and the occupants were asked to undertake moisture generating activities (e.g. cooking and bathing) as usual.

Figure 15 shows the distribution of the maximum average daily RH level monitored in each dwelling. The maximum average daily level recorded was 82% which is within the new criterion of 85%.

Some additional analysis was undertaken to indicate the likely impact to the internal RH levels from reasonably worst external RH levels. This is because internal levels are very dependent on external levels.

The following steps were undertaken:

i. The average weekly vapour pressure level was determined for each room in each dwelling over the week monitoring period from the measured temperature and RH levels. This was similarly undertaken for the external vapour pressure level.
ii. The vapour pressure excess was determined for each room by subtracting the vapour pressure outside from the vapour pressure in the room.
iii. The reasonably worst case vapour pressure level for outside was determined. The London TRY (Test Reference Year) data set was used for external climate conditions. We determined the maximum weekly vapour pressure level over the heating season (SAP 2005 runs suggested that daily average external temperature should be below 10.5 °C during the heating season).
iv. The worst case weekly vapour pressure level from (iii) was added to the excess vapour pressure level from (ii).
v. This was reconverted back to RH level for each room.

The results showed four homes with weekly average levels above 70%, but only one (H8) exceeded 75% (achieved 75.7%). If necessary, windows can be opened to remove excess moisture due to periods of high external levels. Further analysis could usefully investigate the impact of external moisture levels on the daily average and whether the TRY data-set is the most appropriate one to use for such analysis.

Figure 14 Highest weekly average RH level in each dwelling

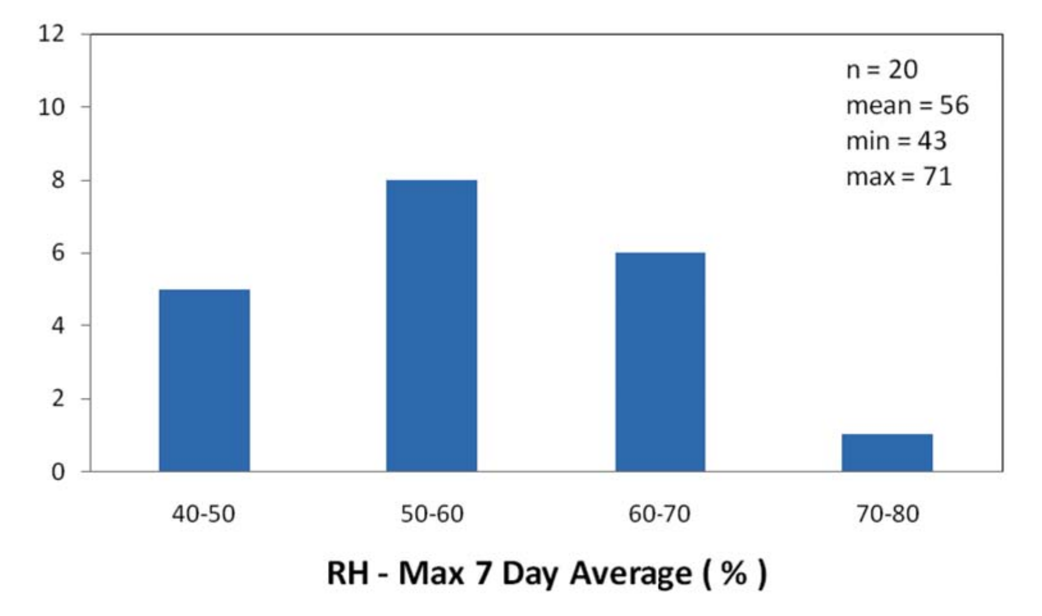
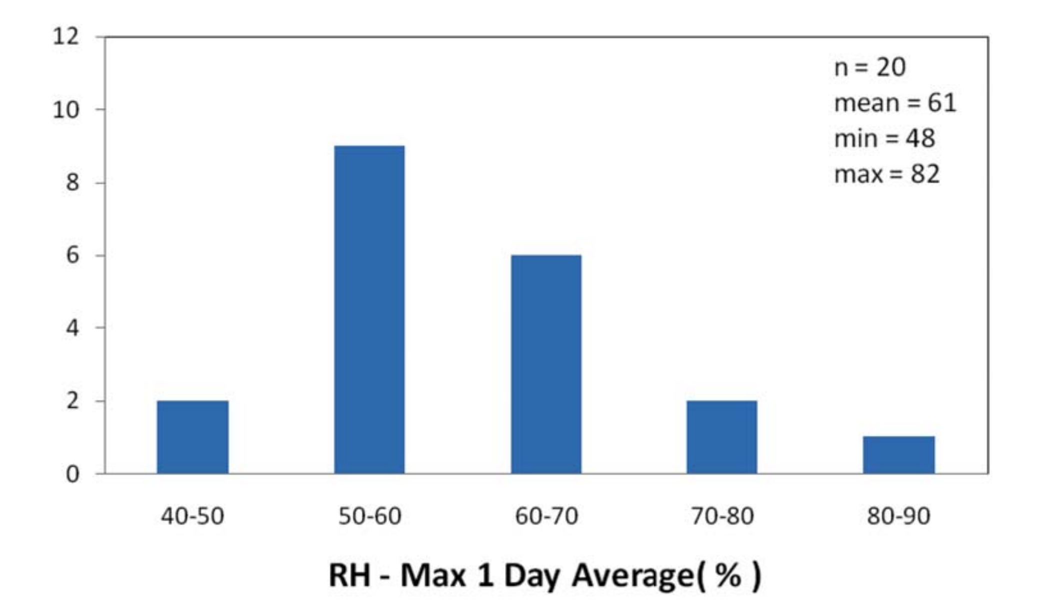


Figure 15 Highest daily average RH level in each dwelling



6.7 Nitrogen dioxide

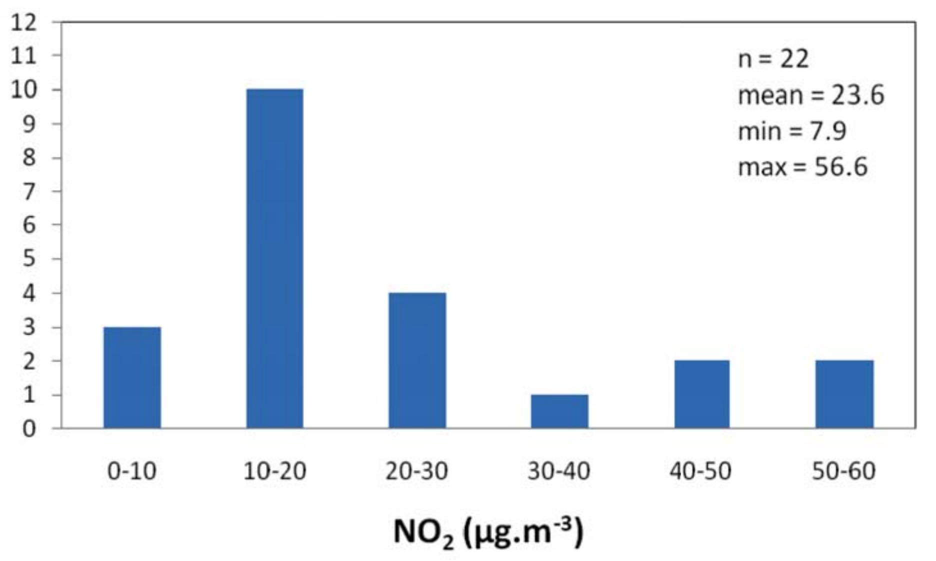
This section provides a summary of the results of the nitrogen dioxide (NO_2) levels. For results of individual dwellings see Table A.8 in the Appendix.

