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Domestic Ventilation with Heat Recovery to Improve Indoor Air Quality

H. B. AWBI and S. J. ALLWINKLE

Department of Mechanical and Industrial Engineering, Napier College, Colinton Road, Edinburgh EH10 5DT, Scotland (U.K.)

SUMMARY

Recently in the U.K., and particularly in Scotland, domestic ventilation systems have been considered as means of reducing condensation in existing housing stock. A simple ventilation model which is suitable for ventilation systems with a heat recovery unit is presented. Using field data of temperature and relative humidity, air supply and extract rates for individual rooms are estimated by applying this model. Unlike conventional systems, extract from bedrooms is considered necessary for the type of dwellings considered to reduce surface condensation.

1. INTRODUCTION

It is only recently that indoor air pollution and the need to cure "sick" buildings has captured the interests of building designers in the U.K. The "sick building syndrome" related to indoor air quality is made up of many different pollutants, however the specific pollutant that causes serious health problems and also building fabric decay in the U.K. is water vapour.

The condensate blights many homes in the U.K. and resulting mould causes premature building fabric degradation. However a report by the Institution of Environmental Health Officers [1] recently stated that the problem is more than cosmetic. It claimed that condensate-induced mould growth and fungal spores were a major cause of allergies and illnesses including asthma, rhinites and conjunctivitis, thereby making the condensation issue a focal point of litigation.

The extent of this problem is borne out in a survey of over 7000 households in Scotland [2] carried out in 1983 which showed widespread complaints from dampness caused by condensation of water vapour. This sample represents 0.5% of all Scottish dwellings, about half of which represent the private sector and the other half represent the public sector.

The problem is more acute among public sector dwellings with 33.4% of households experiencing persistent condensation problems and 20.8% reporting mould growth. An earlier survey conducted in England in 1981 [3] using a sample of about 4500 traditionally-built dwellings (i.e., pre-1976) has shown that 31% are affected by dampness. The extent of the problem in the rest of the U.K. is likely to be similar to that in England and Scotland, with the main causes of the problem attributed to a lack of ventilation and low indoor temperatures. The lack of ventilation is caused by recent changes in domestic habits in the U.K., e.g., replacement of open fires by electric heating and balanced flue gas heaters in addition to draught-proofing measures undertaken by occupiers or housing authorities in pursuit of energy conservation, and the low indoor temperatures are associated with poor thermal insulation of pre-1982 housing stock. The co-existance of these two factors has been the main reason for exceeding the threshold of condensation dampness on the scale mentioned earlier.

A research programme was therefore initiated, the first in the U.K., with the primary objective of curing condensation in public authority housing in Scotland by adding a retrofit ventilation system with heat recovery to the existing housing stock.

This programme was structured to firstly examine the housing stock and to design a system that would best suit these buildings. Existing domestic ventilation practice in the U.K. was also considered but found to be inadequate to deal with this problem.

A model was established based on existing data and is currently being tested in a full-scale

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house with simulated occupancy. If the results are found to be satisfactory then a large-scale test/control monitoring study will be undertaken to further examine the applicability of ventilation systems in occupied houses.

In this paper attention is focused on the ventilation factor only, as the study of the effect of insulation on condensation is a subject in its own right. Although a mechanical ventilation system may reduce the risk of condensation within a dwelling, the penalty on increased energy consumption and thermal comfort deterioration is often unacceptable. When coupled with a heat recovery unit a mechanical ventilator could become viable in terms of energy cost and comfort as has long been demonstrated in Sweden.

Particular attention is given towards the distribution of supply and extract points in the dwellings to minimise the onset of condensation, to reduce energy consumption and to improve air quality against a current background of available systems that are incompatible with the building stock.

