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Interzone Air Movement and its Effect on Condensation in Houses

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ABSTRACT

The work is concerned with measuring interzone air movement and investigating its effect on condensation in traditionally built houses. Air flows through a doorway between the lower and upper floors of a house were measured using a tracer gas technique. To study the effect of the temperature difference on interzone air flows, the lower floor of a house was heated to various temperatures in the range 18–35°C using thermostatically controlled heaters. The upper floor was unheated. Two portable SF_6 systems fitted with electron-capture detectors were used for measurements of interzonal air flow. The doorway coefficient of discharge was found to be a function of the temperature difference between the two floors of the house. In the second part of the paper, the effect of interzone air movement on condensation is considered. A two-zone moisture transfer model was established and the effect of a kitchen extract fan on the air flow patterns in the house is discussed.

NOTATION

A_1, A_2	Air change rates per hour in zones 1 and 2 respectively (h^{-1})
C_d	Coefficient of discharge (dimensionless)
C_1, C_2	Concentrations of the tracer at time t in zones 1 and 2 respectively (arbitrary units)

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d_{v0}	Ambient absolute humidity (g/m^3)
d_{v1}, d_{v2}	Absolute humidities for zones 1 and 2 respectively (g/m^3)
F	Volumetric flow rate (m^3/s)
g	Acceleration due to gravity (m/s^2)
H	Height of the opening (m)
M_{g1}, M_{g2}	Moisture release rates in zones 1 and 2 respectively (g/s)
P_{v1}, P_{v2}	Vapour pressures in zones 1 and 2 respectively (N/m^2)
RH_1, RH_2	Relative humidities in zones 1 and 2 respectively
T	Mean absolute temperature of the two zones (°C or K as specified)
T_1, T_2	Average values of the air temperature in zones 1 and 2 respectively (°C or K as specified)
V_1, V_2	Volumes of zones 1 and 2 respectively (m^3)
W	Width of the opening (m)
β	Coefficient of thermal expansion (K^{-1})
ΔT	Average temperature difference between the two zones (°C or K)
$\Delta\rho$	Air density difference between the two zones (kg/m^3)
ρ	Average air density (kg/m^3)

1 INTRODUCTION

Interzonal air movement in houses is an important factor influencing the transfer of heat between various rooms, control of indoor air quality and condensation. Considerable attention has been given to interzone heat and mass transfers via doorways and algorithm energy models have been developed.[1] To test these algorithms, experimental work has been carried out by various researchers to study natural convection via openings in small-scale models and full-size rooms.[2-4] Although these tests are useful, measurements in houses are essential in order to determine the real air flow patterns and to develop improved algorithms. Some studies[5,6] have been carried out in passive solar houses, but little information has been published on heat and mass transfers in traditionally built houses. Interzone air movements within the house via, for example, the doorway, can create heat losses and draughts, and lead to condensation.

To improve energy efficiency in houses, attempts are made to reduce heat losses which result from poor thermal insulation and high air infiltration rates. The use of wall insulation, draught-proofing and replacement of open fires by flue gas heaters is now common practice and as a result the concentration of indoor air contaminants, particularly water vapour, is increased. The detrimental effects of condensation, including deterioration of building fabric, peeling of wallpaper and mould growth,[7] have become serious and widespread problems affecting buildings in many countries.[8]

In winter, many people, especially those of low income, do not heat their homes as a whole, but only those rooms in use by the occupants. Air movement carries water vapour produced in the kitchen and living room, which are usually heated to 22°C, to other parts of the house, such as the unheated bedrooms, where condensation occurs. Condensation problems cannot be solved by zone heating alone as house insulation, ventilation and air movement are significant factors. It is therefore important to study ventilation and air movement within the house under a range of test conditions.

A number of mathematical models[8] has been developed to study energy and moisture transfers in buildings. Some of these models assume fixed values for the infiltration rate and interzone heat-transfer coefficient, while others regard the building as a single uniformly mixed zone. There is an urgent need to perform experimental studies on moisture and energy transfer so that a unified and accurate model describing these parameters may be developed.

