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Summary An equation is developed for predicting the combined effect of naturally and mechanically induced air flows in buildings and solved by a combination of analytical and iterative methods. The resulting two-dimensional formulation, implemented as a simple computer program, allows rapid, hourly simulation of infiltration in domestic-scale buildings with a range of ventilation strategies. This implementation is used to compare energy use and carbon dioxide emissions for three ventilation strategies—natural ventilation, mechanical extract and balanced, whole-house mechanical ventilation—as a function of dwelling airtightness. This exercise confirms the need for airtightness if the benefits from balanced mechanical ventilation with heat recovery are to be maximised.

Ventilation strategy, energy use and CO_2 emissions in dwellings —a theoretical approach

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List of symbols

g	Acceleration due to gravity ($m\ s^{-2}$)
F	Flow function ($kg\ m^{-2}\ s^{-1}$)
H	Height of building (ground floor to roof) (m)
L	Length on plan of building (m)
c_p	Pressure coefficient (dimensionless)
c	Specific heat capacity of air at constant pressure ($J\ kg^{-1}\ K^{-1}$)
E_v	Ventilation heat demand of the dwelling over a heating season (J)
v	Wind speed ($m\ s^{-1}$)
A	Relative leakage area (dimensionless)
n	Ventilation rate ($ac\ h^{-1}$)
p	Pressure (Pa)
Q	Mass flow ($kg\ s^{-1}$)
z	Height (m)
z_0	Mean height of neutral plane in building (m)
Δz_0	Tilt in neutral plane resulting from wind pressure (m)
T	Temperature (K or °C)
ρ	Density ($kg\ m^{-3}$)

1 Introduction

This paper reports the results of a theoretical modelling exercise that was carried out to explore the impacts on energy use, carbon emissions and effective air change rates of three domestic ventilation strategies—natural ventilation, mechanical extract and whole-house balanced mechanical ventilation with heat recovery (MVHR)—as a function of dwelling airtightness. The work was done as part of the Derwentside Field Project, a field trial of balanced mechanical ventilation with heat recovery in existing, low-rise, local authority housing in the north of England(1). This field trial was set up as a controlled experiment. A group of six houses fitted with whole-house, continuously operating MVHR was compared with a group of six houses equipped with intermittently operated extract-only ventilation in kitchens and bathrooms. Although the field trial showed clear improvements in internal air quality in the MVHR houses, differences in energy use were swamped by other sources of variation, caused by high fabric heat losses and low levels of airtightness in all of the field trial dwellings. The only way to address the questions that the field trial had originally been set up to explore was by the use of analytical and numerical simulation.

The analytical approach that was adopted was based on a general framework developed by Lyberg(2). This framework was used as the basis for a two-dimensional model of a building in which air leakage is uniformly distributed across the elevations and is zero across the ground floor and roof. These simplifying assumptions, while not onerous in the context of the immediate purpose of the exercise, lead to significant simplifications in programming and short computation times. The model was coded in Pascal and used with weather data for Kew (south-east England) to simulate the performance of a simple reference dwelling over a typical heating season. This paper describes the model that was developed and some of the results that were obtained.

2 Modelling infiltration and ventilation

Air flows across the thermal envelope of a dwelling may be driven by naturally generated pressure differences (arising from wind and temperature differences), and by pressure differences generated by mechanical ventilation systems. The magnitude of these flows can be predicted from theoretical assumptions about air flow through openings, or from empirical expressions based on measured data. A theoretical model of air flows can be constructed that predicts, either from first principles or on the basis of empirical flow–pressure relationships, the ventilation rate and ventilation heat load in a dwelling under any combination of weather conditions and internal temperature, with and without mechanical ventilation. Such a model can be used in conjunction with files of real or simulated weather data to produce estimates of the impact of choice of ventilation system and dwelling air leakage on energy use over a typical heating season. Given the difficulty of conducting field trials of ventilation strategies, and the large number of parameters that such field trials would need to investigate to yield a comprehensive picture, such a theoretical approach is an essential complement to empirical studies.