2. FIELD TEMPERATURE AND HUMIDITY DATA

Before a decision could be made on a particular mechanical ventilation strategy to prevent condensation, field measurements of interior and exterior temperatures and vapour pressures were required for the winter season. Data collected by the Building Research Establishment (BRE) from typical Scottish apartments (flats) in Stirling [4] during the winters of 1982 and 1983 were analysed and used for predicting mechanical ventilation rates using an air-to-air heat recovery unit. The data were obtained from four-storey pitched-roof blocks each comprising eight flats with two or three bedrooms per flat. The wall construction was brick–cavity–brick rendered on the exterior surface. The pitched roof was insulated with 75 mm fibre glass and the 50 mm cavity of some walls was filled with polystyrene bead insulation. The nominal U-values for external walls, roof and floor were 1.5, 0.35 and 0.68 W/m^2 K respectively. Ninety seven occupied flats were monitored over a period ranging from one week to eight weeks. Three types of heating systems were used in these dwellings: underfloor electric heating, electric storage heaters, and gas central heating. Some kitchens and bathroom were also provided with extract fans.

The hourly values of air temperature vapour pressure and relative humidity (RH obtained from thermohygrograph recorders were averaged for each monitoring period and each room. The thermohygrographic charts were digitized and frequency distributions and summary statistics were generated by a computer. The monitored rooms in each flat were the living room, kitchen and one of the bedrooms. Records of outside air temperature and RH were also analysed for the same periods. The variation of mean outside vapour pressure with mean temperature is shown in Fig. 1 for the monitoring periods during 1982 and 1983 winters.

For each period, the vapour pressure is directly proportional to the air temperature but the 1982 pressures are greater than those for 1983 because 1982 was a notably severe winter. A similar plot in Fig. 2 of the inside vapour pressures and temperatures for all the rooms and flats monitored shows that the vapour pressure is almost unaffected by the room temperature. The mean RH varied between 70% and 40% corresponding to a mean temperature of 10 - 21 °C. This suggests that the water vapour distribution within each dwelling was uniform and independent of the individual room temperature. It was also noted that most of the data for non-centrally heated bedrooms were to the left of Fig. 2, i.e., bedroom temperatures were the lowest of the three types of rooms monitored and RH was the highest. Other field data [2, 5] also confirm this finding. This is primarily due to the lack of heating and low ventilation in bedrooms which make these rooms high condensation risk zones in non-centrally heated dwellings such as those using storage electric heating, which is particularly common in public sector housing in the U.K.

3. MECHANICAL VENTILATION MODEL

Serious problems associated with condensation in dwellings such as dampness and mould growth are caused by persistent high RH levels inside. Dynamic effects of moisture generation are usually damped out by the absorption and subsequent release of water vapour by building materials and furniture. A dynamic

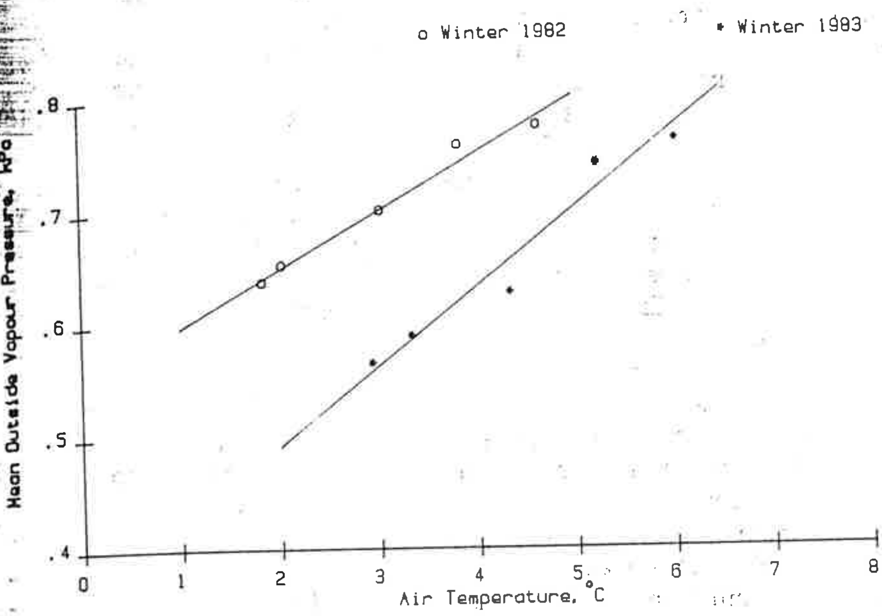

Fig. 1. Variation of outside pressure with temperature over the monitoring periods.

