VENTILATION AND INDOOR AIR QUALITY IN NEW HOMES

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ABSTRACT

Building Regulations in England and Wales require that there is adequate provision for ventilation in new homes and guidance on meeting the requirement is primarily based on the need to control moisture. The guidance was last amended in 1995 and as part of the preparation for a further review BRE undertook a study of ventilation and indoor air quality in homes in England built since 1995.

The main part of the project involved a winter and summer period of monitoring of nitrogen dioxide, carbon monoxide, formaldehyde, volatile organic compounds, particulates, temperature and humidity in 37 homes. Concurrent with pollution measurements were measurements of the rate of air exchange of the indoor air with the outdoors using a perfluorocarbon tracer (PFT) technique. The air tightness of the structure was also determined for each home using a pressurisation test. Subsequently more detailed measurements of pollutants and ventilation were undertaken in five homes. The relationships between house characteristics, occupant behaviour, ventilation rate and concentration of pollutants were assessed and the indoor air quality evaluated with respect to available guidelines.

INTRODUCTION

The quality of indoor air is of concern because population exposure to air pollutants occurs mostly within buildings, particularly within the home, and because poor indoor air quality has been related to complaints by occupants of adverse health and discomfort. Through regulation, governments at national and international level have applied controls on sources of ambient air pollution and required monitoring of levels of certain pollutants such as nitrogen dioxide, particulates and benzene in order to assess the effectiveness of the controls.

The ambient air that enters the building by infiltration and intentional ventilation determines a baseline indoor air quality. During the process of infiltration through small gaps in the structure and when indoors, its composition is modified by interaction with surfaces and by physical and chemical changes in the airborne gases, vapours and particles. Surface interaction may involve sorption of moisture and chemicals which may be later released back into the air when conditions such as temperature and humidity change. The ambient air entering the home will also change by being mixed with air that has been resident in the building for some time. This indoor air will contain gases, vapours (including water and chemicals) and particles released by the many sources of indoor air pollutants present in all homes. These indoor generated pollutants may also interact with surfaces and undergo secondary reactions within the home [1, 2].

Over time the same volume of air will leave the home as entered. Therefore the concentration of contaminants in the indoor environment is in a continued state of flux depending on air exchange rate, the quality of the ambient air, air mixing efficiency, strength of internal sources, chemical reactions and loss of contaminants from the air because of internal sinks.

Prior to the 1990s there were few studies of indoor air quality in UK homes and those that were undertaken focussed on concerns about single pollutants. For example in the late 1970s the influence of gas cookers on the concentration of nitrogen dioxide was reported [3]. During the 1980s formaldehyde vapour was associated with incidents of complaints by some occupants of homes shortly after the installation of urea formaldehyde foam insulation [4] and there was some concern about formaldehyde in dust [5]. Radon in buildings was of concern and national and regional studies were set up to determine the distribution of exposures for the UK population [6].

In 1990 the UK Department of the Environment published the White Paper 'This Common Inheritance' which recognised the importance of indoor pollution for public health. This resulted in the Indoor Environment Study being undertaken by BRE to determine concentrations of nitrogen dioxide, volatile organic compounds (VOCs) and biological particulates in 174 homes over a 12 month period [7]. It was noted that other pollutants were also of concern, including non-biological particulates, semi- and very volatile organic compounds and carbon monoxide, but these were not included because of resource constraints and a lack of appropriate methods. Radon was not included as it was the subject of other major studies. During the course of the study the need for information about levels of indoor air pollutants was endorsed by a House of Commons Select Committee investigation. Evaluation of the significance of findings from indoor air pollution research in the UK was undertaken by the MRC Institute for Environment and Health [8].

In 1997 the Department of the Environment commissioned BRE to undertake a nationally representative survey of a number of indoor pollutants in England. This study achieved measurements of formaldehyde, VOCs, nitrogen dioxide and carbon monoxide in nearly 900 homes. The study produced a database for IAQ in England and established links between some housing characteristics, occupant activities and levels of pollutant [9, 10]. For example mean formaldehyde concentrations tended to be higher in new homes, VOCs were strongly influenced by painting and decorating activities and nitrogen dioxide and carbon monoxide levels were higher in homes with a gas cooker. BRE also undertook more focussed studies for particular pollutants such as benzene in homes with attached garages [11], formaldehyde in new homes [12], the emission of combustion gases from gas cookers [13] and VOCs from construction products [14], and the study of personal exposure [15].