A number of attempts have been made over the years to construct theoretical frameworks for modelling ventilation rates in dwellings. Two of the most influential were constructed by

Warren[3,4], and by Sherman and Grimsrud[5]. Both of these are based on the assumption that pressure differences and air flows arising from different physical mechanisms can be added in quadrature to give an effective whole house mean pressure difference and total ventilation rate.

Lyberg[2] shows that this assumption, while yielding plausible results in certain circumstances, is physically unrealistic in the case of wind- and buoyancy-induced ventilation. Lyberg presents a framework in which pressure differences across each section of the thermal envelope of a dwelling are estimated explicitly, and the resulting air flows are integrated over the whole envelope to give a total ventilation rate. This approach appears to offer a better starting point for calculating air flows and comparing ventilation strategies, and it is the one that is pursued here.

3 The Lyberg model of ventilation

Lyberg's approach to modelling ventilation is based on the following equation:

$$Q_{\text{net}} = \iint AF(|\Delta p|)\varepsilon(\Delta p)\,\mathrm{d}S + Q_{\text{mv}} \tag{1}$$

where A is the relative leakage area (dimensionless), Δp is the pressure difference (Pa) across an infinitesimal section $\mathrm{d}S$ of the thermal envelope, $\varepsilon(x) = +1$ if $x>0$ or -1 if $x<0$, Q_{mv} is the mass flow (kg s^{-1}) of air into the dwelling caused by a mechanical ventilation system, where one is fitted, Q_{net} is the net mass flow of air (kg s^{-1}) across the thermal envelope (clearly mass conservation requires that $Q_{\text{net}} = 0$) and F is the flow function (kg m^{-2} s^{-1}).

In the above formulation, air flows into the dwelling and the corresponding pressure differences are taken as positive. Pressure differences across the thermal envelopes arise from buoyancy and the action of wind. The pressure difference due to buoyancy can be written

$$\Delta p_{\text{stack}} = -\rho g(z - z_0)\frac{\Delta T}{T} \tag{2}$$

where z is the vertical height (m) above some datum, conveniently the bottom of the building, z_0 is the mean height (m) of the neutral plane in the building, ρ is the density of air (kg m^{-3}) at a temperature equal to the mean of the inside and outside temperatures, g is the acceleration due to gravity (m s^{-2}), ΔT is the temperature difference (K) across the thermal envelope and T is the mean of the inside and outside temperatures (~300 K).

The pressure difference due to wind acting on the outside of the building can be written

$$\Delta p_{\text{wind}} = -\frac{1}{2}\rho c_p v^2 \tag{3}$$

where v is the wind speed (m s^{-1}) at a reference point (normally taken to be undisturbed flow at the height of the building) and c_p is the (dimensionless) pressure coefficient at a point on the building thermal envelope.

The total pressure difference across an element of the thermal envelope is, to a very good approximation, equal to the sum of the stack and wind pressures. If one makes suitable simplifying assumptions about the variation of the pressure coefficients over the thermal envelope (for example that the pressure coefficient is constant over each exposed plane face of the building), then the integral in equation 1 can be evaluated analytically and the equation for z_0, the mean neutral plane height, can be solved numerically.

4 Developing a two-dimensional model

A two-dimensional model of a building was developed on the basis of this approach and on the following assumptions.

- The roof and ground floor of the building are airtight—leakage occurs only through the windward and leeward walls of the dwelling and is uniformly distributed over these elements.
- Wind pressure coefficients c_1 and c_2 are assumed to be uniform over the windward and leeward walls of the building, respectively.
- The flow function is assumed to have the form

$$F = a(|\Delta p|)^b \tag{4}$$

Measurements in real buildings consistently show values for b in the range 0.6–0.7, though to simplify analysis, b is often taken as 0.5 and a correspondingly as $\sqrt{(2/\rho)}$[2].

One of the simplest cases to analyse is that of a pressurisation test under perfect conditions (no wind and no inside–outside temperature difference). Under these conditions, equation 1 can be rewritten

$$Q_{\text{test}} = 2A\, a\, HL\, \Delta p_{\text{test}}^{\,b} \tag{5}$$

where Q_{test} is the mass flow of air (kg s^{-1}) through the dwelling during the pressure test, Δp_{test} is the test pressure difference (Pa), H is the height (m) of building (ground floor to roof) and L is the length on plan of building (m).

