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Summary As fabric heat losses decrease with improved thermal insulation, ventilation heat losses, as a fraction of the total, become relatively more important. Thus, further effective energy savings may best be achieved by reducing energy losses associated with excessive ventilation. However, a means of measuring ventilation levels, or the magnitude of the air leakage paths through which ventilation takes place, is required to ensure that sealing of some openings does not result in unacceptably low ventilation rates and the accompanying risks of condensation, mould and poor indoor air quality. The fan-pressurisation technique does not measure ventilation rate directly, but air leakage data may be used for comparisons between houses and to predict ventilation rates which would occur under natural conditions. Air leakage data for a sample of 32 traditionally constructed Scottish dwellings are presented and discussed. The mean air leakage rate in these dwellings was found to be 60% higher than that found in a sample of 100 dwellings throughout the UK. It is concluded that there is considerable scope for reducing air leakage rates, and therefore ventilation heat loss, in many Scottish dwellings.

Ventilation and the leakage characteristics of dwellings

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1 Introduction

Housing consumes almost 28% of the total energy used in the United Kingdom, at a cost of about £9.6 thousand million(1). Until now priority has been given to the provision of additional thermal insulation and proposed new Building Regulations(2) will introduce more stringent thermal insulation standards in new buildings. However, as fabric heat losses decrease with better thermal insulation, ventilation heat losses as a fraction of the total become relatively more important, rising from around 20% to about 50% of the total design heat loss(3). This implies that further cost-effective energy savings may best be achieved by reducing energy losses associated with excessive ventilation.

Elimination of excessive ventilation requires some form of ventilation control but, in practice, this can be difficult. Most British dwellings are naturally ventilated, with air entering or leaving the living space, for the most part completely uncontrolled, via myriad small adventitious openings all over the structure. Furthermore, even in apparently identical dwellings, the number, location and characteristics of these openings can be very different. A means of measuring these openings (i.e. air leakage measurement) is therefore required to ensure that sealing of some openings does not result in unacceptably low ventilation rates and the accompanying risks of condensation and poor indoor air quality. The fan-pressurisation technique, described in this paper, is a quick and convenient means of measuring air leakage.

The shape of the house and type of surrounding terrain should also be considered when attempting to control natural ventilation by limiting the size, type and/or number of openings. Mathematical models for predicting natural ventilation rates in dwellings are now coming into use; these use basic data on such factors plus air leakage data as inputs.

This paper contrasts the methods available for ventilation rate measurements with the method of measuring air leakage, for they are not the same. Air leakage data for a sample of traditionally constructed Scottish dwellings are presented and discussed.

2 Ventilation of domestic buildings

2.1 *Fresh air requirements*

The provision of a supply of fresh air into a building is necessary to dilute common contaminants (carbon dioxide, body odours, tobacco smoke etc) to acceptable concentrations for the health and comfort of the occupants, and may in some cases be required to ensure the safe operation of an open-flued appliance. Ventilation is also important to avoid the build-up of water vapour and to prevent excessive relative humidity which can lead to condensation problems(4,5). The Building Regulations for England and Wales(6) and the Scottish Building Standards(7) specify minimum ventilation requirements, as shown in Table 1.

This supply of fresh air could be provided by a properly designed mechanical ventilation system, but this has the disadvantage of high initial capital cost, running and maintenance costs. The alternative is to use the natural movement of air through the building due to wind and temperature differences. This is the method which is used almost universally in British dwellings.

Table 1 Building regulations minimum ventilation

Room type	Air change rate (ac h^{-1}) or air flow per person ($m^3\ s^{-1}$)†	Minimum ventilator opening as proportion of floor area‡ (%)
Living	0.3–0.8 $m^3\ s^{-1}$	5
Kitchens	6 ac h^{-1}	5
Bathrooms and WCs	3 ac h^{-1}	5

† Scottish Building Standards
‡ Building Regulations—England and Wales

2.2 Natural ventilation

Natural ventilation occurs in a house as a result of pressure differences generated across open areas in the structure. These open areas can be divided into two categories, purpose-provided and adventitious.

Guidance is given for building designers on the number and location of purpose-provided openings[8] (openable windows, air bricks etc) which should be allowed for to meet normal fresh air requirements. The air flow through these openings can be controlled by the occupant to some extent. However, in addition to those planned areas for natural ventilation, there is always an uncontrolled leakage of air through adventitious openings. This component of natural ventilation is termed air infiltration; this can lead to excessive ventilation heat loss.