These and other studies had identified the importance of indoor air and indoor sources for personal exposure to air pollutants and identified house characteristics associated with higher pollutant levels. However none of the studies involved determination of air exchange rate which is an important factor determining the indoor concentration of pollutants. This was in part because of a resource issue and also because of recognised technical difficulties of determining air exchange rate safely in a normally occupied home.

As part of the preparation for a periodic review of the Building Regulations in England and Wales, the Office of the Deputy Prime Minister (ODPM) commissioned BRE to undertake concurrent air quality and air exchange rate measurements in a group of homes built since 1995. The relevant part of the Regulations Part F, and its Approved Document F (ADF), were last revised in 1995 [16]. ADF gives guidance on local air extraction from ‘wet’ rooms, provision for rapid ventilation and for background ventilation throughout the home. The provisions are intended for the occupants to achieve a whole house background air exchange rate of about 0.5 air changes per hour (ach) which is considered necessary for the control of moisture. This paper summarises the work undertaken to validate a method for measuring air exchange rate in occupied homes and to assess air quality and rates of air exchange occurring in a group of homes built since 1995. Full details of this study involving 37 homes are available in a BRE report [17].

DESIGN AND METHODS

There were three main stages to the study;

1. validating a tracer gas method based on release of a tracer gas over a two week period to determine the mean air exchange rate of a home,

2. measuring air quality parameters and simultaneous measurement of air exchange rate and also the determination of airtightness for a group of 37 homes for one study period in winter and one in summer,

3. undertaking more detailed studies in 5 homes with a focus on short term peak concentrations of pollutants.

Validating PFT method for air exchange rate measurement

This involved experiments in BRE test houses to compare measurements of air exchange rate determined by using sulphur hexafluoride (SF_6) as a reference method and a perfluorocarbon tracer (PFT) as the test method. The PFT compound used was PMCH (perfluoromethylcyclohexane).

The first tests were undertaken in an unoccupied end of terrace house (ET) test house in winter 1999/2000 and spring 2000. The house was of timber framed construction, with weather-boarding to the front and back facades above the ground floor windows, other areas being brick clad. For the measurements reported here the test house was set-up with all internal doors open and a normal heating cycle was applied. The only purpose provided ventilation devices used were the trickle vents mounted just above the windows. Three periods of test were undertaken, each of two weeks. For two periods the trickle vents were open and for one they were closed.

Further tests were undertaken during 2002 using a matched pair of detached houses that were constructed with a traditional brick/block frame and cavity wall insulation. One house (D1) was set up with intermittent extract fan operating in the kitchen and bathroom and in the other (House D2) the extracts were on continuously for the test period. Trickle vents were fully open in all tests.

The SF_6 and PFT methods were applied as constant injection methods for determination of air exchange rate. A constant injection of SF_6 tracer gas supplied by cylinder was maintained at up to eight locations in each house and the SF_6 was monitored using an infra red analyser in each location at approximately 30 minute intervals. PFT sources that emit at a known rate that is diffusion controlled were distributed in each room in each house, with the source strength weighted by room volume. Steel tubes containing an adsorbent were placed in each room to determine the PFT concentration in air. After each experiment the PFT samplers were analysed by automated thermal desorption with gas chromatography and electron capture detection (ATD/GC/ECD).

Study of IAQ and ventilation in homes

This main part of the project involved a winter (January to March 2002) and summer (2002) period of monitoring of nitrogen dioxide (NO_2), carbon monoxide (CO), formaldehyde, volatile organic compounds (VOCs), particles (PM_{10}), temperature and humidity in 33 homes. A further four homes used for pilot investigations were also incorporated in the study. The 37 homes included different types of dwellings in various locations in southern England. Thirty four homes had mechanical extract ventilation and three had passive stack ventilators. All homes in the study had central heating with radiators. Three homes used only electricity for cooking, 11 homes used only gas as cooking fuel and 23 homes used both electricity and gas for cooking.

Measurements of airtightness of the house with windows and doors closed, expressed as ach at 50 Pa, were undertaken using a fan pressurisation technique prior to the monitoring of indoor pollutants. The indoor pollutants, except PM_{10}, were measured using diffusive samplers with an exposure period of three days to two weeks, depending on the pollutant. PM_{10} was measured using a pumped gravimetric method with a sampling period of 24 hours. Information was collected about the characteristics of the properties and the activities of occupants using questionnaires. Concurrent with the pollution measurements, the PFT was used to determine the mean rate of air exchange of the indoor air with outside air for the two week period.