This paper is divided into two main sections. The first describes measurements of interzone air movements in a traditionally built house. The second section is focused on the effect of air flow patterns on interzone moisture movements. A two-zone moisture transfer model based on the derived mass flow algorithm is presented. The effect of a kitchen extract fan on air flow patterns in the house is also discussed.

Experimental studies were carried out in a three-bedroomed house in Milton Keynes, UK. The interzonal air flow rate was measured using sulphur-hexafluoride tracer gas, while the temperatures at various points in the house were measured using thermocouples. This paper also describes the SF_6 system and measurement procedure along with an analysis of the experimental results obtained.

2 INTERZONE AIR MOVEMENTS THROUGH A DOORWAY

Figure 1 is a schematic diagram of a house in which the downstairs and upstairs are designated zones 1 and 2 respectively. Air can infiltrate from outside the house into each zone (F_{01} and F_{02}) and exfiltrate from each zone to the outside (F_{10} and F_{20}). In addition, air can be exchanged between the two zones in both directions (F_{12} and F_{21}). The air flow rate between the two zones may be varied by heating zone 1 to different temperatures. Assume a doorway of height H and width W separates the two zones. The mean temperatures for zones 1 and 2 are T_1 and T_2, respectively. The pressure

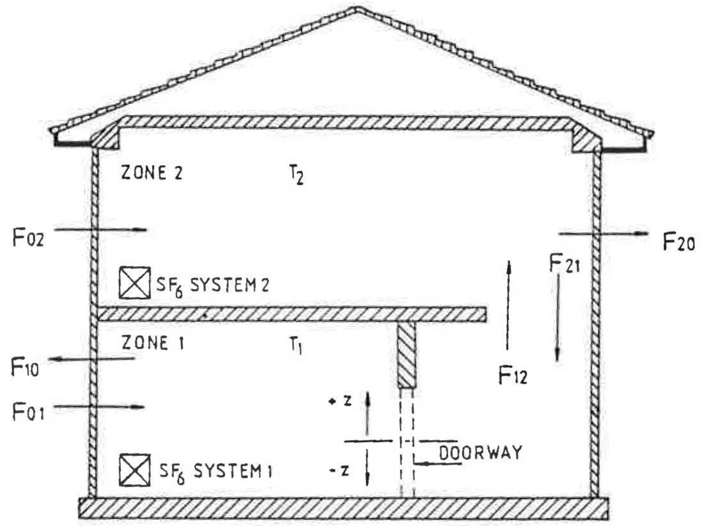

Fig. 1. Interzone air flows in a house via a doorway.

difference at the centreline ($z = 0$) is zero. The pressure difference, ΔP, caused by stack effect at height z, is

$$\Delta P = P_1 - P_2 = (\rho_1 - \rho_2)gz \tag{1}$$

The volumetric flow rate through an infinitesimal area may be estimated by applying the orifice equation as follows:

$$dF = C_d W(dz)(2\Delta P/\rho)^{0\cdot 5} \tag{2}$$

Substituting from eqn (1) into (2) and integrating gives the flow through the top half of the doorway:

$$F = \int_{z=0}^{z=H/2} dF = (C_d W/3)[gH^3 \Delta\rho/\rho]^{0\cdot 5} \tag{3}$$

Because the coefficient of thermal expansion, $\beta = 1/T = -\Delta\rho/(\rho\Delta T)$, eqn (3) can be rewritten as follows:

$$F = (C_d W/3)[gH^3 \Delta T/T]^{0\cdot 5} \tag{4}$$

In the above analysis, it has been assumed that the flow of air is one-dimensional and the viscous effect has been neglected. The influence of viscosity, the temperature distribution in each zone and the shift of the neutral plane are given in Ref. 9. The coefficient of discharge for a doorway in a vertical partition separating a two-zone enclosure is dependent on a number of parameters, such as the Reynolds number, size of the doorway, zone geometries and experimental conditions. Various values have been measured in previous studies, but a theoretical value of 0·61 has been used by many researchers.[2]