The pressure differences which induce the flow of air through both purpose-provided and adventitious openings are caused by the action of wind (wind effect) and buoyancy (stack effect)[9]. The wind generates a pressure distribution over the external surface of the dwelling, the nature of which is related to wind speed and wind direction as well as the shape of the house and the nature of its surroundings. Ventilation due to buoyancy is a function of the differences between the internal and external temperatures of a heated house, which creates density and hence pressure differences across the structure. The stack effect is generally small in relation to wind pressures, except in the case of tall buildings with vertical shafts or where an open flue is installed.

3 Review of measurement techniques

3.1 Ventilation rate measurements—general

The ventilation rate of a space is conventionally expressed as a number of air changes per unit time. If the locations of air flow into a building were known, the total air flow could be measured, in theory, using conventional anemometric methods. This, however, is not the case, and this necessitates the use of indirect methods involving a tracer substance. An inert gas or vapour can be used provided it is non-toxic and can be easily measured over an appropriate range of concentrations. The three most widely used tracer methods are[10] exponential decay, constant gas emission and constant gas concentration.

3.2 Ventilation rate measurement by the decay method

For this measurement a quantity of tracer gas is released in the enclosure and thoroughly mixed, producing an initially high value of concentration. The air change rate is determined simply from the logarithmic gradient of the decay in the concentration of the tracer with time.

3.3 Ventilation rate measurement by constant gas emission

In this case pure tracer gas is injected continuously over the measurement period at a constant rate. To obtain adequate mixing, injection is normally at as many points as possible.

Over a long time the tracer concentration in the enclosure approaches an equilibrium value which is used to calculate the ventilation air change rate R.

The main difficulty with this method is that there is likely to be a long stabilisation period, normally several time constants (R^{-1}), before an equilibrium can be attained. Furthermore it is found that it is unusual for the concentration to remain constant over the period of the test due to changing weather conditions around the building[11]. This difficulty may be avoided by an alternative method in which the tracer concentration is measured at regular intervals and a ventilation rate calculated for each interval. An average value of ventilation rate is then found which removes fluctuations due to the changing weather conditions.

3.4 Ventilation rate measurement at constant concentration

This is a recent development which employs a microprocessor in a feedback loop from the measuring instrument to a tracer injection device. The injection rate is varied to keep the concentration at a constant value over the measurement period. The total amount of tracer injected and the concentration maintained are used to compute the ventilation rate.

3.5 Choice of ventilation rate measurement method

The particular technique which is finally chosen for any given application depends on the information required. If it is the rates of air movement between rooms in a house or between a house and its roof that are of interest, the decay method may be preferred, but if individual room ventilation rates to outside are required then the constant concentration method would be more appropriate. Constant injection is often used when time-averaged data are required.

Tracer methods are the only ones available for the direct measurement of naturally occurring air change rates in buildings. However there are several disadvantages associated with them.

(*a*) Single measurements are of limited value. Several tests are required to cover a range of meteorological conditions and they are therefore unsuitable for making a rapid check on building air change rates or for comparing the performance of different structures or retrofit measures.

(*b*) The accuracy of the method depends on the complete mixing of the tracer with the enclosure air and even with the use of mixing fans this can involve some difficulty.

(*c*) Tracer techniques are cumbersome for use in occupied dwellings, especially in the case of the constant concentration variant for which the equipment can be bulky.

3.6 Air leakage measurements

An alternative approach to the tracer gas methods described above involves the determination of the leakage characteristics of a building or its components. Air leakage characteristics can be obtained by measuring the flow rate of air q required to maintain a steady pressure difference (ΔP) across the building envelope. This flow rate, q, is termed the air leakage rate, and it is normal practice to measure q for a range of steady pressure differences up to 50 Pa.

The magnitude of air flow through any opening is a function of its geometry, the Reynolds number and the pressure difference.