Peak levels study

During the winter 2002/3, more detailed studies were undertaken in five homes. These homes were selected to include those with the highest levels of indoor pollutants. For these, short term pumped sampling of pollutants was applied as well as longer term diffusive sampling. Ventilation rate measurements were also undertaken.

RESULTS

Table 1 shows results of the validation tests of the PFT method for measuring air exchange rate in homes. These show good agreement between the two methods of measurement with most tests being within 10% and the greatest difference being 20%. Table 2 summarises the results of measurements of air exchange rate and the air tightness tests in the main study of 37 homes.

Table 3 summarises the measurements of some of the IAQ parameters in the main study. Data is presented for the living room (except PM_{10} in kitchen) although measurements were also undertaken in other rooms and outdoors. Data for individual VOCs is also available in the BRE report [17].

Table 1 Results of PFT method validation in test houses

House	Period	Air exchange rate [h^{-1}]		Conditions
		SF_6	PFT	
ET	1	0.48	0.51	Trickle vents open
	2	0.38	0.35	Trickle vents open
	3	0.16	0.17	Trickle vents closed
D1	1	0.26	0.23	Internal doors open, windows closed
	2	0.21	0.21	Internal doors open, windows closed
	3	0.14	0.17	Internal doors intermittently open, windows closed
	4	0.22	0.20	Internal doors and windows intermittently open
D2	1	0.44	0.41	Internal doors open, windows closed
	2	0.42	0.35	Internal doors open, windows closed
	3	0.35	0.39	Internal doors open , windows open intermittently
	4	0.35	0.28	Internal doors and windows open intermittently

Table 2 Summary of measurements of two week mean air exchange rate and air tightness (air exchange rate at 50 Pa) in main study

statistic	Winter ach	Summer ach	Air tightness at 50 Pa ach
Arithmetic Mean	0.44	0.62	12.9
Stand. Deviation	0.11	0.23	3.7
Geometric Mean (GM)	0.43	0.57	12.3
Minimum	0.19	0.19	4.8
Maximum	0.68	1.06	20.2

Table 3 Summary of results of IAQ measurements in 37 homes in the main study

Season	statistic	CO ppm	NO_2 ppb	PM_{10} ($\mu g\ m^{-3}$)	HCHO ($\mu g\ m^{-3}$)	TVOC ($\mu g\ m^{-3}$)	RH (%)
winter	GM	0.1	7.9	22.3	23.8	137	42
	min	0.0	2.8	10.2	10	48	22
	max	0.7	21.9	112.9	75	713	61
summer	GM	0.2	8.9	49.1	26	160	52
	min	0.1	3.6	21.2	1	63	32
	max	0.4	18.9	133.7	61	365	63

The results from the measurements were statistically analysed, based on data from questionnaires, including house characteristics and occupant activity diaries. The main results from the measurements and the statistical analysis may be summarised as follows:

Ventilation

In winter, 68% of homes had a whole house ventilation rate below the minimum design value of 0.5 ach, which according to BRE research is necessary to avoid condensation. In summer, 30% of homes had a whole house ventilation rate below 0.5 ach. Homes where windows were open ‘most or all of the time’ had significantly (probability of ≥95%) higher ventilation rates than other homes, both in winter and summer.

There was no statistically significant relationship between the reported use of trickle vents and extract fans on ventilation rates in winter. The trickle vents were fully open in only 4 of the study homes and fully closed in 13. However, homes where trickle vents were used ‘most or all of the time’, as recorded by the occupiers, had significantly higher ventilation rates than other homes, in summer. Also, homes with the lowest ventilation rates in winter had the trickle vents fully closed. This indicates that the lack of use of trickle vents is an important reason for the ventilation rate being below the design value of 0.5 ach in many homes.

The ventilation rate was not correlated with the air leakage rate. This shows that factors other than the airtightness of the structure, such as the behaviour of occupants with respect to provision of ventilation are significant determinants of the ventilation rate. The mean air leakage rate was similar to that found for the general UK housing stock in a previous study (13.1 ach at 50 Pa in a sample of 471 dwellings [18]). It is noticeable that 70% of homes had air leakage rates greater than the recommended value of 10 $m^{-3}h^{-1}m^{-2}$ envelope area at 50 Pa, which can be approximated to 10 ach at 50 Pa, in Approved Document L1 of the Building Regulations.

Indoor air pollutants

Two-week mean CO concentrations did not exceed the World Health Organisation (WHO) 8-hour average guideline [19] of 8.6 ppm in any home in the main study of 37 homes, but exceeded the 1-h and 8-h WHO guidelines in one home with gas cooking, in the winter peak level study of 5 homes.