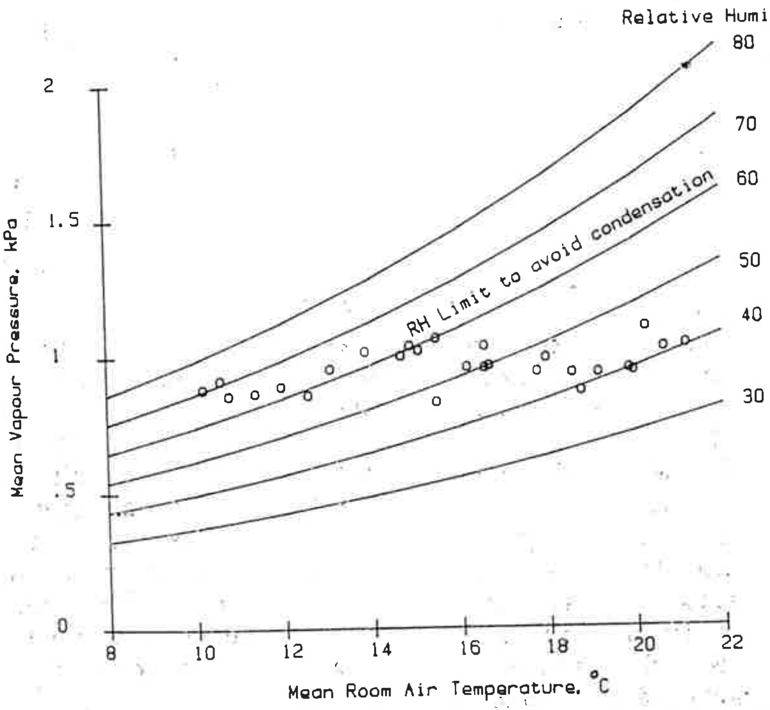

Fig. 2. Measured vapour pressure in monitored flats during winters of 1982 and 1983.

model is only necessary if a detailed analysis of the dynamic interaction between the heating system, building envelope and fluctuating weather conditions is required. However, for the purpose of estimating a ventilation rate for a constant air volume domestic ventilation system, a steady-state moisture transfer model is considered to be sufficient.

The moisture in the air inside the dwelling is equal to the difference between the water vapour ingress and the egress plus the moisture generated inside the dwelling due to occupancy, Fig. 3. The rate of moisture increase inside is therefore

$$\frac{d\omega_i}{dt} = Q_o\rho_o\omega_o - Q_e\rho_e\omega_e + m_g - m_f \qquad (1)$$

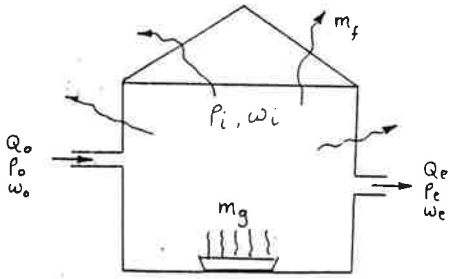

Fig. 3. Moisture transfer through a house.

where

Q = volume of air flow rate (m^3/s)
ρ = density of air (kg/m^3)
ω = specific humidity (kg/kg)
m_g = rate of moisture generation within the dwelling (kg/s)
m_f = rate of moisture transfer through the building fabric by diffusion (kg/s)

and subscripts i, o and e refer to inside, outside, and extract air respectively. Assuming a steady-state moisture transfer and that $\omega_e = \omega_i$, $\rho_e = \rho_i$ and $Q_e\rho_e = Q_o\rho_o$ (i.e., a constant mass flow of dry air), eqn. (1) may be simplified to

$$\omega_i = \omega_o + (m_g - m_f)/\rho_o Q_o \tag{2}$$

Using standard atmospheric pressure, the outside density is given as

$$\rho_o = \frac{p_o}{RT_o} = \frac{101.325}{0.287T_o} = \frac{353}{T_o}$$

where T_o is the absolute outside temperature in units of K, and the dimensional constant 353 has the units kgK/m^3. Hence, eqn. (2) becomes

$$\omega_i = \omega_o + \frac{T_o}{353Q_o}(m_g - m_f) \tag{3}$$

Given the ventilation rate and the outside air condition, the specific humidity inside may be calculated from eqn. (3) if m_g and m_f are known. It should be noted that this equation applies to a detached dwelling and may not be valid for a multi-family building where cross-ventilation from adjacent dwellings could be significant.