Figure 16 provides the distribution of the average NO_2 levels measured in the kitchen over the monitoring period. The mean concentration of NO_2 recorded in the sample was 24 $\mu g.m^{-3}$. This increased to 29 $\mu g.m^{-3}$ if you consider only those 64% of dwellings that used gas for cooking.

Four dwellings exceeded the recommendation in ADF that NO_2 levels should not exceed 40 $\mu g.m^{-3}$ as a long term average.

- Three homes were installed with fans that were not adjacent to the cooker and achieved approximately 50% of the recommended flow rate. Hence, this is a plausible explanation for the high NO_2 levels.
- Within the fourth home, the occupants did not use extract ventilation during cooking even though requested to do so. The occupant commented in the daily diary that the noise level of the fan was a nuisance, therefore the fan was not used.

Figure 16 Distribution of NO_2 concentrations



6.8 TVOCs

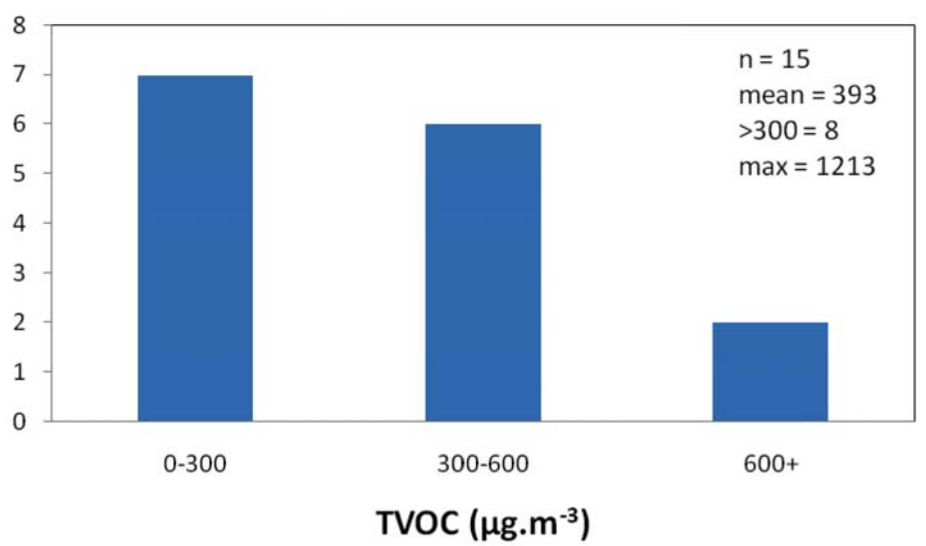
This section provides a summary of the results of the TVOC levels measured in the living room and master bedroom. For results of individual dwellings see Table A.9 in the Appendix. There was an error in the analysis of a batch of TVOC sample tubes which voided results for seven of the dwellings.

Figure 17 provides the distribution of the highest TVOC levels monitored in each home. 53% were higher than the guideline figure of 300 $\mu g.m^{-3}$ in ADF 2006.

Three of these dwellings had levels between 300–330 $\mu g.m^{-3}$. Given the accuracy of the detection technique, these levels could actually have been below 300 $\mu g.m^{-3}$ (or even higher). However, even if just below 300 $\mu g.m^{-3}$, they are approaching this guideline value and hence still a cause for concern.

Reviewing the data, overall there is no clear indication of a particular source or sources of TVOCs that is causing this high level. For one of the dwellings above 600 $\mu g.m^{-3}$ (H7), the occupant did smoke in the main bedroom (the room of the highest reading) which may have significantly impacted on the results directly or indirectly through the use of any odour-masking chemical products. However, smoking also took place in three other dwellings (H5, H6, H8) and the results did not show this significant rise. Hence it is not clear whether smoking is the cause. For the other dwelling above 600 $\mu g.m^{-3}$, there was no obvious source from the completed questionnaire and the occupants had already moved by the time we followed up after the monitoring period.

Figure 17 Highest TVOC concentration in each dwelling



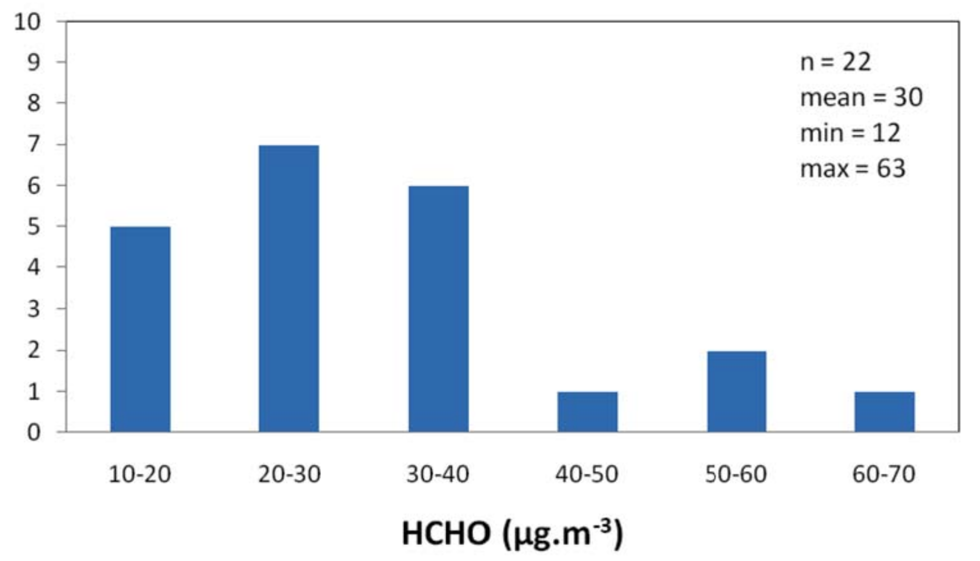
6.9 Formaldehyde

This section provides a summary of the results of the formaldehyde (HCHO) levels measured in the living room and master bedroom. For results of individual dwellings see Table A.10 in the Appendix.

Figure 18 provides the distribution of the highest formaldehyde levels monitored in each home. All results were less than the WHO guideline level for effects on health and comfort of 100 μg.m^{-3} (WHO 2000) averaged over 30 minutes.

Formaldehyde levels monitored during the study were averaged over three days. The highest level recorded during the monitoring period was 63 μg.m^{-3} in a master bedroom. It would be expected that there would be some variation in these three days such that there would be 30-minute periods that would be higher. Assuming the sources are predominantly formaldehyde based resins, e.g. in wood based products, then the rate of emission will be quite steady, although somewhat elevated at higher temperatures and humidities. Pollutant concentrations are more likely to vary due to variations in ventilation rate – there are likely to be some periods of significantly lower ventilation rate due to falls in external driving forces. Assuming that this would result in maximum 30-minute levels double that of the three-day readings, it would suggest that at most three dwellings would have exceeded the WHO criterion. It is interesting to note that the three highest levels corresponded to the three dwellings with the lowest air permeability levels (H7, H18, H20).