For openings with a characteristic dimension greater than about 10 mm (e.g. airbricks and open windows and doors) the function of geometry and Reynolds number may be regarded as a constant and is usually referred to as the discharge coefficient[9]. For other types of openings such as cracks around windows and doors, the form of the function is much more complicated and it is necessary to determine the 'crack flow' relationship empirically. It is convenient

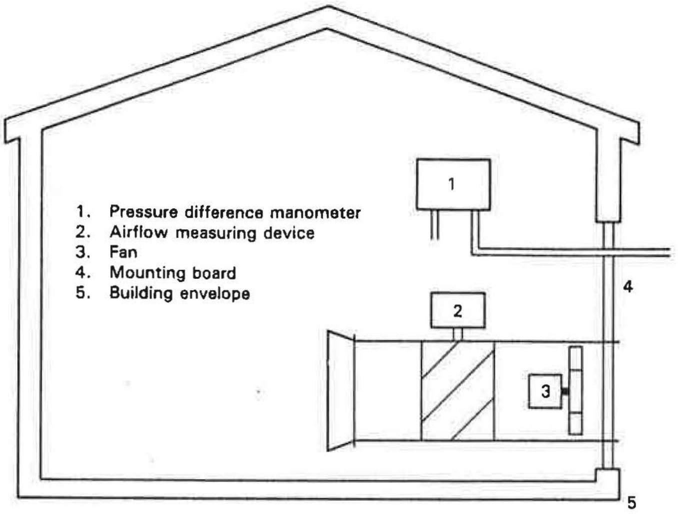

Figure 1 Fan pressurisation installation (schematic)

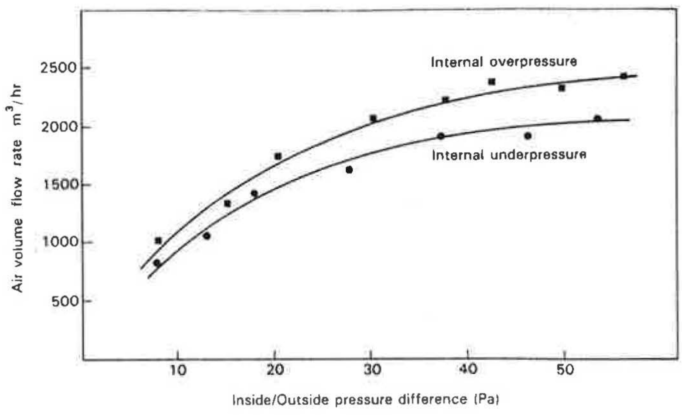

Figure 2 Typical house leakage characteristics

to fit measured values to a simple power law expression, generally of the form

$$q = K\,\Delta P^{n} \tag{1}$$

More complex expressions which can be more easily justified theoretically have been developed[12] but these are currently less widely used than the power law. Manufacturers and others have tested the leakage characteristics of building components in the laboratory for many years, but in recent years this technique has been extended to 'whole house' leakage testing. The design details of the apparatus used by experimenters to determine house air leakage characteristics vary, but the essentials of the method, described below, are the same.

A large variable-speed fan is sealed into a suitable opening in the external fabric of the dwelling, usually a doorway or window (Figure 1). The flow rate is measured corresponding to a range of pressure differences between 10 and 16 Pa and the results are presented as a curve of volume flow versus pressure difference (Figure 2). The equipment is normally designed so that the flow direction can be reversed and the leakage characteristics obtained for both positive and negative pressure differences. The curve of flow against pressure difference can be fitted by an expression of the form given in equation 1 and the constants k and n obtained.

The parameters k and n are useful in that they allow the data to be expressed in a simple form, but they do not represent any simple physical characteristics of the air leakage paths. Normally n is between 0.5 and 0.7.

Whole-house pressurisation testing is quick and easy and produces fundamental information on the airtightness of a structure. This information is independent of meteorological conditions as the measurements are taken in relatively calm weather and at pressure differences well above those generated across a structure by wind and temperature, which are normally of the order of 1 to 5 Pa[13]. While airtightness cannot as yet be directly related to ventilation rates occurring naturally, it is a measure of the 'ventilation potential' of a building. Several prediction models have been proposed which enable ventilation rates to be calculated from air leakage data[13–15]. However, all such models require information on the surface pressure coefficients for typical house shapes, arrangements, and surroundings, which is at present very limited.

When carrying out air leakage tests it is important to realise that the leakage measured represents not only the leakage to the outside but also any cross-leakage to adjacent houses. It is also observed that the results of pressurisation and depressurisation tests differ because of the effect of pressing open or sucking tight components such as windows and doors. Also, the flow characteristics of a complex air leakage path may depend upon the direction in which the air is passing through it.