To estimate the air-flow rate through the doorway, measurements were carried out using a single-tracer gas technique.[10] This technique was used as it is simple and requires less expensive equipment than does the multi-tracer gas technique. Several tracer gases are available, but sulphur hexafluoride has been chosen for this work as it has desirable tracer gas characteristics in terms of detectability, safety and cost, and has been used successfully in previous air movement studies.[10-12]

The experimental procedure was as follows. A certain quantity of tracer gas is released in zone 1 while all its doors and windows are closed. Following tracer gas mixing, the communication door between the two zones is opened and the decay of tracer gas is then monitored. Some tracer gas will be carried into zone 2 where it will mix with air and some will return to zone 1. If one applies the tracer material balances in each zone, assuming that a steady state exists and that the concentration of tracer gas in the outside air is negligible, then the rate of change of tracer concentration in zone 1 at time t is given by

$$V_1\, dC_1/dt = -C_1(F_{10} + F_{12}) + C_2F_{21} \tag{5}$$

Similarly, the rate of change of tracer concentration in zone 2 at time t is given by

$$V_2\, dC_2/dt = C_1F_{12} - C_2(F_{21} + F_{20}) \tag{6}$$

The other two flow rates can then be determined using the continuity equations as follows:

$$F_{01} = F_{12} + F_{10} - F_{21} \tag{7}$$

$$F_{02} = F_{20} + F_{21} - F_{12} \tag{8}$$

Tracer gas equations were solved using the Sinden[13] method, with the modification of introducing the discrete time model as described in detail in Ref. 14. The tracer gas technique used in this work has been validated in the laboratory by measuring the air flow between two small chambers with an independent flow meter. The agreement between the SF_6 tracer calculation of air flow and that measured with a calibrated flow meter was $\pm 5\%$.

2.1 Experimental

Air flow measurements were carried out using two portable microcomputer systems (Fig. 2). The two systems are identical in construction and are described in detail by Riffat *et al.*[15] In essence, each system consists of the following major components: a sampling and injection unit, a column, a