When the building is in normal occupation, the patterns of flow across the envelope of the dwelling can be represented by a vertical cross section through the dwelling as shown in Figure 1.

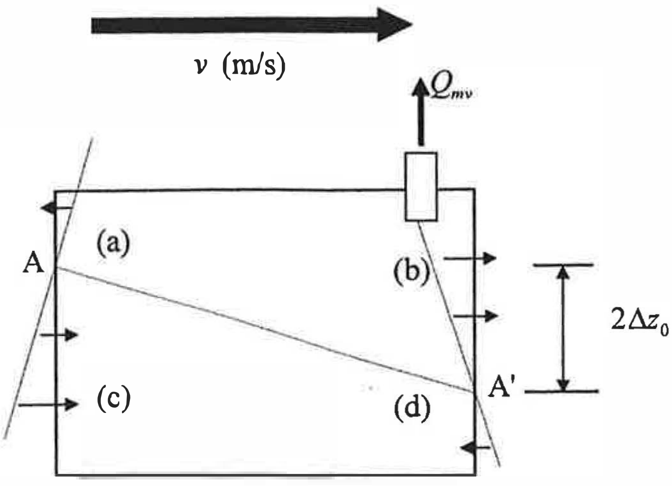

Figure 1 Vertical cross section through dwelling, showing direction and magnitude of infiltration and exfiltration across envelope. AA' is the neutral plane within the dwelling and Δz_0 is a measure of the tilt in the neutral plane produced by the action of the wind

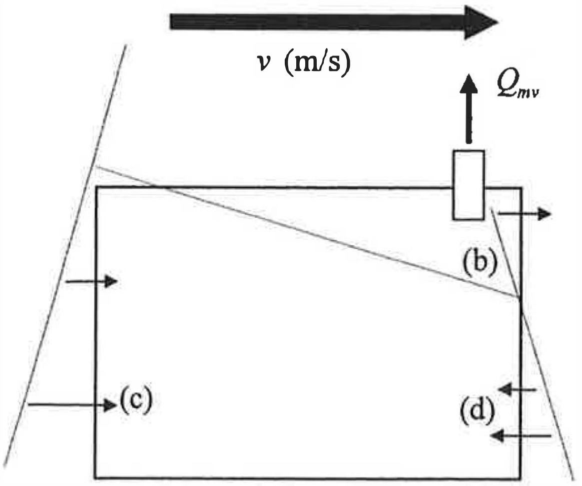

Figure 2 Disappearance of the windward exfiltration zone (*a*) due to the action of wind and mechanical extraction of air from the dwelling

In general there are four zones in Figure 1, which are labelled (*a*) windward exfiltration, (*b*) leeward exfiltration, (*c*) windward infiltration and (*d*) leeward infiltration. Depending on the relative wind speed, inside–outside temperature difference and rate at which air is extracted from the dwelling mechanically, up to two of these zones may disappear, as shown in Figure 2. The heights of the neutral plane on the windward and leeward faces differ owing to the pressure of the wind. It is convenient to represent this height difference by the quantity $2\Delta z_0$ (m) (see Figure 1).

The value of Δz_0 can be obtained by considering the stack and wind pressures on the envelope of the building. Thus

$$\frac{1}{2}\rho(c_1 - c_2)v^2 = \rho g \frac{\Delta T}{T} 2\Delta z_0 \tag{6}$$

and hence

$$\Delta z_0 = (c_1 - c_2)v^2\left(\frac{T}{4g\Delta T}\right) \tag{7}$$

It is now possible to write a set of equations for the air flow across the various parts of the building envelope in the general case of non-zero wind and inside–outside temperature difference, and with the possibility of a mechanical extract or supply system acting as an additional source of air flow across the building envelope. The pressure difference across the vertical elements of the envelope is given by

$$\Delta p = -\rho g(z - z_0)\frac{\Delta T}{T} \tag{8}$$

Substituting into equation 1, and replacing the double integral by a single integral to acknowledge the two-dimensional nature of the model, we get