At present the main applications for whole house fan pressurisation testing can be summarised as follows.

(*a*) Comparison of the airtightness of different buildings with each other and with airtightness standards.

(*b*) Assessment of retrofit measures to reduce air leakage.

(*c*) Determination of the potential, if any, for air infiltration reduction in a dwelling.

(*d*) To provide data for ventilation prediction models.

Table 2 Airtightness standards for Norway and Sweden expressed as maximum air change rates (ac h^{-1}) at 50 Pa

Country	Type of building	Leakage factor (ac h^{-1})
Sweden[17]	Detached and terraced, single-family houses	3.0
	Other residential buildings of not more than two storeys	2.0
	Residential buildings of 3 or more storeys	1.0
Norway[16]	Detached and terraced, single-family houses	4.0
	Other residential buildings of not more than two storeys	3.0
	Residential buildings of three or more storeys	1.5

In Norway and Sweden this technique is used routinely and strict standards of airtightness[16, 17] are recommended for all new buildings. These standards are given as allowable leakage rates expressed in air changes per hour at a generated pressure difference of 50 Pa, as shown in Table 2. In addition the authorities of the USA, Canada, Norway and Sweden have standard methods for the use of fan pressurisation equipment, although in North America no airtightness standards are reported[18-21]. In the UK the method is popular among researchers but commercial interest is only now beginning to grow. No British Standard Test Method has as yet been approved, but BRE have published a recommended procedure for pressurisation testing[22].

The pressurisation method is quick and simple to perform and is ideally suited to large scale testing in occupied dwellings. Therefore this measurement system has been adopted for the experimental work of this study.

4 Experimental

The purpose of the study was to collect data on the airtightness of traditionally constructed Scottish dwellings. Fan pressurisation and depressurisation experiments were carried out on a sample of 30 occupied homes from two local authority housing schemes in Glasgow. The sample of houses was selected to consist of six groups of five identical house designs.

4.1 Air leakage test equipment

A variety of fan pressurisation rigs have been developed in the United Kingdom, the main difference between them being the method used for measuring the air flow through the fan. The equipment for this work was designed and calibrated by the Building Research Establishment and is shown in Figure 3. The air volume flow rate is measured using an electronic vane anemometer fixed on the duct axis downstream of a honeycomb flow straightener. The fan speed is adjustable using a variac transformer and the pressure difference across the building envelope is measured using a digital micromanometer. A calibration equation for the apparatus, relating air volume flow rate to indicated anemometer velocity, was obtained using the BRE pressurisation fan calibration chamber.

4.2 Test dwellings—general

The homes investigated were chosen from two postwar peripheral housing schemes, Castlemilk and Cambuslang, which are located approximately seven miles from the centre of Glasgow. Testing was completed between November 1985 and February 1986, and specific dwelling types were selected to cover a range of sizes and a variety of room layouts.

4.3 Castlemilk dwellings

All of the dwellings tested in this area were flats of traditional cavity-brick construction with dual pitch roofs. They were built between 1958 and 1959 and have suspended timber floors. Only end terrace flats that were tested to ensure that most leakage areas would be to outside. The house constructions investigated in Castlemilk have been designated as house types 1–3; a brief description of each follows.

House type 1 are small purpose-built pensioners' flats of internal volume 101 m^3 with three rooms. They are 2-storey with wooden sliding-sash, single glazed windows.

House type 2 are 3-storey purpose built, step block flats. They have five rooms and a total internal volume of 152 m^3. All windows are single glazed casement, metal at the front and wooden at the rear. These are the only dwellings in the sample which have casement windows.

House type 3 are flats with a volume of 165 m^3 and five rooms. The windows are wooden sliding sash with single glazing. The building has three storeys.

4.4 Cambuslang dwellings

House types 4–6 are all of traditional cavity-brick construction with dual pitch roof and suspended floors. They were built between 1957 and 1958, and all have sliding-sash single glazed windows.

House type 4 are 2-storey end-terraced houses with five rooms and an internal volume of 165 m^3.