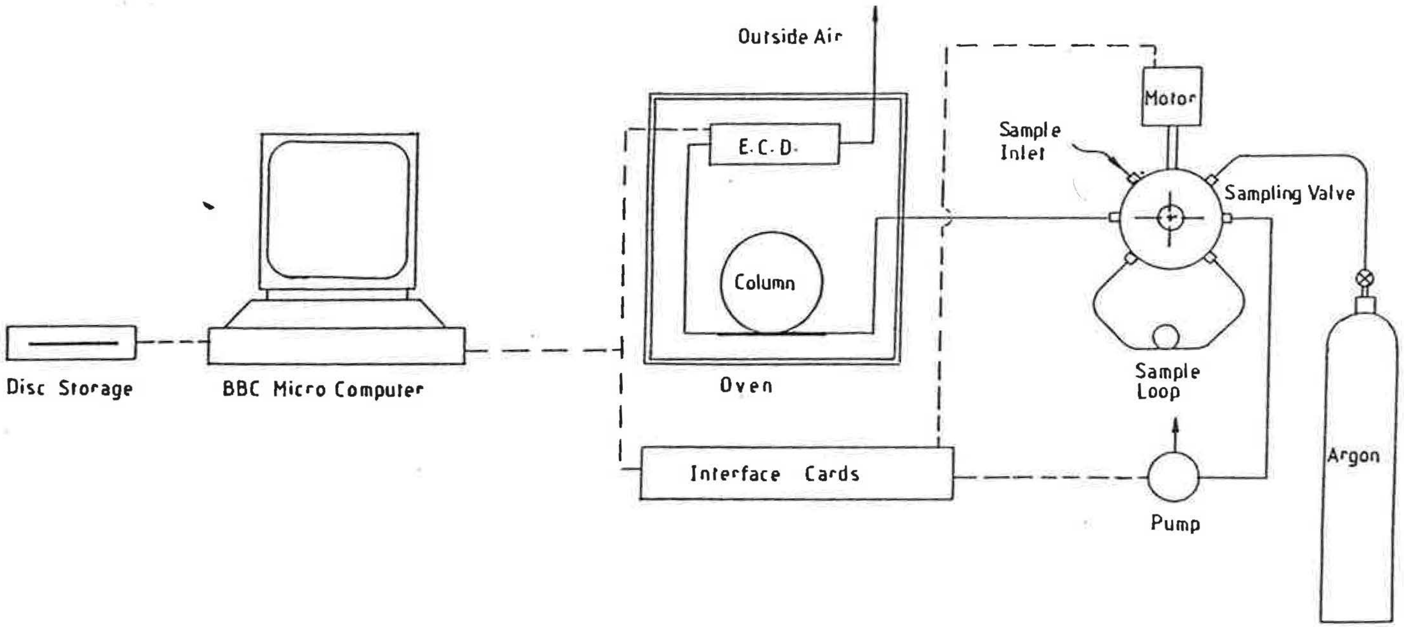

Fig. 2. The portable SF_6 system.

chromatographic oven, an electron-capture detector and a microcomputer and interface.

The sampling unit consists of a two-position, six-port valve, connected to a 0·5 cm^3 sampling loop. The valve can be rotated to position 1 or 2 using a small motor. The separation column was made by packing a 1·5 m length × 4·3 mm i.d. nylon tube with 60–80 mesh aluminium oxide. The column was held at 35°C in a thermostatically controlled electric oven. The electron-capture detector, which uses a ^{63}Ni radioactive cell, was made by Pye-Unicam Ltd, Cambridge, UK.

Temperature measurements were carried out at various points in each zone using copper–constantan thermocouples. The outside temperature and wind speed during the measurement period were also recorded. A data logger, type MDL1000, with a built-in cold junction compensation network, was used for this purpose.

Measurements of interzone air movements were carried out in a three-bedroomed, semi-detached house. The downstairs floor, zone 1, has a volume of 65·5 m^3 and contains a living room, dining room and kitchen. The upstairs, zone 2, has a volume of 92 m^3 and contains a bathroom, three bedrooms, stairway and hall. The two zones are separated by a single doorway. The space heating in this house was accomplished using a hot-water radiator system. In order to achieve high temperatures in zone 1, four additional thermostatically controlled electric heaters were used.

To estimate the air-flow rates between the two zones, two SF_6 systems were used. The first system was used to collect samples from zone 1, while the second was used to collect samples from zone 2. At the beginning of each test the communication door between the two zones was closed and gaps between the door and its frame were sealed with tape. This prevented tracer gas leakage prior to starting the test. A known volume of tracer gas was released downstairs from a syringe where it was mixed with air using an oscillating desk-fan. After a mixing period of about 30 min the sealing tape was removed and the communication door was opened. Samples were taken every 3 min for a total experimental time of 90 min. The SF_6 systems analysed the samples *in situ* to provide instantaneous readings of gas concentration in each zone.

Several experiments were carried out in this house under a variety of temperature differences between the two zones. In some experiments the house central-heating system and electric heaters were switched off. In other experiments, only the lower floor was heated, to temperatures in the range 18–35°C. The heaters in zone 1 were switched on about 5 h before the beginning of a test to enable the heaters and air in the zone to reach a steady temperature. The temperature difference between the two zones, the outside temperature and wind speed for various tests are given in Table 1.