$$\begin{aligned} Q_{\text{net}} &= \int AF(|\Delta p|)\varepsilon(\Delta p)\,\mathrm{d}S + Q_{\text{mv}} \\ &= LAa\left(\rho g\frac{\Delta T}{T}\right)^b \left[\begin{array}{l} -\displaystyle\int_{z_0+\Delta z_0}^{H} (z - z_0 - \Delta z_0)^b\,\mathrm{d}z \\ -\displaystyle\int_{\max(z_0-\Delta z_0,0)}^{H} (z - z_0 + \Delta z_0)^b\,\mathrm{d}z \\ +\displaystyle\int_{0}^{\min(z_0+\Delta z_0,H)} (z_0 + \Delta z_0 - z)^b\,\mathrm{d}z \\ +\displaystyle\int_{0}^{z_0-\Delta z_0} (z_0 - \Delta z_0 - z)^b\,\mathrm{d}z \end{array}\right] + Q_{\text{mv}} \\ &= 0 \end{aligned} \tag{9}$$

The four integrals in equation 9 correspond to the four zones, (*a*) to (*c*), respectively, shown in Figure 1. Each of the integrals in equation 8 is to be taken as zero if the lower limit of integration exceeds the upper. Integrating the above, we obtain

$$\frac{LAa(\rho g\,\Delta T/T)^b}{(b+1)} \left[\begin{array}{l} -(H - z_0 - \Delta z_0)^{b+1}|_{z_0+\Delta z_0<H} \\ -(H - z_0 + \Delta z_0)^{b+1}|_{z_0-\Delta z_0<H} \\ +(\Delta z_0 - z_0)^{b+1}|_{z_0>H} \\ +(z_0 + \Delta z_0)^{b+1} \\ -(z_0 + \Delta z_0 - H)^{b+1}|_{z_0+\Delta z_0>H} \\ +(z_0 - \Delta z_0)^{b+1}|_{\Delta z_0<z_0} \\ -(z_0 - \Delta z_0 - H)^{b+1}|_{z_0-\Delta z_0>H} \end{array}\right] + Q_{\text{mv}} = 0 \tag{10}$$

The above equation can be solved iteratively for the unknown z_0, thus providing a complete description of air flows across the building envelope, subject to the limitations imposed by the simplifying assumptions listed above. The positive and negative terms in the above equation, representing infiltration and exfiltration, respectively, can be separated. The sum of the infiltration terms in the above equation is given by

$$Q_{\inf} = \frac{LAa(\rho g\,\Delta T/T)^b}{(b+1)} \left[\begin{array}{l} +(z_0 + \Delta z_0)^{b+1} \\ -(z_0 + \Delta z_0 - H)^{b+1}|_{z_0+\Delta z_0>H} \\ +(z_0 - \Delta z_0)^{b+1}|_{\Delta z_0<z_0} \\ -(z_0 - \Delta z_0 - H)^{b+1}|_{z_0-\Delta z_0>H} \end{array}\right] \tag{11}$$

In the case of balanced mechanical ventilation systems, the total flow of air through the dwelling will be equal to the sum of the flow generated directly by the mechanical system, plus $Q_{\inf}$. In the case of extract-only systems, the total flow of air through the dwelling will be equal to $Q_{\inf}$.

5 Modelling infiltration and ventilation in dwellings

The first application of the model described above has been to investigate the impacts on energy use and internal air quality of a number of ventilation strategies in dwellings as a function of airtightness. For the purposes of this exercise, the modelled dwelling was a two-storey terraced house, typical of a substantial portion of the UK housing stock. The internal floor area was 89 m^2 and the volume was 223 m^3. Pressure coefficients were taken as 0.7 and -0.3 over the windward and leeward walls, respectively(6). Local shelter was assumed to reduce these pressure coefficients by a factor of 2(4), and the effects of non-normal incidence by a further factor of 2, resulting in a four-fold overall reduction. A further simplification in this exercise was to assume a pressure-flow exponent $b = \frac{1}{2}$, and correspondingly $a = \sqrt{(2/\rho)}$.