Normally the occupancy moisture generation rate can be estimated [6, 7] and the fabric moisture transfer may be calculated using

$$m_f = \left(\frac{A_w}{R_w} + \frac{A_f}{R_f} + \frac{A_r}{R_r}\right)\Delta p \tag{4}$$

where

R = vapour resistance of building fabric (kNs/kg)
A = surface area of fabric (m^2)
Δp = vapour pressure difference between inside and outside (kPa)

and subscripts w, f and r refer to wall, floor and roof respectively.

The natural air infiltration rate for typical draught-proofed dwellings in the U.K. [8, 9] is of the order of 0.5 air change per hour (ach). This is a large rate in comparison, for example, with about 0.2 ach for an average Swedish dwelling [10]. With such a large air infiltration the moisture transfer across the fabric is much smaller than that which occurs by air infiltration through cracks and openings in the building fabric. Indeed, calculations have shown this to be the case. Hence, m_f in eqn. (3) may be ignored and the equation becomes

$$\omega_i = \omega_o + \frac{T_o}{353Q_o}m_g \tag{5}$$

where Q_o is the volume flow rate supplied from outside, either naturally or naturally *and* mechanically.

Equation (5) is a moisture balance equation which applies to natural and mechanical ventilation. Assuming the same moisture generation in the dwelling for both mechanical and natural ventilation and using subscripts n and m to denote natural and mechanical ventilation respectively, it follows from eqn. (5) that

$$Q_n(\omega_i - \omega_o)_n = Q(\omega_i - \omega_o)_m$$

where

Q_n = air supply rate by natural ventilation (m^3/s).
Q = total of mechanically and naturally supplied air flow rate (m^3/s).

Since $\omega_{on} = \omega_{om} = \omega_o$, then

$$\frac{Q}{Q_n} = \frac{\omega_{in} - \omega_o}{\omega_{im} - \omega_o} \tag{6}$$

In terms of partial vapour pressures, the equation becomes

$$\frac{Q}{Q_n} \approx \frac{p_{in} - p_o}{p_{im} - p_o} \tag{7}$$

The total ventilation rate, Q, required to maintain a certain vapour pressure in the dwelling, p_{im}, can be obtained from eqn. (7) given the natural infiltration rate and the outside vapour pressure.

For unbalanced mechanical ventilation and when the extract air flow rate, Q_e, is considerably greater than the supply air flow rate, Q_s, it is shown in the Appendix that the mechanical extract and supply flow rates are given approximately as

$$\frac{Q_e}{Q_n} = \frac{p_{in} - p_o}{p_{im} - p_o} \tag{8}$$

and

$$\frac{Q_s}{Q_n} = \frac{1}{r}\left(\frac{p_{in} - p_o}{p_{im} - p_o}\right) \tag{9}$$

where r is the ratio of mechanical extract rate to mechanical supply rate, Q_e/Q_s.

4. MECHANICAL VENTILATION RATES

Equation (7) can be applied to estimating the ratio of mechanical to natural ventilation rates, Q/Q_n, which is required to maintain a given vapour pressure p_{im} within a dwelling. Average data for p_o and p_{in} were obtained from field measurements. Natural ventilation rates, Q_n, for the test dwellings were not available, however a value of 0.5 ach was assumed throughout. The interior vapour pressure in the presence of mechanical ventilation is determined by the room temperature and the desired relative humidity. It is widely believed that condensation will occur if the average RH is allowed to increase above 70% [3, 5]. However, due to cold interior surfaces as a result of inadequate insulation, the temperature of room surfaces is often lower than the dew point temperature corresponding to this value of RH. A more relevant maximum RH for most U.K. dwellings would be 60%. This is the winter RH limit also recommended by Meyringer [6] for predicting mechanical ventilation rates for German dwellings.