TABLE 1
Experimental Conditions

Run no.	Temperature difference between zones 1 and 2 (°C)	Outside temperature (°C)	Wind speed (m/s)
1	0·5	9·5	4·0
2	1·6	7·7	2·0
3	3·4	8·4	4·1
4	4·4	1·7	4·5
5	5·6	8·5	3·4
6	6·6	1·8	3·7
7	7·6	5·9	2·0
8	8·1	5·3	2·0
9	13·0	4·6	2·6

2.2 Specimen results and discussion

Figures 3 and 4 show tracer gas concentration vs time for two temperature differences. The smoothness of the tracer decay curve indicates that the mixing of tracer gas with air in both zones was uniform. Tests were carried

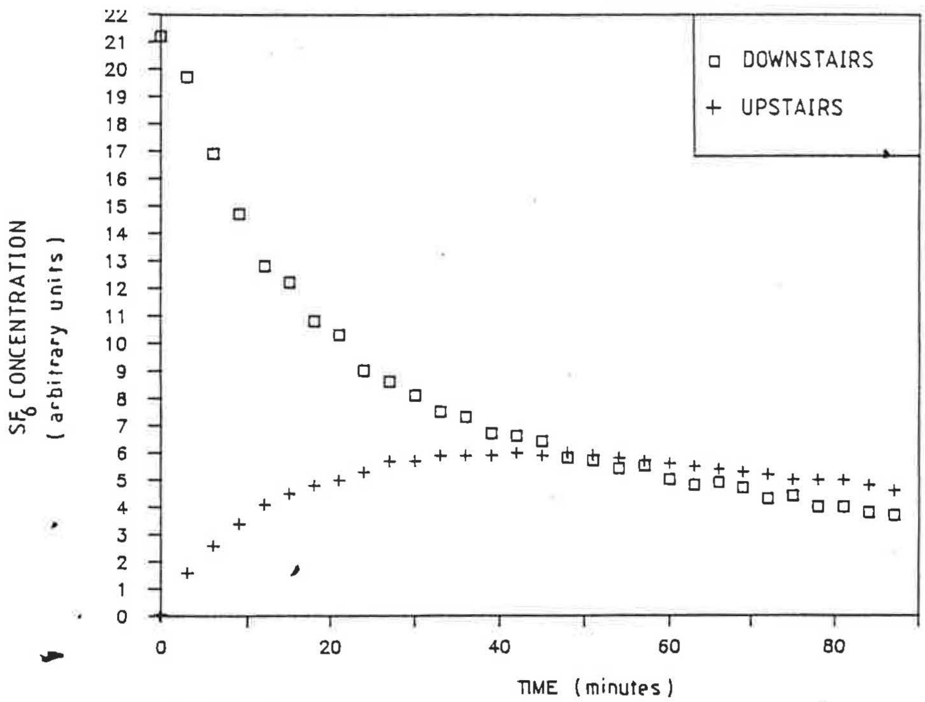

Fig. 3. The decay of SF_6 tracer gas in zones 1 and 2; $\Delta T = 1{\cdot}6°C$.