The useful ventilation heat demand for the modelled dwelling was calculated using a simple model in which

$$E_v = \int_{\text{heatingseason}} Q_{\text{inf}} c \, \Delta T \, dt \qquad (12)$$

where E_v is the ventilation heat demand (J) of the dwelling over a heating season, and c is the specific heat capacity of air at constant pressure (J kg^{-1} K^{-1}). ΔT is evaluated with the internal temperature T_{in} taken as 20°C for external temperature T_{out}<15°C. This represents the bulk of the heating season. For T_{out}<15°C,

$$T_{in} = 15 + 5 \exp[-(T_{out} - 15)/5] \qquad (13)$$

to take account of the tendency for internal temperatures to float up at the beginning and end of the heating season, as external temperatures rise. For the purposes of this exercise, the heating season was taken as running from 1 October to 30 April inclusive.

The model described above was implemented in Pascal. The program is compact, and is able to simulate a heating season's ventilation at hourly intervals in approximately 8 s on a 166 MHz PC. The model was used with weather data for Kew 1967. This particular weather datafile did not include wind direction, hence the correction for off-normal incidence. It would be trivial to extend the model to include the effect of wind direction explicitly, but the results are unlikely to be affected significantly. Some of the results from this exercise are presented below. Estimates of delivered energy use and carbon emissions have been based on the following additional assumptions:

- Space heating is supplied by a condensing gas-fired heating system, with a seasonal efficiency of 90%.
- The carbon coefficients of natural gas and electricity are taken as 0.2 and 0.58 kg CO_2 $(kWh)^{-1}$, respectively. The latter is appropriate for the UK electricity system in the late 1990s, but is likely to overestimate the environmental impact of electricity in the twenty-first century.

5.1 Natural ventilation

Figure 3 shows the performance characteristics of natural ventilation and some of the fundamental problems associated with it. Ventilation ratio is the ratio of mean ventilation rate, over the heating season, to design ventilation rate, taken here as 0.5 ac h^{-1}. The underventilation index is the fraction of hours in the heating season for which a naturally ventilated dwelling will be underventilated without additional window opening. At leakage rates below about 8 ac h^{-1} at 50 Pa, underventilation is almost assured. However, even at this level of leakage, the ventilation rate averaged over the heating season is significantly greater than the design ventilation rate. A dwelling of average UK leakiness (about 14 ac h^{-1} at 50 Pa), maintained at an internal temperature of 20°C, will almost always be adequately ventilated during the heating season, but the mean ventilation rate over the heating season will be more than twice the design ventilation rate. This overventilation leads to significant penalties in terms of energy consumption and carbon emissions, as well as to thermal discomfort (draughts under windy conditions and excessive vertical temperature gradients under calm, cold conditions). Lower internal temperatures would tend to lead to lower ventilation rates, particularly in the warmer parts of the year.

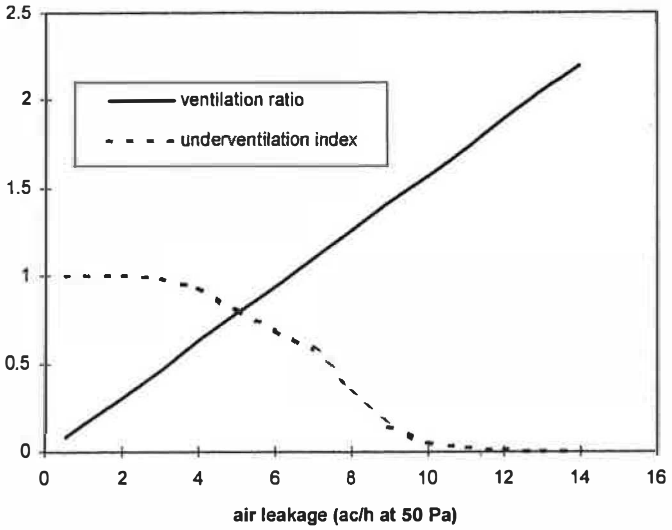

Figure 3 Ventilation and underventilation in a naturally ventilated dwelling

One of the incidental outputs from the model described here is the ratio of air leakage at 50 Pa (n_{50}) to heating season mean infiltration rate. This ratio is, in principle, climate- and building-dependent, but for the purposes of rough calculation it is often assumed to take a value of 20. The value that emerged from this exercise, with a pressure-flow exponent of $\frac{1}{2}$, was in the region of 13. Had a more realistic value of the pressure-flow exponent been used, say 0.65, this ratio would have been higher, in the region of 20.