Figure 18 Highest formaldehyde concentration in each dwelling



Chapter 7

Discussion

7.1 Are intermittent extract flow rates sufficient?

The purpose of intermittent extract ventilation is to provide extract ventilation in rooms where there are significant indoor pollutant sources. This is to both minimise the pollutant levels in those rooms and to minimise the spread of pollutants to the rest of the building. Extract ventilation is located in the kitchen to remove combustion pollutants from cooking and other moisture generating activities, e.g. washing-up. Extract ventilation is also located in bathrooms to remove moisture generated in the air from bathing and showering.

The results from this study suggest that the intermittent extract flow rates may be insufficient to control moisture levels generated in the wet rooms. Excessive levels were recorded in the wet rooms of three homes (H15, H16, H20) against the monthly RH criterion. In each case, the exceedance occurred in the bathroom and not the kitchen. This analysis is based on the reasonable assumption that the actual monthly levels in these homes were similar to the recorded weekly levels.

However, the results may be at least partially explained by the low air exchange rates in these homes. In two of the homes, the bathroom extract rates actually met CLG recommended levels (H15 and H20). The air exchange rate in all three of these homes was low (0.20 – 0.24 ach) and would tend to generally increase the relative humidity level throughout the home.

Based on the same assumptions, the monthly RH levels were also high in the habitable rooms of three homes. These occurred in the living room for H16 and in the bedroom for H11 and H20.

Again, low exchange rates are expected to have a significant influence on these results. RH levels in habitable rooms are controlled by a combination of extract ventilation to minimise dispersal from wet rooms to the rest of the dwelling and background ventilation to remove moisture produced elsewhere in the dwellings, for example through respiration. Insufficient extract ventilation is likely to be one factor allowing dispersal to the rest of the home. However, in all three homes it is noted that the air exchange rate is low (0.20 – 0.27 ach).

Further analysis considered a reasonably worst case external moisture scenario. One dwelling (H8) exceeded the 75% RH ADF 2010 criterion for weekly average indoor RH levels and three other dwellings approached this level (H2, H15, H20). In these cases, either the intermittent extract could have been used for a longer period or windows could have been opened for short periods. It is worth noting that of the four dwellings, three had air permeability below 5 $m^3.h^{-1}.m^{-2}$, although the sample size is very small to make any conclusive judgement based on this. It is also worth noting that these highest levels always occurred in the bathroom.

It is perhaps surprising that the RH levels were not higher more generally, as in many cases intermittent extract ventilation and/or trickle ventilator areas did not meet ADF 2006 guidance. Focusing particularly on the wet rooms here (background ventilation is discussed further on), there are two plausible explanations.

- The extract flow rates were chosen for ADF based on reasonably worst cases moisture generation rates. These may not have occurred in practice because of user behaviour (e.g. lower moisture production during cooking than predicted) or relatively low occupancy. (ADF assumes two people sleep in the master bedroom and one person sleeps in each other bedroom, but, in practice, all apart from one of the dwellings had at least one bedroom unoccupied during the monitoring period.)
- The occupants may not have closed the internal doors to the wet rooms during moisture production. Hence, the moisture levels would have been reduced in these rooms but spread and diluted throughout the rest of the dwelling.

The intermittent extract flow rates were not sufficient to control nitrogen dioxide levels. In four dwellings, levels exceeded those recommended by ADF. However, as discussed in Section 6.7, three of the dwellings had extract flow rates approximately half that recommended by ADF and if the fans had been properly installed this should have addressed this problem. A further dwelling did not use their cooker hood as it was too noisy. Whilst it is important to recognise this problem, it does suggest that if the cooker hood had been used, nitrogen dioxide levels would have been controlled.

Overall the results from this study suggest that the intermittent extract flow rates are sufficient and should not be changed. This includes the more airtight dwellings in the sample. However, it is important that cooker hoods and extract fans are properly installed.

7.2 Are trickle ventilator areas sufficient?

7.2.1 Introduction

The purpose of background ventilation, of which trickle ventilators are a means to achieving it, is to remove non-localised pollutants spread around the dwelling as well as remove pollutants that 'escape' extract ventilation which, in practice, can never be 100% effective (e.g. if the kitchen door is open during cooking, some cooking pollutants will be extracted by the fan and others spread to the rest of the dwelling through the open door).

Of all of the pollutants monitored in the habitable rooms, the RH and TVOC levels exceeded consultation ADF 2010 pollutant criteria. The formaldehyde levels from sources around the home were sufficiently low. There may be problems from formaldehyde in airtight homes – this is a relatively small study and care should be taken in extrapolating the results to the whole new building stock. However, by adequately controlling RH and TVOCs, it may significantly control other pollutants as well.

We shall first review the correlation of pollutants with airtightness. It is worthwhile reviewing this relationship given the purpose of the study.

We shall next review whether TVOC levels are high because of inadequate installation and inspection or because the ventilation areas recommended in ADF 2006 are insufficient. In doing so, some approximations will need to be made as it is difficult to know exactly the impact of inadequate installation and inspection. This analysis focuses on TVOC levels, rather than RH levels, as there was a greater prevalence of TVOC levels exceeding the IAQ criteria. It is assumed that if TVOC levels were adequately controlled, this should suffice for RH levels as well.

7.2.2 Pollutant levels versus airtightness

We first review the evidence for a correlation between the air permeability and indoor pollutant levels. Due to the relatively small sample size, we have not undertaken detailed statistical analysis.

Table 3 compares air permeability against pollutant levels. The table has been ordered from lowest to highest air permeability. The table focuses on pollutant levels in habitable rooms (ie extract fans should address high pollutant levels produced intermittently in wet rooms).

The pollutants' levels are colour coded:

- the highest third in red
- the middle third in yellow
- the lowest third in green.

The table suggests, given the limitations of the sample size, the anticipated correlation between air permeability and pollutant levels. Relatively high levels are observed in the five most airtight dwellings.

However, there may be a confounding factor here. Four of the five more airtight dwellings are flats. As highlighted in Section 6.4, it is thought that the flats may be significantly under-ventilated due to them having effectively a single façade but the ventilation system being designed for a multi-sided façade.

Table 4 still suggests that even with the flats removed, there is a correlation between air permeability and indoor pollutant levels. However, it is less clear.

It is not surprising that there is not a clear correlation between airtightness and indoor pollutant levels. For example, pollutant emission rates will vary between dwellings. Furthermore, as highlighted earlier, the installed capacity of the ventilation systems shows significant variation.