In the main study, two-week mean NO_2 concentrations from diffusive sampling exceeded the WHO annual NO_2 guideline of 21 ppb in six homes in winter. All of these (apart from one) used gas as cooking fuel. In summer, only one home with gas cooking exceeded the above guideline. In the peak level study, the one-week NO_2 concentrations from active sampling in winter exceeded the WHO annual mean of 21 ppb in the kitchen of one home with gas cooking. The 1-hour guideline of 105 ppb was exceeded in three homes with gas cooking in winter and in the kitchen of two homes in summer.

In winter, the 24-h PM_{10} concentrations in kitchens were below the UK Air Quality Strategy ambient air quality objective of 50 $\mu g\ m^{-3}$ (24-h mean) except in two smoker’s homes. In summer, the air quality objective was exceeded in 14 out of 34 homes. In the peak level study, the air quality objective for PM_{10} was exceeded only in one home with cigarette smoking, both in winter and summer.

The main factors influencing the levels of inorganic gases were gas cooking, occupancy (with households with more people having higher pollutant levels) and location (with highest values in towns and lower levels in suburban and rural areas). There was no significant difference between these groups in the levels of indoor PM_{10}.

The three-day mean formaldehyde (HCHO) concentrations were within the WHO air quality guideline of 100 $\mu g\ m^{-3}$ for a 30-minute exposure period, both in winter and summer main study. In the peak level study, three-day mean formaldehyde concentrations in summer exceeded the 30-minute WHO guideline of 100 $\mu g\ m^{-3}$ in the second bedroom of two homes, and a 30-minute measurement exceeded the guideline in one home.

In winter, the two-week mean total volatile organic compounds (TVOC) concentrations exceeded 300 $\mu g\ m^{-3}$ in three homes. There are no WHO or UK guidelines for TVOC concentrations in indoor air, but 300 $\mu g\ m^{-3}$ has been proposed by some groups [20]. In summer, TVOC concentrations in nine homes exceeded 300 $\mu g\ m^{-3}$. In the winter peak level study, two-week mean, whole house TVOC concentrations exceeded 300 μgm^{-3} in three homes. The highest reading for any location was 643 μgm^{-3} (in second bedroom). In the summer peak level study, two-week mean TVOC levels were within the recommended guideline levels only in one home with high average ventilation rates (1.18 ach).

TVOC levels were influenced by the age of home, with the newest homes having the highest mean levels, in the living room and bedroom. TVOC concentrations were significantly higher in homes where painting had been done in the previous four weeks, both in winter and summer. In summer, TVOCs in bedrooms were significantly lower in homes with bedroom windows or trickle vents being open more. When homes were placed into three groups of lower, medium and higher air exchange rate, homes with the lower rate had significantly higher concentrations of TVOC. This was statistically significant for living rooms in winter and for bedrooms in summer.

The home average relative humidity in summer (mean: 52%, range 41%-63%) was higher than the corresponding winter results. There were no significant correlations between the relative humidity and measured hours of extract fan use, in winter or summer. The occupants reported that condensation was ‘no problem at all’ in 24 of the 37 homes studied and in one home the occupants regarded it as a ‘severe problem’. This was a two bedroom flat with four occupants, and during the winter monitoring period the air change rate (0.48 ach) and whole house humidity (49%) were similar to the average value for the 37 homes. In the peak levels study, one of the 5 homes which had the lowest ventilation rate (0.19 ach) and the lowest temperature (home average 13 ^{o}C), had periods during the winter monitoring period when RH was greater than 70% for more than two hours, ranging from 20% of the time in the kitchen to 0% in the living room and bedroom 1.

CONCLUSION

The study provides a snapshot of ventilation and indoor air quality (IAQ) in a small sample of a range of types of homes built since 1995. It is unique in the UK by combining simultaneous measurements of ventilation and IAQ together with records of occupant behaviour and household characteristics. Statistical analysis has been applied but the study is limited by the small number of homes and the large number of confounders for studying relationships between ventilation and IAQ.

The present study shows that ventilation rates can be below design values and guidelines for air quality can be exceeded in some homes. Further work is therefore required in order to understand the factors producing these adverse conditions, in order to provide guidance on prevention without unacceptable high ventilation rates. In particular, the studies should focus on the use of the ventilation provisions, such as trickle vents and extract fans, in a controlled manner, in order to evaluate benefits for

IAQ and ventilation that would be achieved by more knowledgeable occupants and/or changes to the provision. A further issue is evaluation of the benefit of further source control, such as reductions in the emission of VOCs from products in the home, in order to reduce indoor concentrations without increasing rates of ventilation.