There are significant omissions from the analysis presented here. The most important is that of window opening behaviour. Window opening significantly increases the ventilation rate in dwellings, and in principle can prevent underventilation in airtight dwellings. This would tend to raise the ventilation ratio, and reduce the underventilation index in the above figure, at values of n_{50} below about 10 ac h^{-1}.

It is likely that window opening behaviour in practice is hysteretic and imprecise, resulting in wide swings in ventilation rate, with periods of underventilation alternating with periods of overventilation. In households that value air quality, the ventilation ratio might rise above 1, even in an airtight dwelling. Simultaneously, the index of underventilation would fall, but probably not to zero. In households that place greater value on energy conservation than on air quality, it is possible for natural ventilation in an airtight house to outperform mechanical ventilation in terms of energy and carbon emissions, by the simple expedient of not opening the windows.

5.2 *Mechanical extract ventilation versus balanced MVHR*

Once the decision has been taken to rely on mechanical ventilation, measures to increase airtightness will tend to reduce the space heating requirement of the dwelling, and reduce the effect of external weather conditions on the distribution of ventilation within the dwelling.

There is a subtle difference in the ways in which extract-only and balanced MVHR systems interact with external weather as air leakage is reduced. This arises because balanced MVHR systems do not affect the pressure difference across the dwelling envelope, while extract-only systems do.

As a dwelling fitted with an extract-only ventilation system is made more airtight, one observes a transition from a situation in which the flow of air across the dwelling envelope is controlled by naturally occurring pressure differences arising from wind and buoyancy, to a situation in which air flow is determined by the action of the mechanical extract system and is independent of external weather conditions. The modelling suggests that this transition takes place in the region of

$$n_{50} \approx 6n_{\text{design}} \qquad (14)$$

where n_{design} is the design ventilation rate (ac h^{-1}) (see Figures 4 to 6). Under typical UK conditions this corresponds to an air leakage of about 3 ac h^{-1} at 50 Pa for dwellings with a design ventilation rate of 0.5 ac h^{-1}. We will refer to this level of air leakage as the critical air leakage, n_{critical}. With extract-only ventilation, when air leakage has been reduced to n_{critical}, further reductions in air leakage have little or no effect on ventilation heat loss. With balanced MVHR, there is no critical air leakage rate and no transition. Reductions in air leakage will reduce both total ventilation rate and ventilation heat loss, at all levels of air leakage down to zero. These comments are summarised in Table 1.

Figures 4, 5 and 6 show carbon dioxide emissions from the modelled dwelling, for the three ventilation strategies (natural, extract-only and balanced MVHR) as a function of air leakage rate. The line representing natural ventilation is not extended to air leakage rates less than 5 ac h^{-1} at 50 Pa, on the grounds that underventilation is likely to become a significant problem for dwellings that are more airtight than this. Figure 4 depicts an efficient MVHR unit (fan power 30 W, heat recovery efficiency 80%), Figure 5 a unit of intermediate efficiency (fan power 50 W, heat recovery efficiency 60%) and Figure 6 an inefficient MVHR unit (fan power 80 W, heat recovery efficiency 50%). The extract-only system with which each of these is compared is assumed to be comparatively

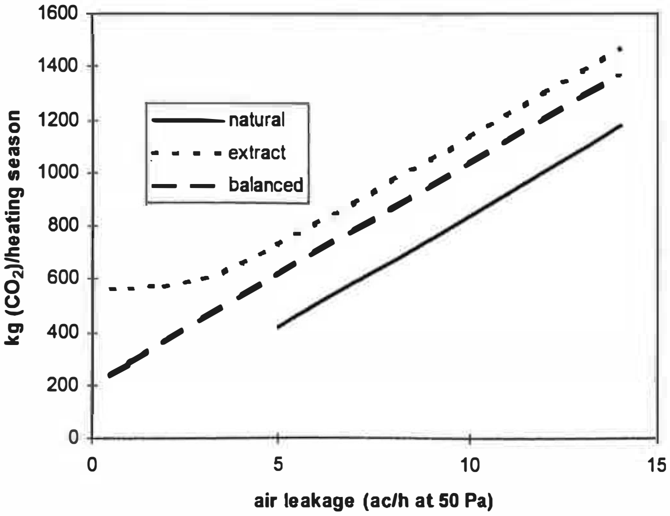

Figure 4 Ventilation-related carbon dioxide emissions: high-efficiency balanced MVHR compared with extract-only and natural ventilation