Applying eqn. (7) the ratio Q/Q_n was calculated for each room that was monitored to maintain 60% RH in the room. Assuming equal ventilation ratios for bedrooms and also that the total volume of all bedrooms is equal to the combined volume of living room, dining room and kitchen, an average ratio for the dwelling was obtained. By averaging the dwelling temperature it was then possible to plot Q/Q_n for each type of dwelling with average air temperature in the dwelling and the results are shown in Fig. 4. The results suggest that a ventilation ratio of at least 2 (i.e., 1 ach) will be needed to maintain an RH of 60% or lower throughout the dwellings that were monitored.

In distributing this ventilation ratio to different rooms of a dwelling, attention must be given towards:

(i) zones of large moisture generation;

(ii) zones of low or high temperatures in the dwelling;

(iii) zones of high fresh air requirement;

(iv) zones with a large number of external walls and windows since these are usually cold surfaces that promote surface condensation.

This will necessitate different air supply and extract rates to different zones of a dwelling not only to minimize the risk of condensation in each room but also to optimize the additional demand on energy for space heating which is imposed by mechanical ventilation.

Most commercially available domestic ventilation systems with heat recovery supply the air to the living room and bedrooms and extract it from the kitchen, bathroom and living room. This ventilation strategy is considered to be energy wasteful due to the continuous extraction of large flow rates from "warm" zones (i.e., kitchen, bathroom and living room) some of which are only high moisture generation zones for a very short time of the day. Such systems do not extract from bedrooms which are the only moisture generation zones at night. Furthermore, most field data show that bedroom temperatures are at least 4 K or 5 K lower than other rooms which makes them susceptible to surface condensation particularly during the night.

Assuming a continuous supply of air to the living room, dining room, kitchen and bedrooms and continuous extract from bedrooms and bathrooms and intermittent extract from the kitchen (i.e., only when moisture is being generated), supply and extract rates are calculated for a typical semi-detached or a terraced U.K. house of floor area 87 m^2, Fig. 5. These values are given in Table 1. An extract/supply ratio of 1.15 has been assumed to maintain an acceptable supply air temperature to the rooms as most commercially available plate

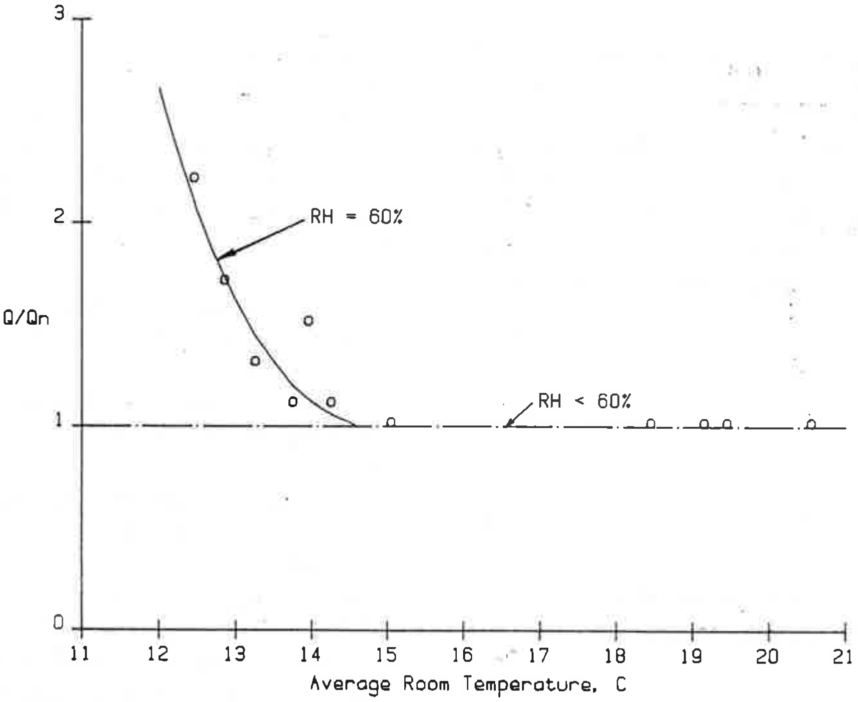

Fig. 4. Mechanical-to-natural-ventilation ratio for flats with 60% maximum RH.