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REFERENCES

1. Weschler C (2002). Connections: Particles, sensory offending filters, the 'sink' effect and nasal pungency thresholds. Proceedings of Indoor Air 2002, 1, 1-11, Monterey, July 2002.

2. Rohr (2003). Indoor chemistry and health: where are we going? Proceedings of Healthy Buildings 2003, 1, 301-307.

3. ECA (1989). Indoor pollution by nitrogen dioxide in European countries. European Concerted Action on Indoor Air Quality and its Impact on Man, report no. 3, EUR 12219 EN, Commission of the European Communities, Luxembourg.

4. Crump D and Gardiner D (1987). Sources and concentrations of aldehydes and ketones in indoor environments in the UK. Proceedings of Indoor Air'87, 2, 666-670, Berlin, August 1987.

5. Brown V, Crump D and Gardiner D (1988). Sources and concentrations of formaldehyde in household dusts. In: Perry R and Kirk P. Indoor and Ambient Air Quality, 423-430, Selper Ltd, London.

6. Brown L, Green B, Miles J and Wrixon A. (1984). Radon exposure of the UK population. Proceedings of Indoor Air'84, 2, 61-66, Stockholm, August 20-24 1984.

7. Berry R, Brown V, Coward S, Crump D, Gavin M, Grimes C, Higham D, Hull A, Hunter C, Jeffrey I, Lea R, Llewellyn J and Raw G (1996). Indoor air quality in homes, The Building Research Establishment Indoor Environment Study, BRE Reports BR299 and BR300, CRC Ltd, Watford, UK.

8. IEH (2001). Indoor air quality in the home: Final report on DETR contract EPG 1/5/12. Institute for Environment and Health, Leicester, UK. (www.le.ac.uk/ieh/publications)

9. Coward S, Llewellyn J, Raw G, Brown V, Crump D and Ross D (2001). Indoor air quality in homes in England. BRE Report BR 433, CRC Ltd, Watford, UK.

10. Coward S, Brown V, Crump D, Raw G and Llewellyn J (2002). Indoor air quality in homes in England: Volatile organic compounds. BRE Report BR 446, CRC Ltd, Watford, UK.

11. Mann H, Crump D and Brown V (2001). Personal exposure to benzene and the influence of attached and integral garages. J Royal Society for the Promotion of Health, 121, 1, 38-46.

12. Mann H and Crump D R (1999). Formaldehyde in new and refurbished homes
Proceedings of the 8th International conference on Indoor Air Quality and Climate (Indoor Air'99), Edinburgh, 8-13 August 1999, Vol. 4, p. 153-158.

13. Ross D and Wilde D (1999). Continuous monitoring of nitrogen dioxide and carbon monoxide levels in UK homes. Proceedings of 8th Int. Conf. on Indoor Air Quality and Climate, Scotland, August 1999, Vol. 3, pp. 147-152.

14. Yu C and Crump D (2002). VOC emissions from building products. BRE Digest 464. CRC Ltd, Watford, UK.

15. Crump D R, Bland B, Mann H, Brown V M and Ross D (1999). Personal Exposure to air pollutants in Herts, England. Proceedings of the 8th International conference on Indoor Air Quality and Climate (Indoor Air'99), Edinburgh, 8-13 August 1999, Vol.5, p. 288-293.

16. DoE (1995). The Building Regulations 1991 – Approved Document F: Ventilation. HMSO, London, ISBN 0-11-752932-X.

17. Dimitroulopoulou S, Crump D, Coward S, Brown V, Squire R, Mann H, White M, Pierce B and Ross D (2004), Ventilation, air tightness and indoor air quality in homes in England built after 1995. BRE report (in press), CRC Ltd, Watford, UK.

18. Stephen R (1998). Airtightness in UK dwellings: BRE's test results and their significance. BRE Report 359, BRE, Watford, UK.

19. WHO (2000). Air quality guidelines for Europe. World Health Organisation Regional Office for Europe, European Series No. 91, Copenhagen.

20. Crump D, Raw G, Upton S, Scivyer C, Hunter C and Hartless R (2002). A protocol for the assessment of indoor air quality in homes and office buildings. BRE report BR 450, CRC Ltd, Watford, UK.