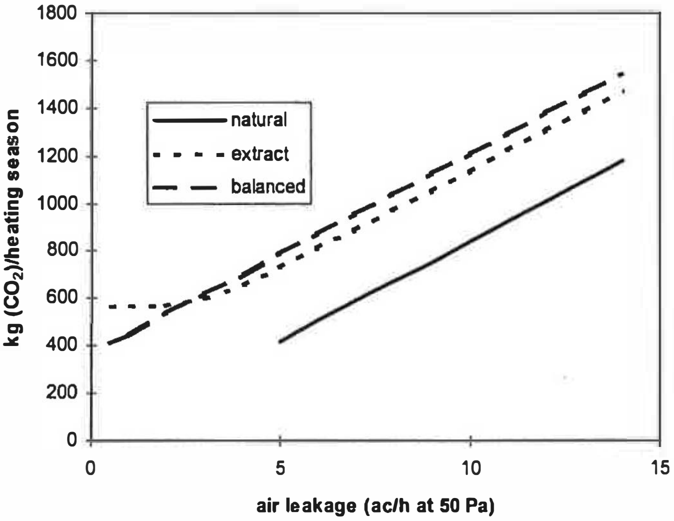

Figure 5 Ventilation-related carbon dioxide emissions: medium-efficiency balanced MVHR compared with extract-only and natural ventilation

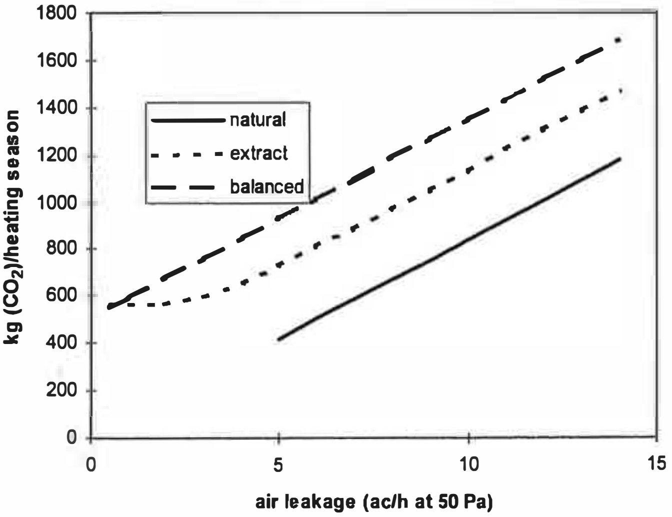

Figure 6 Ventilation-related carbon dioxide emissions: low-efficiency balanced MVHR compared with extract-only and natural ventilation

Table 1 Effect of air leakage on performance of extract-only ventilation

$n_{50}>n_{\text{critical}}$	$n_{50}<n_{\text{critical}}$
Ventilation heat loss falls as air leakage is reduced	Total ventilation heat loss is independent of air leakage
Distribution of air flow across dwelling envelope and between and within rooms, and heat loads in individual rooms are sensitive to external weather conditions	Distribution of air flow across dwelling envelope and between and within rooms becomes increasingly stable as air leakage falls towards zero
Effective ventilation rate can fall to zero on leeward side of house	

efficient, with a continuous electrical power requirement of 5 W. The picture presented by these three graphs is complex and worthy of some discussion.

Figure 4 shows that provided fan-motor and heat recovery efficiency are high enough (the figures assumed here are attainable using currently available technology), balanced MVHR will outperform efficient extract-only systems at all levels of air leakage. The graph also shows that *both* mechanical ventilation options, in reasonably airtight dwellings, will outperform unassisted natural ventilation in leaky dwellings, while eliminating underventilation. The carbon emission curves shown represent the minimum achievable, assuming no window opening. This assumption is most likely to be an underestimate of the true situation in naturally ventilated dwellings. The performance advantage of MVHR compared with extract-only ventilation is of the order of 100 kg per annum for $n_{50} \geq 5$ ac h^{-1}, but rises steeply for air leakage rates below the critical leakage rate. At a leakage rate of 0.5 ac h^{-1}, the performance advantage of high-performance balanced MVHR is more than 320 kg per annum compared with extract-only ventilation. It should be noted that these air leakage rates are significantly lower than those characteristic of the UK housing stock(7,8). A leakage rate of 1 ac h^{-1} has, to the author's knowledge, been achieved just once in the UK(9). However, lower figures are achieved regularly both in continental Europe and in Canada(10,11).