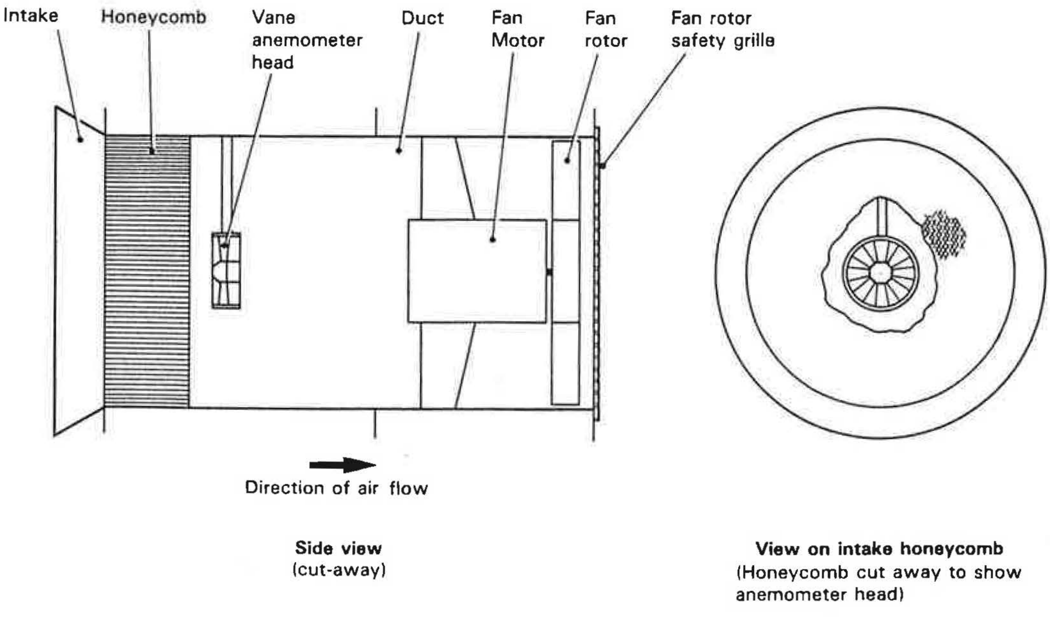

Figure 3 BRE pressurisation apparatus

House type 5 are purpose built, 3-storey flats, having five rooms, and an internal volume of 157 m^3.

House type 6 are small single-storey, semi-detached pensioners' houses with four rooms and a volume of 107 m^3.

4.5 Test procedure

A typical example of each house type was surveyed before testing began and all relevant construction details recorded for future reference. When the fan testing was being carried out, any differences between the dwelling under test and the standard information for that house type were carefully noted (e.g. extra ventilators, recently replaced windows etc).

The tests were arranged with the tenants on a day-to-day basis, as long term planning was not possible due to the influence of weather. It is recommended(22) that testing should not take place when the average wind strength is above force three on the Beaufort scale. As a large proportion of the dwellings in the sample had coal fires installed, at least one day's notice was required to ensure that fires were not burning on the day of the test.

On arrival at a dwelling, the following steps were carried out in order.

(*a*) *Wind strength check.* Wind strength was assessed according to the Beaufort wind scale both visually and with a hand-held anemometer. If the average wind force was greater than three, the test was postponed.

(*b*) *Preparation of dwelling.* All windows and adjustable openings not intended for ventilation purposes were closed. Mechanical extract devices were sealed. Chimneys were also sealed to prevent soot being sucked into the building. All internal doors were opened to allow free movement of air.

(*c*) *Setting up of equipment.* The pressurisation apparatus was mounted on a plywood board which was fitted and taped into the front doorway of the dwelling. A small-bore pressure difference tube was run from the inside through the mounting board to a T-piece connector. From this connector one tube was run to the front wall of the dwelling and the other to the back wall. Both tubes were terminated with an equal T-piece. The micromanometer and anemometer instruments were set up inside the dwelling.

(*d*) *Start of measurement.* With the fan at full speed ten pairs of pressure and flow readings were recorded and mean values obtained. The fan speed was adjusted and this procedure repeated for eight other pressure differences down to 10 Pa. The indoor air temperatures were measured in several rooms of the dwelling before, after, and during the test to give an average. The outside strength and direction, and outdoor temperatures were also noted before and after the test. The apparatus was then rearranged to extract air from the building (depressurisation test) and the above procedure repeated.