Table 3 Comparison of air permeability and pollutant level

Property details		Air permeability		Ventilation	RH (habitable rooms)		TVOCs	HCHO
ID	House type	Test Method A	Test Method C		Weekly average	Worse weekly average	Max	Max
		$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	Ach	% RH	% RH	$\mu g.m^{-3}$	$\mu g.m^{-3}$
H20	Flat	2.96	4.32	0.24	71.0	74.6	535	50
H15	Flat	3.37	4.92	0.23	61.2	73.6	n/a	55
H11	Flat	3.45	4.32	0.27	65.0	69.3	n/a	37
H7	Terrace-End	3.89	6.25	0.44	53.8	66.5	976	63
H18	Flat	4.1	5.02	0.42	58.7	63.7	1213	35
H1	Detached	4.12	6.22	0.55	50.4	62.4	224	30.2
H19	Flat	4.52	5.09	0.23	49.9	61.2	572	28.1
H8	Terrace-Mid	4.89	7.22	0.62	58.1	75.7	311	22.3
H12	Semi-Det	4.96	7.35	0.99	56.0	66.5	n/a	19.6
H5	Terrace-End	4.98	7.81	0.26	53.9	67.5	111	16.4
H6	Terrace-Mid	5.13	7.37	0.70	46.8	n/a	204	29
H10	Terrace-Mid	5.37	7.82	0.38	42.5	58.2	191	11.7
H9	Terrace-End	5.49	8.25	0.37	46.0	65.9	330	31
H2	Detached	6.45	9.77	0.47	62.2	73.5	464	31
H14	Semi-Det	7.02	9.67	0.43	54.5	63.8	n/a	32
H16	Semi-Det	7.18	8.67	0.2	66.3	n/a	n/a	46
H3	Detached	8.28	11.53	0.49	43.1	57.8	156	19.9
H13	Detached	8.58	13.11	0.97	41.8	56.6	n/a	13.1
H17	Detached	8.84	11.3	0.45	52.3	56.7	n/a	24.8
P1	Semi-Det	9.51	13.3	0.38	n/a	n/a	53	15.5
P2	Semi-Det	10.61	13.74	0.34	n/a	n/a	231	19
H4	Detached	11.6	14.9	0.71	39.8	55.9	320	24.5

Table 4 Comparison of air permeability and pollutant level (without flats)

Property details		Air permeability		Ventilation	RH (habitable rooms)		TVOCs	HCHO
ID	House type	Test Method A	Test Method C		Weekly average	Worse weekly average	Max	Max
		$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	Ach	% RH	% RH	$\mu g.m^{-3}$	$\mu g.m^{-3}$
H7	Terrace-End	3.89	6.25	0.44	53.8	66.5	976	63
H1	Detached	4.12	6.22	0.55	50.4	62.4	224	30.2
H8	Terrace-Mid	4.89	7.22	0.62	58.1	75.7	311	22.3
H12	Semi-Det	4.96	7.35	0.99	56.0	66.5	n/a	19.6
H5	Terrace-End	4.98	7.81	0.26	53.9	67.5	111	16.4
H6	Terrace-Mid	5.13	7.37	0.70	46.8	n/a	204	29
H10	Terrace-Mid	5.37	7.82	0.38	42.5	58.2	191	11.7
H9	Terrace-End	5.49	8.25	0.37	46.0	65.9	330	31
H2	Detached	6.45	9.77	0.47	62.2	73.5	464	31
H14	Semi-Det	7.02	9.67	0.43	54.5	63.8	n/a	32
H16	Semi-Det	7.18	8.67	0.2	66.3	n/a	n/a	46
H3	Detached	8.28	11.53	0.49	43.1	57.8	156	19.9
H13	Detached	8.58	13.11	0.97	41.8	56.6	n/a	13.1
H17	Detached	8.84	11.3	0.45	52.3	56.7	n/a	24.8
P1	Semi-Det	9.51	13.3	0.38	n/a	n/a	53	15.5
P2	Semi-Det	10.61	13.74	0.34	n/a	n/a	231	19
H4	Detached	11.6	14.9	0.71	39.8	55.9	320	24.5

7.2.3 Review of TVOC levels

First, it is informative to review the TVOC levels in more detail. The levels are shown in Table 5, compared to other parameters. The data have been sorted by TVOC level.

The Table highlights the following:

- those air permeability levels with Method A below 5 $m^3.h^{-1}.m^{-2}$ @ 50 Pa
- the five lowest levels of Method C and ventilation.

As before, from this limited sample size, there is a suggestion that the high TVOC levels occur in more airtight properties. The five of the eight properties with high TVOC levels had air permeabilities below 5 $m^3.h^{-1}.m^{-2}$. Perhaps of more concern is that the other three were leakier and, if they had been more airtight, the ventilation would be expected to be less and consequently the TVOC levels would have been higher.

As referred in the previous sub-section, not all airtight properties are expected to have high pollutant levels, e.g. it depends on the presence of sources. This is a possible explanation for the three dwellings, with an air permeability below 5 $m^3.h^{-1}.m^{-2}$, having acceptable VOC levels.

It is also noted that three of the four highest level homes are flats which is explored further below.

Finally, it is important to note that TVOCs were chosen in ADF to represent organic compounds as it was to be the most sensitive marker for organic compounds. If TVOCs are less than the guideline level of 300 $\mu g.m^{-3}$, then typically individual organic compounds (e.g. formaldehyde, toluene, benzene) should also be below health-based guidelines for these specific compounds.

Table 5 Review of TVOC levels

House ID	House type	TVOC	Percentage above 300 $\mu g.m^{-3}$	Method A	Method C	Ventilation
		$\mu g.m^{-3}$	%	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	Ach
P1	Semi-Det	53	0	9.5	13.3	0.38
H5	Terrace-End	111	0	5.0	7.8	0.26
H3	Detached	156	0	8.3	11.5	0.49
H10	Terrace-Mid	191	0	5.4	7.8	0.38
H6	Terrace-Mid	204	0	5.1	7.4	0.7
H1	Detached	224	0	4.1	6.2	0.55
P2	Semi-Det	231	0	10.6	13.7	0.34
H8	Terrace-Mid	311	4	4.9	7.2	0.62
H4	Detached	320	7	11.6	14.9	0.71
H9	Terrace-End	330	10	5.5	8.3	0.37
H2	Detached	464	55	6.5	9.8	0.47
H20	Flat	535	78	3.0	4.3	0.24
H19	Flat	572	91	4.5	5.1	0.23
H7	Terrace-End	976	225	3.9	6.3	0.44
H18	Flat	1213	304	4.1	5.0	0.42

7.2.4 Impact of installing inadequate trickle ventilation

This next step is to estimate the impact on the TVOC levels from the fact that insufficient trickle ventilation was installed in some homes. If sufficient trickle ventilation was installed, how would the TVOC levels vary?

In doing this analysis, we make a number of assumptions.

- Firstly, we assume that the ventilation rate is proportional to the air leakage rate at 50 Pa. This assumption is the basis of the 1/20th rule of thumb (see Sherman, 1987[2]).

Hence:

$$\text{Ventilation} = k.\ ACH_{50}$$

where k = the proportionality constant.

We already know the air pressure test results with and without the trickle ventilation open. We can then estimate the increase in ventilation rate, if the correct amount of trickle ventilation was included as follows.

$$\text{Ventilation}_{\text{corrected}} = k.\ \left(\left(\frac{\textit{trickle vent (ADF)}}{\textit{trickle vent (installed)}}\ x\ [ACH_C - ACH_B]\right) + ACH_B\right)$$

where ACH_B and ACH_C are the air leakage rate results at 50 Pa for Methods B and C, respectively.

- Second, we assume that the ventilation rate is inversely proportional to the TVOC pollutant concentration (ie ventilation rate = 1/TVOC level). This is reasonable. It is the standard formula for pollutant concentration in equilibrium. It assumes that the outdoor concentration has a small impact on the internal levels which is suggested by the results in this and other studies.