Figure 5 shows that with MVHR systems of intermediate efficiency, air leakage is the key factor in determining whether balanced MVHR or extract-only ventilation will give the lowest CO_2 emissions. In dwellings with air leakage above the critical value, extract-only systems are likely to give the lowest overall emissions, while in more airtight dwellings balanced MVHR gives the lowest emissions. With intermediate efficiency MVHR, the difference in performance between MVHR and extract-only ventilation is relatively small, ranging from +150 kg per annum at $n_{50} = 0.5$ ac h^{-1} to −70 kg per annum for $n_{50} >> n_{\text{critical}}$.

Figure 6 shows that low-performance domestic MVHR systems will always be outperformed by efficient extract-only ventilation. Intrinsically low performance arises where the MVHR unit is itself poorly designed and manufactured, with low-efficiency fan-motor sets, undersized heat exchangers, internal leaks that allow the heat exchanger to be bypassed, and so on. Poor performance can also be caused by poor ductwork design, poor installation and poor commissioning. The Derwentside Project has shown how important the last two can be(1).

6 Conclusions

This paper describes an analytical approach that allows the dynamic numerical simulation of infiltration and ventilation rates in buildings. The approach is based on an elegant formulation due to Lyberg(2). An implementation of the approach in the programming language Pascal was found to be compact and fast. Although the implementation that is described here is two-dimensional, the approach could easily be extended to the third dimension.

The original motivation for undertaking this work was the difficulty experienced by the author and his colleagues in measuring empirically the impact of ventilation strategy on energy use in the context of a field trial. The approach was used to explore the circumstances under which balanced MVHR systems will lead to lower overall carbon dioxide emissions from ventilation than from extract-only systems. Despite the obvious limitations of the implementation, the author is confident that the conclusions are qualitatively robust, and indeed that they can play an important part in evaluating ventilation options for housing in the UK and elsewhere.

The most important practical conclusions from this work are as follow.

— Predictably, the lowest levels of energy use and carbon emissions will be achieved in very airtight dwellings with efficient MVHR systems. If properly designed, installed, commissioned and maintained, these systems guarantee air quality, and a high level of thermal comfort. Results presented above suggest that a high-performance, balanced MVHR system in a very airtight dwelling can reduce carbon dioxide emissions by 200–300 kg per annum compared with an extract-only system in the same dwelling.

— The scope for achieving reductions in energy use with MVHR depends critically on the efficiency of the equipment used. Low-performance equipment may not achieve savings at all compared with the simpler and cheaper option of extract-only ventilation. Equipment of intermediate performance will achieve substantial savings only in relatively airtight dwellings. The point at which the two ventilation options break even in terms of carbon emissions under these conditions is at a leakage of about 3 ac h^{-1} at 50 Pa. Finally, equipment that is efficient by current standards may offer advantages at all levels of air leakage compared with extract-only ventilation.

— Under circumstances where air leakage rates below this level cannot be guaranteed, extract-only ventilation may perform as well as, or better than, balanced MVHR, depending on the performance of the MVHR system.

Airtightness appears to be the key to reducing carbon emissions attributable to ventilation, regardless of which mechanical ventilation strategy is chosen. The identification of the need for air leakage rates less than 3 ac h^{-1} at 50 Pa to maximise the benefit from MVHR is consistent with the picture that emerges from a study of national codes for domestic ventilation(12), and accords with practical experience from mechanical ventilation systems elsewhere(13). Advice currently available in the UK is that MVHR should not be installed in dwellings with air leakage rates of more than 7 ac h^{-1} at 50 Pa(14). The results presented above suggest that this does not go far enough.

Acknowledgements

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