5 Results

The initial processing of results involved the calculation of mean outdoor and indoor temperatures. The mean anemometer values were then converted to give the air flow through the fan q_k in units of m^3h^{-1} using the calibration equation.

5.1 Indoor/outdoor temperature correction

The value q_k represents the volume flow rate of air through the pressurisation apparatus, which may not necessarily be the same as the volume flow of air through the building fabric because of differences between indoor and outdoor temperatures(22).

In the case of a pressurisation test, outside air is passed through the apparatus and into the building. This air then mixes with the indoor air and may change in temperature and hence volume. The indoor air temperature is normally higher, and so the volume flow out through the fabric of the dwelling is greater than the measured incoming flow. A correction was therefore applied to the value of q_k, such that

$$q_{\text{vout}} = q_k\left(\frac{T_i + 273}{T_o + 273}\right)$$

where q_{vout} is the leakage flow rate out of the dwelling (m^3h^{-1}), T_i is the indoor air temperature (°C), and T_o is the outdoor air temperature (°C).

A similar correction was applied to the depressurisation results, but in this case indoor air is passed through the apparatus. Thus

$$q_{\text{vin}} = q_k\left(\frac{T_o + 273}{T_i + 273}\right)$$

where q_{vin} is the leakage flow rate into the dwelling (m^3h^{-1}).

5.2 Curve fitting and extrapolation of results

The corrected data points were then used to generate a dwelling characteristic curve, and this allowed the leakage rate to be predicted for any chosen pressure difference. As mentioned in section 3.2, it is reasonable to assume a power curve fit for the leakage data which has the form

$$q = k\,\Delta p^n$$

A standard statistical package ('MINITAB' by Thomas A Ryan(23) was used to perform this curve fit. The data from the tests were analysed in parallel with the testing, as far as was possible, so that any invalid results could be quickly identified and the tests repeated.

5.3 Summary of test results

It was discovered that several tests had to be repeated as wind had affected the results, producing vastly different pressurisation and depressurisation curves, and poor correlation coefficients for the linear curve fit. It was observed that in some cases at relatively moderate wind speeds (= 2 on the Beaufort scale) it was difficult to obtain results due to wind 'tunnelling' through the stairways of some flats. Although guidance is given(22) on the range of wind speeds under which tests can be successfully carried out, it was found that local terrain and orientation could greatly affect the influence of wind on the measurements. It was, however, clear from the stability of the manometer readings at the time of test whether the results would be satisfactory.

Two additional dwellings of type 1 and type 5 were also located and tested, giving in total 32 measurements. Table 3 summarises the curve fit parameters for each test, along with the calculated air flow rate for a pressure difference of 50 Pa.

The fitted curves in all cases have correlation coefficients r^2 between 0.990 and 1.000 and the pressurisation and depressurisation curves agree closely; the depressurisation curve lies slightly below the pressurisation curve for most of the measurements. The separation of those curves increases with increasing wind speed.