Taking these two assumptions, the results are shown in Table 6. In this analysis, the TVOC levels are reduced where there was previously under-installed trickle ventilation. For comparison, TVOC levels are increased where previously there was an excessive trickle ventilation rate compared to ADF 2006. Note that the analysis was not possible for dwellings P1, P2, H9 and H10 due to a lack of equivalent area information on the trickle ventilator to determine the degree of any under or over installation.

Overall, while this does have an impact, it is not significantly reducing those homes with the highest TVOC levels. H4 and H8 are now less than or equal to 300 $\mu g.m^{-3}$, but this is still a cause for concern as they are still approaching the guideline level (and, could be expected on a different week's monitoring period, to exceed it). Even if the above assumptions are underestimates, doubling any reduction noted here would still not bring the high TVOC results significantly below 300 $\mu g.m^{-3}$, if at all.

[2] Sherman, M H (1987) Estimate of infiltration from leakage and climate indicators. *Energy and Buildings*, 10, pp. 81–86.

Table 6 Analysis of TVOC results due to incorrectly installed trickle ventilation capacity

House ID	House type	Method A	TVOC (original)	TVOC (new)	Change
		$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$\mu g.m^{-3}$	$\mu g.m^{-3}$	%
P1	Semi-Det	9.5	53		
P2	Semi-Det	10.6	231		
H1	Detached	4.1	224	185	-17
H2	Detached	6.5	464	488	+5
H3	Detached	8.3	156	172	+10
H4	Detached	11.6	320	300	-6
H5	Terrace-End	5.0	111	109	-2
H6	Terrace-Mid	5.1	204	198	-3
H7	Terrace-End	3.9	976	890	-9
H8	Terrace-Mid	4.9	311	296	-5
H9	Terrace-End	5.5	330		
H10	Terrace-Mid	5.4	191		
H18	Flat	4.1	1213	1126	-7
H19	Flat	4.5	572	530	-7
H20	Flat	3.0	535	472	-12

7.2.5 Building more airtight dwellings

It is also interesting to see the potential impact if all of the dwellings were built at least to 4 $m^3.h^{-1}.m^{-2}$. Hence for those properties leakier than this, the impact of a more airtight property was determined applying the same techniques as in Section 7.2.4. This is shown in Table 7 below.

The results suggest very significant increases in TVOC levels. If all dwellings had an air permeability built to 4 $m^3.h^{-1}.m^{-2}$ or better, nine homes would now exceed 300 $\mu g.m^{-3}$.

It should also be noted that this would also impact on the other pollutant levels.

- Similar percentage increases could be expected for formaldehyde. However, analysis showed that this does not tend to take the levels above 100 $\mu g.m^{-3}$. The highest formaldehyde levels were for the more airtight dwellings and hence only a small increase, if at all, is observed by assuming an air permeability of 4 $m^3.h^{-1}.m^{-2}$. For those leakier dwellings, the levels were fairly low to start with and, even with increases, the results were still relatively low.

- An increase would also be expected in moisture levels. However, the percentage increase would be less than that for TVOCs and formaldehyde. Indoor moisture levels arise from both indoor and external sources. To a first approximation, the external sources provide a background level whatever the air permeability. The air permeability has a greater impact on internal sources – an improved air permeability stops moisture from escaping the dwelling and, therefore, increasing the indoor levels.

Table 7 Impact of improving airtightness on TVOC levels

House ID	House type	Method A	TVOC (original)	TVOC (new)	Change
		$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$\mu g.m^{-3}$	$\mu g.m^{-3}$	%
P1	Semi-Det	9.5	53	91	+71
P2	Semi-Det	10.6	231	445	+93
H1	Detached	4.1	224	228	+2
H2	Detached	6.5	464	620	+33
H3	Detached	8.3	156	248	+59
H4	Detached	11.6	320	653	+104
H5	Terrace-End	5.0	111	127	+14
H6	Terrace-Mid	5.1	204	241	+18
H7*	Terrace-End	3.9	976		
H8	Terrace-Mid	4.9	311	355	+14
H9	Terrace-End	5.5	330	403	+22
H10	Terrace-Mid	5.4	191	231	+21
H18	Flat	4.1	1213	1237	+2
H19	Flat	4.5	572	637	+11
H20[1]	Flat	3.0	535		

*These dwellings already had an air permeability better than 4 $m^3.h^{-1}.m^{-2}$, so no analysis was undertaken

7.2.6 Inadequate ADF guidance in flats

There is a suggestion that a contributing factor in flats is inadequate guidance in ADF. Flats 18 to 20 had two external façades, hence the trickle ventilation design reflected this. However, they were essentially single sided, in that one of the façades was short in length and thus little cross ventilation would occur in practice. It may have been better if the ventilation guidance for single-sided façades was followed or another ventilation system adopted.

It is difficult to assess the impact here. Assuming that better guidance would result in a doubling of the ventilation rate from purpose-provided ventilation, according to similar calculation as in Section 7.2.4, this would reduce the TVOC levels by a further 15–30%. The results would be for H18–20: 893, 444 and 331 $\mu g.m^{-3}$, respectively.

7.2.7 Impact of door undercuts

This is to consider the impact of undercuts being less than recommended by ADF2006. Just over 50% of the door undercuts did not achieve 10 mm and only one dwelling had all of its door undercuts achieving this target.

As shown in Table 8, there appears no clear correlation between door undercuts and TVOC levels. Door undercuts were not measured in the pilot homes and hence these results are not presented here.

This lack of a clear correlation can be explained by several factors. Again, there will be different source emission rates in different homes. Furthermore, the impact of door undercuts depends on whether internal doors are left open and whether there are any other routes for air to move around the dwelling (i.e. internal leakage through gaps, cracks separating internal rooms).

Table 8 Impact of door undercuts

House ID	House type	TVOC	Undercuts (all rooms)	Undercuts (habitable rooms only)
		μg.m^{-3}	mm	mm
H5	Terrace-End	111	9	6
H3	Detached	156	16	16
H10	Terrace-Mid	191	9	14
H6	Terrace-Mid	204	4	5
H1	Detached	224	11	13
H8	Terrace-Mid	311	7	7
H4	Detached	320	12	13
H9	Terrace-End	330	7	7
H2	Detached	464	11	13
H20	Flat	535	7	10
H19	Flat	572	9	12
H7	Terrace-End	976	5	5
H18	Flat	1213	9	11

7.2.8 Discussion

From this study, it is not possible to provide conclusive evidence that dwellings built to 3-4 m^3.h^{-1}.m^{-2} or tighter (ie those homes for which ADF 2006 does not provide guidance) need additional ventilation compared to that recommended in ADF 2006. This is mainly due to the need to estimate for effects of inadequate installation and inspection. Furthermore, in the case of flats, better guidance is needed for single-sided ventilation.

However, overall, there is the suggestion that additional ventilation is needed for more airtight dwellings for the following reasons.