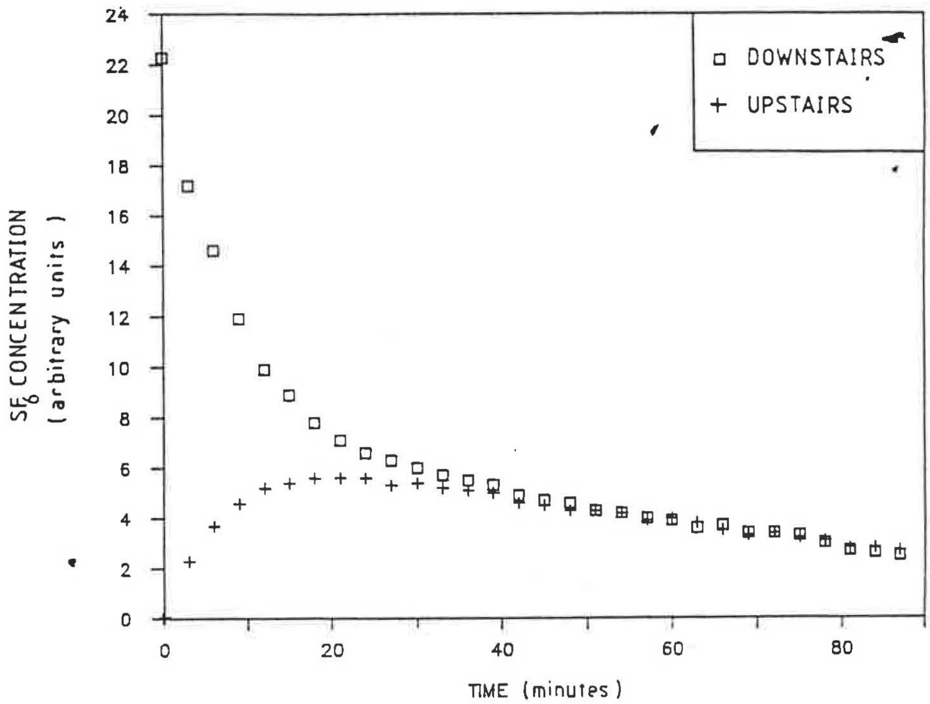

Fig. 4. The decay of SF_6 tracer gas in zones 1 and 2: $\Delta T = 13°C$.

out for average temperature differences between 0·5 and 13 K. These experiments showed that the total air exchange between the two zones through the doorway is a function of the temperature difference.

To evaluate the coefficient of discharge for the doorway, the air flow rate measured using the tracer gas technique was divided by the theoretical air flow rate described in Section 1 as follows:

$$C_d = \frac{\text{measured air flow rate using tracer gas}}{(W/3)[gH^3 \Delta T/T]^{0 \cdot 5}} \quad (9)$$

The coefficient of discharge was found to decrease from about 0·61 to 0·22 as the temperature difference between the two zones increased from 0·5 to 13 K. These results correlated well with

$$C_d = 0 \cdot 0835[\Delta T/T]^{-0 \cdot 313} \quad (10)$$

The decrease in coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of some cold air from the upper floor into the inflowing warm air from downstairs. In addition, the increase in density difference can cause an increase in turbulence within the two zones which influences the coefficient of discharge.