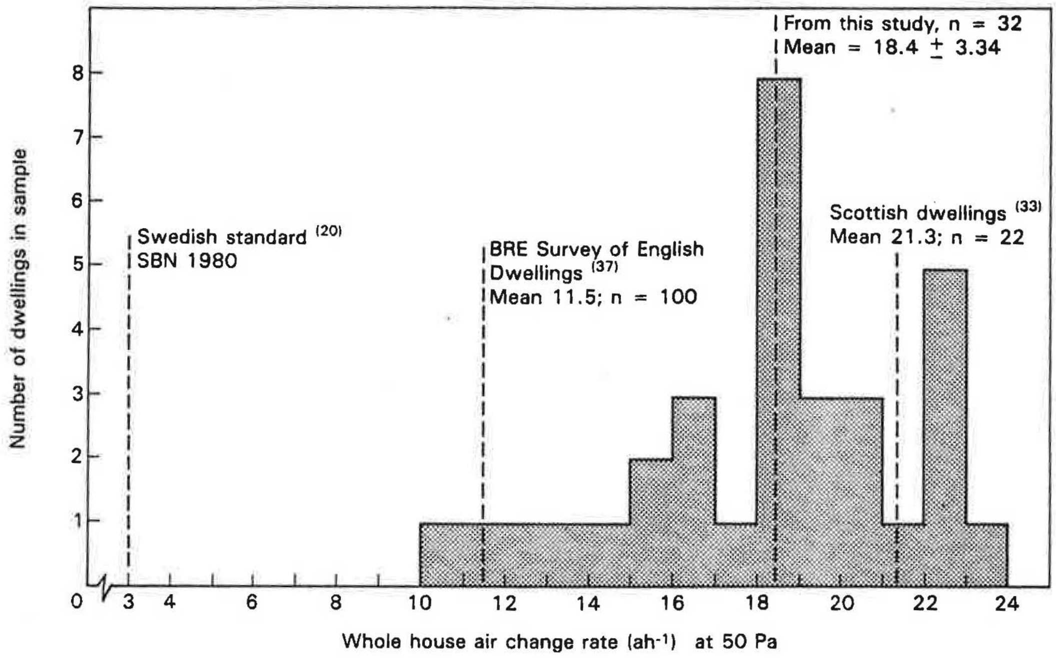

Figure 4 Comparison between results from sample houses and other leakage data

Table 3 Summary of test results

Dwelling type	House no.	Initial test results: Pressurisation K	n	r^2	$q50$	Depressurisation K	n	r^2	q_{50}	Averaged pressurisation and depressurisation results: Ave. q_{50}	$(ach^{-1})_{50}$
	1.1	212.5	0.584	0.999	2088	172.9	0.634	0.999	2064	2076	20.5
	1.2	140.1	0.620	1.000	1582	145.3	0.617	0.999	1625	1604	15.9
1	1.3	239.9	0.575	0.999	2271	189.5	0.634	0.998	2260	2266	22.4
	1.4	188.5	0.606	1.000	2014	175.9	0.613	1.000	1934	1974	19.5
	1.5	188.9	0.588	0.998	1888	174.2	0.610	0.993	1897	1892	18.7
	1.6	160.1	0.626	0.999	1853	169.2	0.622	0.999	1929	1891	18.7
	2.1	259.7	0.636	1.000	3124	268.5	0.613	0.999	2957	3040	20.0
	2.2	241.1	0.578	0.999	2314	158.9	0.676	0.994	2234	2274	15.0
2	2.3	233.8	0.594	0.998	2392	305.9	0.519	0.999	2329	2360	15.5
	2.4	270.5	0.572	0.999	2540	223.2	0.627	1.000	2595	2567	16.9
	2.5	225.7	0.167	0.999	2524	237.1	0.600	1.000	2480	2502	16.5
	3.1	226.0	0.645	0.998	2818	248.7	0.623	0.997	2845	2831	17.2
	3.2	406.7	0.580	0.993	3933	297.1	0.639	0.999	3618	3775	22.9
3	3.3	308.4	0.620	0.999	3487	308.2	0.611	0.999	3365	3426	20.8
	3.4	133.5	0.860	0.969	3860	334.3	0.609	0.999	3621	3740	22.7
	3.5	388.3	0.577	0.991	3711	175.2	0.774	0.992	3619	3665	22.2
	4.1	361.4	0.550	0.998	3111	256.1	0.633	1.000	3046	3078	18.6
	4.2	297.8	0.614	0.998	3284	233.2	0.659	0.998	3075	3180	19.3
4	4.3	417.7	0.524	0.996	3245	355.2	0.565	0.999	3244	3244	19.7
	4.4	378.8	0.499	0.993	2731	178.0	0.708	0.999	2840	2786	16.9
	4.5	321.8	0.580	0.996	3118	234.7	0.647	0.997	2954	3036	18.4
	5.1	272.7	0.600	0.999	2855	249.5	0.631	0.996	2949	2902	18.5
	5.2	173.8	0.644	0.999	2159	175.2	0.638	0.999	2124	2141	13.6
5	5.3	143.4	0.659	0.997	1887	200.0	0.588	0.998	1996	1941	12.4
	5.4	186.1	0.557	0.995	1646	197.2	0.551	0.998	1702	1674	10.7
	5.5	163.9	0.598	1.000	1698	146.4	0.640	0.998	1790	1744	11.1
	5.6	273.1	0.607	0.998	2935	255.6	0.631	0.999	3017	2976	18.9
	6.1	256.0	0.582	0.999	2492	241.4	0.599	1.000	2511	2502	23.4
	6.2	221.5	0.608	0.997	2393	200.3	0.638	0.999	2427	2410	22.5
6	6.3	222.9	0.594	0.999	2274	197.9	0.630	0.999	2323	2298	21.5
	6.4	176.6	0.619	0.996	1991	109.8	0.750	0.988	2065	2028	18.9
	6.5	184.7	0.612	0.998	2021	203.6	0.580	0.999	1972	1996	18.6

The air flow rate through the building fabric has also been calculated for a pressure difference of 50 Pa (q_{50}). It has become common to express leakage in this way for comparison purposes and it enables the volume of data to be reduced to proportions which can be easily handled. It is clear from Table 3 that the calculated q_{50} results for the depressurisation and pressurisation tests are very similar.