- Eight of the 15 homes with TVOC measurements had levels above the level of 300 μg.m^{-3} recommended in ADF 2006.
- The projected impact on TVOC levels of the dwellings in this sample being tightened to 4 m^3.h^{-1}.m^{-2} appears to significantly outweigh likely effects from under installation of trickle ventilation. Furthermore, it is likely to result in nine of the 15 homes with TVOC levels above 300 μg.m^{-3}.
- Three of the dwellings with the highest TVOC levels are flats. These may have been significantly under-ventilated as they were designed for two-

sided ventilation but ventilation was effectively only single-sided. It is not clear whether better design would have reduced levels below 300 $\mu g.m^{-3}$. However, this still leaves five to six dwellings with levels above 300 $\mu g.m^{-3}$.

- It is anticipated that having all door undercuts at least 10 mm would help. However, it is unclear from the results the benefit that this would have.

There is an additional confounding factor. It is possible that the trickle ventilators, while producing the equivalent area in the laboratory, may not be achieving this on installation taking into account their actual surroundings which could impede flow. This is something that should be considered in further work.

Finally, it is important to note that in practice, occupants do not use their ventilation system to full capacity (trickle vents are not always open and fans are not always used). Hence, the actual pollutant levels in dwellings will likely be higher than those recorded in this study.

7.3 Are dwellings Part F compliant?

All dwellings tested are Part F compliant in that they have been given approval through the building control process.

However, the study has demonstrated many cases where the recommendations given in ADF 2006 have not been met. The key differences from the ADF recommendations are as follows:

- Many intermittent extract flow rates do not meet those recommended in ADF. Every dwelling had at least one fan or cooker hood that did not provide the recommended extract rate. It is thought that this resulted in, at least, the nitrogen dioxide levels exceeding WHO guidelines in at least three dwellings.
- 72% of dwellings had total trickle ventilator area below that recommended in ADF.
- Only one dwelling had all door undercuts of 10 mm or greater.

7.4 Are dwellings Part L compliant?

All dwellings tested are Part L compliant in that they have been given approval through the building control process.

Two homes exceeded the maximum level of 10 $m^3.h^{-1}.m^{-2}$ required by ADL 2006 for dwellings sampled. It is not possible to know if these dwellings exceeded 10 $m^3.h^{-1}.m^{-2}$ on completion, as they may not have been included in the developer's air permeability test sample. It is feasible that the dwellings achieved 10 $m^3.h^{-1}.m^{-2}$ on completion and the air permeability increased post-completion due to drying out of the properties and/or work undertaken by the occupants.

7.5 Should we change air pressure testing for Part L compliance?

These results question the need to move from BS EN 13829 Method A to Method B. There is relatively little difference between the two sets of results (mean of 0.2 $m^3.h^{-1}.m^{-2}$; maximum of 0.5 $m^3.h^{-1}.m^{-2}$).

The advantages of making this change are as follows:

- It provides a more accurate assessment of the leakage of the construction of the dwelling. This will become more important as air permeability further improves and the relative contribution from non-sealed trickle ventilation increases.
- It allows for the fact that some trickle ventilators are designed not to close to ensure that there is some ventilation at their minimum setting. This may become more prevalent as homes become more airtight due to concern that occupants will close trickle ventilation in airtight homes because of inadequate information and result in poor indoor air quality and potential health effects.

This needs to be balanced by the additional time and effort to seal and unseal all natural ventilation openings given the relatively small air permeability reduction.

7.6 Should we undertake air pressure testing for Part F compliance?

The study investigated whether it was possible to determine the total trickle ventilation equivalent area through testing in-situ. The proposal was to undertake air pressure testing with the trickle ventilators sealed and then opened and through analysis of the resultant data determine the equivalent area.

This study has not demonstrated the robustness of the approach. The approach, at present, is not able to determine the equivalent area with sufficient accuracy. However, further development of this approach (e.g. undertake air pressure tests at lower pressure differences) may make it a useful technique.

Chapter 8

Conclusions and recommendations

The key results from this study can be summarised as follows:

- We have monitored 22 dwellings built to Parts F and L 2006, with trickle ventilation and intermittent extract. Ten of the 22 dwellings tested (46% of total sample including pilot homes, 50% of main sample) achieved an air permeability of less than 5 $m^3.h^{-1}.m^{-2}$.
- Nearly three-quarters of the dwellings (72% of sample) did not have sufficient trickle ventilation installed to meet ADF 2006. In the worst case, only just over half (57%) of the recommended trickle ventilation was installed.
- 52% of the internal doors failed to achieve the 10 mm gap under the doors recommended in ADF 2006.
- Less than half of the kitchen or bathroom fans achieved the flow rates recommended in ADF 2006. Furthermore, none of the fans located away from the cooker achieved the recommended flow rates in the kitchen.
- All relative humidity levels monitored over a week-long period were within the new daily and weekly relative humidity guideline levels proposed in the consultation version of ADF 2010. However, making reasonable assumptions, it would be expected that approximately four homes would have monthly relative humidity levels that would exceed the newly proposed monthly relative humidity guideline level.
- Four homes had levels of nitrogen dioxide in the kitchen that exceeded that recommended in ADF 2006. A key issue in these cases was insufficient installed flow where fans are located away from the cooker.
- All homes had acceptable levels of formaldehyde.
- Over half of the homes with TVOC measurements had levels exceeding that recommended in ADF 2006. It is important to note that in developing ADF 2006, TVOCs were chosen to represent organic compounds. A review of indoor air quality results suggested that if the TVOC guideline level of 300 $\mu g.m^{-3}$ was met, then individual chemical health-based guideline levels (e.g. benzene, toluene, formaldehyde) should also be met.

The key conclusions from these results are as follows:

- It is difficult to make a conclusive judgement as to whether or not the current recommended natural ventilation provisions in ADF 2006 are sufficient for airtight homes. The study is relatively small and the conclusions should only be treated as indicative. Furthermore, in all cases, the capacity of the ventilation system did not meet that recommended in ADF 2006.
- The intermittent extract rates appear to be sufficient. It is important to ensure that they are installed correctly to provide the capacity recommended in ADF 2006. There is no evidence from this study that with correct installation, the extract rates should be increased for more airtight dwellings.
- The trickle ventilator sizes appear to be insufficient. Even allowing for installation issues for the ventilation system as a whole, at least a significant minority of TVOC levels would be expected to exceed the recommended guideline level, particularly for the more airtight homes. VOCs are produced by building products and the activities of the occupants such as smoking, use of personal hygiene products and interior decorating. It may seem pedantic to change the design of a ventilation system just to better control one pollutant, but the long term effects on health due to exposure to VOCs are not well documented, and it seems prudent to err on the side of caution. Furthermore, the TVOC criterion was selected as a sensitive marker for individual organic chemical compounds (ie if TVOC levels are below the criterion, previous research suggest that individual organic chemical compounds would also be below recognised indoor or outdoor health-based levels for these pollutants). There are also other hazards to health that are affected by ventilation, such as house dust mites, which are associated with respiratory illnesses including asthma. We do not currently attempt to control these under Part F because their breeding success is influenced by heating and hygiene practice as much as ventilation. Improving ventilation would be a step in the right direction to limit this risk.
- Better guidance needs to be provided for the natural ventilation of flats. While the flats had two façades, and were ventilated as 'multi-sided façades' according to ADF 2006, they were effectively single façades as the second façade was limited. The ventilation and indoor air quality results suggest that these homes were under-ventilated.
- It is important to note that in practice, occupants do not use their ventilation system to full capacity (trickle vents are not always open and fans are not always used). Hence, the actual pollutant levels in dwellings will likely be higher than those recorded in this study.