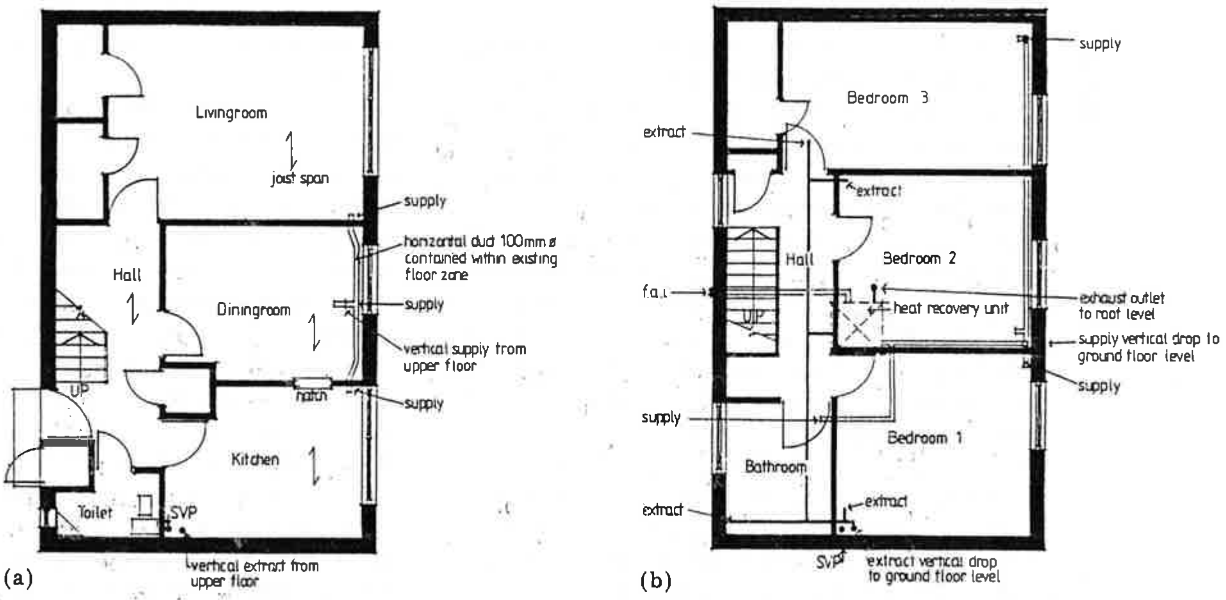

Fig. 5. Positions of supply and extract registers. (a) Ground floor plan; (b) upper floor plan, supply ═══, extract plan, supply ═══, extract ━━━

heat exchangers have an effectiveness of between 60% and 70%.

5. SYSTEM EVALUATION

The ventilation system was designed, based on the parameters previously discussed, and installed in a two-storey house (Fig. 5). The design further recognised that the condition of the existing housing stock is varied both in size and construction but, more important, that there is a variation in the thermal performance of the structure and different infiltration rates, and although it would be possible to seal all houses to the required level, the cost of upgrading all houses to the same thermal insulation level would be too high.