5.4 Analysis of results

In order to compare the results of this survey of Scottish dwellings with other leakage data, the averages of the pressurisation and depressurisation q_{50} measurements have been determined for each dwelling to produce a single figure which describes the leakage of each house. In line with Swedish practice[21], the equivalent average air change rates at 50 Pa applied pressure difference have been determined and are also shown in Table 3. Using those figures a histogram has been drawn of air change rate at 50 Pa against the number of dwellings falling into intervals of one air change per hour (Figure 4). This produces a distribution of air change rate which has a mean of 18.4 and a standard deviation of 3.34 ac h^{-1}.

The mean result from a separate survey of 22 Scottish dwellings carried out in 1982[24] is marked on this histogram along with BRE mean data from a survey comprising a varied sample of 100 dwellings measured elsewhere in the UK[25].

A comparison of values shows that this present survey agrees broadly with other available data on Scottish homes, and indicates that Scottish traditionally constructed dwellings with suspended timber floors may be less airtight than other UK dwellings. The homes in this survey are seen to have average air leakage rates 60% greater than those measured by BRE.

The Swedish standard of air leakage which is applied to newly constructed dwellings[17] is also shown on Figure 4. This standard is implemented by performing spot leakage measurements on houses just before occupation, and aims for air change rates well below those achieved in British housing. It must, however, be appreciated that the tight Swedish homes are fitted with mechanical ventilation systems which ensure adequate fresh air supply and reduce the possibility of condensation and excessive air relative humidities. It would be unwise to reduce air leakage to such low values in this country unless combined with mechanical ventilation, or severe condensation problems would result. However, the results do indicate that there may be considerable scope for reduction in air leakage through dwellings in Britain in general, and in Scotland in particular.

6 Conclusions

The aim of this paper was to review the techniques available for measuring ventilation and airtightness of dwellings, and to investigate the air leakage characteristics of traditionally constructed Scottish dwellings built around 1960.

The main conclusion drawn from this study is that traditionally constructed Scottish dwellings with suspended timber floors are less airtight than a mixed sample of 100 UK dwellings measured previously by BRE. The sample of 32 dwellings studied had a mean air change rate at 50 Pa pressure difference of 18.4 ac h^{-1} in comparison with 11.5 ac h^{-1} for the BRE survey.

It is clear that there does exist scope for energy conservation by reducing the air leakage rates of homes in Scotland in particular, and the UK in general. More information is, however, now required on the exact location of the leakage paths within buildings. This would enable effective measures for leakage reduction to be carried out in the future.

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Ventilation and the leakage characteristics of dwellings

The paper by Galbraith *et al.*[1] is weak and out of date in its section 2.1 on fresh air requirements. The authors say that ventilation is needed to dilute pollution produced by occupants, of which tobacco smoke is of course a part. Twenty years ago I taught that, but times have changed: we now choose to surround ourselves with many items that give off pollution, of which modern plastic upholstery and modern carpet underlays are but two. How much ventilation is needed to reduce the concentrations of organic vapours to 'safe' levels? Indeed, what are 'safe' levels? During my working life 'safe' levels of exposure to nuclear radiation have fallen continuously, so that what is considered 'safe' (by interested parties) now, is negligible compared with what was 'safe' in the past. One pollution—not produced by occupants—is always with us: the radioactive gas radon, produced by the radioactive decay of uranium, present, in very small quantities, everywhere. Radon comes out of building materials which have been in the ground, and as we ventilate less (to save energy?) the radon concentration rises, and so does the incidence of lung cancer. Galbraith *et al.* take their ventilation requirements from Building Regulations and Standards, and their paper is concerned with other matter, but what I outline ought to have been mentioned.

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