The key recommendations from this study are as follows:

- It is important that the ventilation system should be installed correctly and inspected to provide the ventilation capacity as designed.
- Further evidence needs to be obtained to substantiate the indicators from this study. However, there are sufficient grounds to support the proposal to increase trickle ventilators in dwellings having an air permeability equal to or tighter than 4 $m^3.h^{-1}.m^{-2}$. This is based on the levels of TVOCs observed, and the implications for individual organic compounds. This could also have benefits in controlling other hazards to health, but this is difficult to quantify.
- This was a relatively small study. A larger study is necessary, building on the findings of this study, to better determine indoor air quality levels achieved in airtight dwellings in which the ventilation system is installed correctly.
- Given the relatively high level of TVOCs, greater consideration should be given to reducing source strength by product controls.

Appendix A

Detailed results

Table A.1 Summary of air permeability test results

Property details		Air permeability				
ID	House type	Test Method A	Test Method B	Test Method C	A-B Difference	A-B Difference
		$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	$m^3.h^{-1}.m^{-2}$ @ 50 Pa	%
P1	Semi-Det	9.51	9.14	13.30	0.37	3.9
P2	Semi-Det	10.61	10.18	13.74	0.43	4.1
H1	Detached	4.12	3.98	6.22	0.14	3.4
H2	Detached	6.45	6.23	9.77	0.22	3.4
H3	Detached	8.28	7.81	11.53	0.47	5.7
H4	Detached	11.60	11.19	14.90	0.41	3.5
H5	Terrace-End	4.98	4.88	7.81	0.10	2.0
H6	Terrace-Mid	5.13	4.99	7.37	0.14	2.7
H7	Terrace-End	3.89	3.85	6.25	0.04	1.0
H8	Terrace-Mid	4.89	4.73	7.22	0.16	3.3
H9	Terrace-End	5.49	5.59	8.25	-0.10	-1.8
H10	Terrace-Mid	5.37	5.36	7.82	0.01	0.2
H11	Flat	3.45	3.30	4.32	0.15	4.3
H12	Semi-Det	4.96	4.86	7.35	0.10	2.0
H13	Detached	8.58	8.10	13.11	0.48	5.6
H14	Semi-Det	7.02	6.73	9.67	0.29	4.1
H15	Flat	3.37	3.23	4.92	0.14	4.2
H16	Semi-Det	7.18	6.65	8.67	0.53	7.4
H17	Detached	8.84	8.48	11.30	0.36	4.1
H18	Flat	4.10	3.99	5.02	0.11	2.7
H19	Flat	4.52	4.43	5.09	0.09	2.0
H20	Flat	2.96	2.80	4.32	0.16	5.4
Mean		6.15	5.93	8.54	0.22	3.3
Min		2.96	2.80	4.32		
Max		11.60	11.19	14.90		

Table A.2 Summary of trickle ventilation equivalent areas

Property details		**Equivalent area**		
ID	**House type**	**Recorded**	**ADF recommended**	**Recorded/ recommended**
		mm²	**mm²**	
P1	Semi-Det	N/A[1]	35,000	
P2	Semi-Det	N/A[1]	35,000	
H1	Detached	53,770	85,000	0.63
H2	Detached	40,500	35,000	1.16
H3	Detached	41,900	30,000	1.40
H4	Detached	75,300	95,000	0.79
H5	Terrace-End	42,500	45,000	0.94
H6	Terrace-Mid	27,500	30,000	0.92
H7	Terrace-End	40,000	50,000	0.80
H8	Terrace-Mid	35,000	40,000	0.88
H9	Terrace-End	N/A[2]	30,000	
H10	Terrace-Mid	N/A[2]	30,000	
H11	Flat	25,470	35,000	0.73
H12	Semi-Det	33,600	45,000	0.75
H13	Detached	64,800	40,000	1.62
H14	Semi-Det	38,500	35,000	1.10
H15	Flat	25,470	35,000	0.73
H16	Semi-Det	41,400	40,000	1.04
H17	Detached	56,700	60,000	0.95
H18	Flat	25,470	35,000	0.73
H19	Flat	21,750	35,000	0.62
H20	Flat	25,470	35,000	0.73
Mean				0.92
Min				0.62
Max				1.62

[1] Not measured in pilot study.

[2] Total geometric area of 57,300 mm² measured in both dwellings.

Table A.3 Summary of trickle ventilation positions (recorded on initial survey)

Property details		Number of installed trickle vents	Trickle ventilator position	
ID	**House type**		**Open**	**Closed**
P1	Semi-Det	13	0	13
P2	Semi-Det	10	3	7
H1	Detached	21	19	2
H2	Detached	16	0	16
H3	Detached	17	2	15
H4	Detached	30	0	30
H5	Terrace-End	17	4	13
H6	Terrace-Mid	12	3	9
H7	Terrace-End	16	7	9
H8	Terrace-Mid	14	0	14
H9	Terrace-End	7	0	7
H10	Terrace-Mid	7	7	0
H11	Flat	13	11	2
H12	Semi-Det	14	7	7
H13	Detached	22	17	5
H14	Semi-Det	15	12	3
H15	Flat	16	7	9
H16	Semi-Det	9	9	0
H17	Detached	21	0	21
H18	Flat	7	6	1
H19	Flat	3	2	1
H20	Flat	11	8	3
Overall		311	124 (40%)	187 (60%)

Table A.4 Summary of air exchange rate results

Property details	Air exchange rate			
ID	**PFT**	**PFT**	**ADF Table 1.1b**	**Measured/ ADF recommended**
	ach	**l/s**	**l/s**	
P1	0.38	24.2	21.0	1.15
P2	0.34	21.4	21.0	1.02
H1	0.55	61.4	52.1	1.18
H2	0.47	26.1	24.2	1.08
H3	0.49	18.9	17.8	1.06
H4	0.71	77.5	51.7	1.50
H5	0.26	15.3	27.5	0.55
H6	0.70	35.6	21.2	1.67
H7	0.44	31.1	31.6	0.98
H8	0.62	36.7	27.1	1.35
H9	0.37	15.3	19.5	0.78
H10	0.38	15.8	19.8	0.80
H11	0.27	9.4	17.0	0.56
H12	0.99	57.2	27.6	2.07
H13	0.97	52.8	26.8	1.97
H14	0.43	21.7	23.4	0.93
H15	0.23	7.5	17.0	0.44
H16	0.20	11.4	25.1	0.45
H17	0.45	35.0	36.6	0.96
H18	0.42	14.2	17.0	0.83
H19	0.23	11.4	23.0	0.50
H20	0.24	8.1	17.0	0.47
Mean	0.46	27.6		1.01
Min	0.20	7.5		0.44
Max	0.99	77.5		2.07

Table A.5 Summary of mechanical extract rates

Property details	Extract rates				
ID	Kitchen hood/ fan above cooker	Kitchen fan away from cooker	Bathroom	En-suite	WC
	l/s	l/s	l/s	l/s	l/s
P1	28.0		3.0	4.5	6.0
P2	31.0		1.5	7.0	3.0
H1	32.0		7.7	5.7	9.4
H2	28.0		6.0	15.0	
H3	27.9		17.0		
H4	9.0		14.9	3.4	12.1
H5		34.5	18.2		10.4
H6		32.7	4.5		3.6
H7		34.3	11.6		4.1
H8		Fan not working	15.1		
H9	25.6		13.3		16.3
H10	15.2		14.3		16.6
H11	21.6		11.1		
H12		34.0	10.3		3.9
H13	19.5		3.1		2.1
H14	15.1		18.5	17.8	
H15	Could not test[1]		15.7		
H16		35.0[3]	5.2		17.0
H17	25.5		5.8	6.2	
H18	21.6				
H19	28.8		2.2[2]	7.0	
H20	21.6		19.1[2]		
Mean	23.4	34.2	10.4	8.3	8.7
Min	9.0	32.7	1.5	3.4	2.1
Max	32.0	35.0	19.1	17.8	17.0

1 Fan fitted but unable to achieve a sufficient seal for test.
2 Difficult to seal to undertake test.
3 Tested without diffuser.