The system was designed from proprietory units, i.e., heat exchanger, ducting, diffusers,

TABLE 1
Ventilation rates for test house

Room	Volume (m^3)	Natural ventilation (m^3/h)	Total ventilation (ach)		Mechanical ventilation (m^3/h)		Net mechanical ventilation (m^3/h)
			Supply	Extract	Supply	Extract	
Living	37.0	18.5	1.5	0.5	37.0	—	+37.0
Dining	22.2	11.1	1.5	0.5	22.2	—	+22.2
Kitchen	21.5	10.8	1.5	0.5/2*	21.5	0/32.3*	+21.5/—10.8*
Bath	10.3	5.2	0.5	2	—	15.5	—15.5
WC	4.7	2.3	0.5	2	—	7.0	—7.0
Bedroom 1	27.0	13.5	1	2	13.5	40.5	—27.0
Bedroom 2	24.7	12.3	1	2	12.3	37.0	—24.7
Bedroom 3	25.8	12.9	1	2	12.9	38.7	—25.8
Hall, Stairs, Store, Etc	33.4	16.7	0.5	0.5	—	—	—
Total	206.6	103.3	—	—	119.4	138.7	—19.3

*Extract damper increases mechanical extract to 1.5 ach.

etc., and an economic layout was selected so that minimum disruption and minimum loss of space is incurred to the house. The selected house was tested for air tightness using pressurisation and infrared thermography and was further sealed to give the required natural air infiltration rate of 0.5 ach by draught-stripping doors, windows and floors.

The system was then installed and balanced and a test programme is due to be implemented during the 1986/87 winter period with continuously monitored variables to be collected every 30 minutes to provide a data base for analysis. The house is furnished but unoccupied, to simulate the hygroscopic values that exist in houses without including the major variable, i.e., the human factor.

The results of this test programme will be published at a later date.

6. CONCLUSIONS

A single zone ventilation model has been presented to estimate the ventilation rate required to maintain a specific relative humidity in a dwelling for the purpose of reducing large-scale surface condensation of water vapour in winter. The model has been applied to field data from occupied dwellings to obtain an average ventilation rate for Scottish dwellings. Using this model and the field data, it was possible to calculate ventilation rates for different zones of a typical two-storey dwelling. These rates formed the basis for designing the air distribution system for the dwelling which incorporated an air-to-air heat recovery unit.

Although the model was based on Scottish climatic data and was applied to a Scottish construction, it may be adapted to other climatic conditions and different construction methods. For this purpose, an average natural ventilation rate will be required for the type of dwelling being investigated.

The model allows for different air change rates to be used for different zones providing that the required net air change rate for the dwelling is attained. Differences between the air supply and extract rates for each zone have been found necessary to restrict the diffusion of moisture from high to low moisture level zones and furthermore to optimize the energy demand for heating.

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APPENDIX

Unbalanced mechanical ventilation

For an unbalanced supply and extract mechanical ventilation system it follows from eqn. (5) in Section 3 that

$$Q_n(\omega_i - \omega_o)_n = Q(\omega_i - \omega_o)_m \qquad \text{(A1)}$$

where

$$Q = Q_s + Q_n' = Q_e + Q_n''$$

= total air flow rate due to natural and mechanical ventilation (m^3/s)

Q_s and Q_e are the mechanically supplied and extracted air flow rates respectively, and Q_n' and Q_n'' are the air flow rates entering and leaving the natural ventilation path of the building respectively.

For balanced mechanical ventilation,

$$Q_n'' \approx Q_n' \approx Q_n$$

but for unbalanced ventilation,

$$Q_n'' \neq Q_n'$$

When $Q_e > Q_s$ the pressure inside the building is lower than the pressure outside, hence $Q_n'' \to 0$ and $Q \approx Q_e$ and eqn. (A1) becomes

$$Q_n(\omega_i - \omega_o)_n = Q_e(\omega_i - \omega_o)_m$$

Hence, the mechanical extract rate will be given as

$$Q_e = Q_n \frac{(\omega_{in} - \omega_o)}{(\omega_{im} - \omega_o)} \approx Q_n \frac{(p_{in} - p_o)}{(p_{im} - p_o)} \qquad \text{(A2)}$$

and the mechanical supply rate as

$$Q_s = \frac{Q_n}{r} \frac{(\omega_{in} - \omega_o)}{(\omega_{im} - \omega_o)} \approx \frac{Q_n}{r} \frac{(p_{in} - p_o)}{(p_{im} - p_o)} \qquad \text{(A3)}$$

where

$$r = \frac{Q_e}{Q_s}$$