Table A.6 Summary of average relative humidity levels over monitoring period

Property details	Relative humidity				
ID	**Outside**	**Bathroom**	**Kitchen**	**Living room**	**Bedroom**
	% RH	**% RH**	**% RH**	**% RH**	**% RH**
H1	78.4	48.2	45.9	46.7	50.4
H2	70.1	63.4	57.0	62.2	60.3
H3	71.7	43.4	46.4	42.6	43.1
H4	60.2	43.0	39.0	36.1	39.8
H5	73.6	55.1	55.3	52.5	53.9
H6	n/a	47.6	46.9	44.4	46.8
H7	74.2	55.7	50.3	53.8	53.7
H8	73.6	63.7	53.1	53.6	58.1
H9	67.6	54.4	51.6	42.6	46.0
H10	68.8	49.1	48.1	41.2	42.5
H11	71.3	52.7	57.6	61.2	65.0
H12	67.5	57.1	52.4	52.3	56.0
H13	62.8	45.3	37.8	36.6	41.8
H14	62.6	53.7	52.7	51.8	54.5
H15	70.5	67.5	56.6	58.1	61.2
H16	n/a	66.8	60.0	66.3	62.4
H17	71.8	52.1	49.9	48.8	52.3
H18	61.0	60.6	46.5	54.1	58.7
H19	67.2	56.1	48.1	48.6	49.9
H20	69.2	71.0	53.6	58.6	71.0
Mean	69.0	55.3	50.4	50.6	53.4
Min	60.2	43.0	37.8	36.1	39.8
Max	78.4	71.0	60.0	66.3	71.0

Table A.7 Summary of maximum average daily relative humidity levels

Property details	Relative humidity			
ID	Bathroom	Kitchen	Living room	Bedroom
	% RH	% RH	% RH	% RH
H1	49.7	49.4	51.0	52.3
H2	66.8	64.3	68.9	63.8
H3	45.8	49.4	46.0	45.6
H4	48.3	46.5	46.6	47.3
H5	58.8	60.2	56.1	58.9
H6	52.3	50.5	47.7	49.8
H7	58.2	52.9	55.4	55.2
H8	66.9	55.5	55.9	60.3
H9	58.3	53.9	45.0	49.3
H10	52.8	49.7	43.9	44.7
H11	61.2	59.8	63.3	66.9
H12	66.3	60.4	60.2	64.0
H13	50.2	41.2	38.6	44.9
H14	55.8	56.1	54.3	56.9
H15	73.8	60.3	60.4	62.9
H16	82.2	63.6	70.1	65.4
H17	59.2	58.8	54.2	59.2
H18	64.8	51.7	60.9	65.1
H19	58.3	50.5	51.4	51.7
H20	73.5	55.5	60.6	73.5
Mean	60.2	54.5	54.5	56.9
Min	45.8	41.2	38.6	44.7
Max	82.2	64.3	70.1	73.5

Table A.8 Nitrogen dioxide results (averaged over one week)

Property details		Nitrogen dioxide levels	
ID	**House type**	**Kitchen**	**Outside**
		µg.m^{-3}	**µg.m^{-3}**
P1[1]	Semi-Det	31.0	33.9
P2[1]	Semi-Det	17.6	39.9
H1[1]	Detached	15.9	21.2
H2[1]	Detached	19.2	31.4
H3[1]	Detached	12.9	21.1
H4[1]	Detached	24.2	31.6
H5[1]	Terrace-End	56.6	21.4
H6[1]	Terrace-Mid	26.2	21.9
H7[1]	Terrace-End	47.3	21.5
H8	Terrace-Mid	23.8	21.8
H9	Terrace-End	19.3	35.5
H10	Terrace-Mid	18.5	40.3
H11	Flat	11.4	33.3
H12[1]	Semi-Det	22.9	13.2
H13[1]	Detached	16.1	19.5
H14[1]	Semi-Det	17.4	18.9
H15	Flat	9.6	22.9
H16[1]	Semi-Det	55.0	26.1
H17[1]	Detached	44.8	2.4
H18	Flat	9.6	18.1
H19	Flat	7.9	*
H20	Flat	11.3	31.1
Mean		23.6	25.1
Min		7.9	2.4
Max		56.6	40.3

* Sample missing.

[1] Gas cooking.

Table A.9 Total volatile organic compounds (TVOCs) results (averaged over one week)

Property details	TVOC levels		
ID	Living room	Master bedroom	Outside
	$\mu g.m^{-3}$	$\mu g.m^{-3}$	$\mu g.m^{-3}$
P1	53	<40	<40
P2	<40	231	<40
H1	168	224	<40
H2	285	464	103
H3	<40	156	<40
H4	112	320	<40
H5	90	111	<40
H6	114	204	<40
H7	708	976	<40
H8	219	311	<40
H9	251	330	<40
H10	191	171	<40
H11	n/a	n/a	n/a
H12	n/a	n/a	n/a
H13	n/a	n/a	n/a
H14	n/a	n/a	n/a
H15	n/a	n/a	n/a
H16	n/a	n/a	n/a
H17	n/a	n/a	n/a
H18	1147	1213	<40
H19	572	446	<40
H20	56	535	<40
Mean	264	379	<40
Min	<40	<40	<40
Max	1147	1213	103

Table A.10 Formaldehyde results (averaged over three days)

Property details	Formaldehyde levels		
ID	Living room	Master bedroom	Outside
	$\mu g.m^{-3}$	$\mu g.m^{-3}$	$\mu g.m^{-3}$
P1	10.5	15.5	0.8
P2	15.9	19.0	6.3
H1	21.9	30.2	0.9
H2	21.2	31.0	6.7
H3	19.9	18.9	1.1
H4	12.0	24.5	2.4
H5	16.3	16.4	1.3
H6	24.0	29.0	2.0
H7	63.0	54.0	1.8
H8	14.0	22.3	3.0
H9	24.0	31.0	1.0
H10	11.7	11.4	1.8
H11	37.0	37.0	2.3
H12	19.2	19.6	2.4
H13	10.2	13.1	2.8
H14	25.2	32.0	0.9
H15	55.0	46.0	1.6
H16	46.0	36.0	1.6
H17	14.8	24.8	1.8
H18	35.0	31.0	1.5
H19	25.0	28.1	0.6
H20	27.0	50.0	2.0
Mean	24.9	28.2	2.1
Min	10.2	11.4	0.6
Max	63.0	54.0	6.7

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