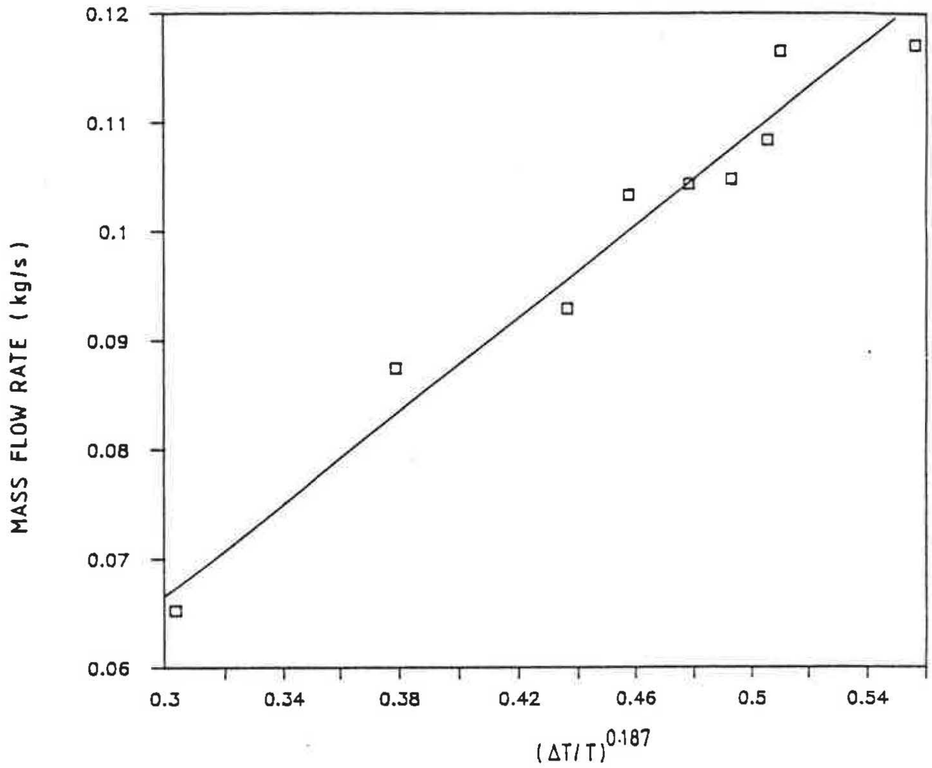

Fig. 5. The mass flow rate vs $[\Delta T/T]^{0 \cdot 187}$.

By substituting from eqn (10) into eqn (4), the mass flow rate between the two zones can be given in the form

$$M = 0 \cdot 0278 \rho W (gH^3)^{0 \cdot 5} [\Delta T/T]^{0 \cdot 187} \qquad (11)$$

The mass flow rate vs $[\Delta T/T]^{0 \cdot 187}$ is shown in Fig. 5. It is clear from this figure that the flow rate increases linearly with $(\Delta T/T)^{0 \cdot 187}$.

3 INTERZONE MOISTURE TRANSFERS

The occurrence of condensation in houses depends on the following parameters:

(1) temperature and moisture content of the air in each room;
(2) temperature and moisture content of the incoming air;
(3) surface temperature and cold bridges in the room;
(4) thermal resistance and permeability of the construction material; and
(5) ventilation rate and interzone air movements

Only the ventilation and interzone air movement factors are considered in this investigation, as separate studies of effects of thermal insulation and cold bridges have been carried out by other researchers.[8] The moisture content in the air within a house is raised above the moisture content of the external air by evaporation of moisture mainly from cooking, washing, drying and the metabolic processes of the occupants. The increase in the amount of water vapour within a warm zone raises the vapour pressure of the air and causes the moist air to convect to areas of lower vapour pressure, i.e. poorly heated bedrooms and the unheated roof space.

3.1 A two-zone moisture transfer model

A steady-state moisture transfer model is used to estimate internal vapour pressure. The model treats the house as two separate zones, as shown in Fig. 1. It is assumed that the moisture release rate in zone 1 is M_{g1} and that in zone 2 is M_{g2}. The amount of moisture transfer in each zone can be calculated by applying equations describing the conservation of mass of water.

The rate of moisture increase in zone 1 is given by

$$d(d_{v1})/dt = F_{01}\,d_{v0} + F_{21}\,d_{v2} - F_{10}\,d_{v1} - F_{12}d_{v1} + M_{g1} \tag{12}$$

Similarly, the rate of moisture increase in zone 2 is given by

$$d(d_{v2})/dt = F_{02}\,d_{v0} + F_{12}\,d_{v1} - F_{20}\,d_{v2} - F_{21}d_{v2} + M_{g2} \tag{13}$$

Assuming a steady-state moisture transfer in the two zones, eqns (12) and (13) become respectively

$$F_{01}\,d_{v0} + F_{21}\,d_{v2} - F_{10}\,d_{v1} - F_{12}d_{v1} + M_{g1} = 0 \tag{14}$$

$$F_{02}\,d_{v0} + F_{12}\,d_{v1} - F_{20}\,d_{v2} - F_{21}d_{v2} + M_{g2} = 0 \tag{15}$$

Rearranging eqns (14) and (15) for d_{v1} and d_{v2}, substituting for d_{v2} from eqn (14) into eqn (15) and substituting for d_{v1} from eqn (15) into eqn (14), the following equations are obtained:

$$d_{v1} = \frac{[F_{01}(F_{20}+F_{21}) + F_{02}F_{21}]}{(F_{10}+F_{12})(F_{20}+F_{21}) - F_{12}F_{21}}\,d_{v0} + \frac{F_{21}M_{g2} + (F_{20}+F_{21})M_{g1}}{(F_{10}+F_{12})(F_{20}+F_{21}) - F_{12}F_{21}} \tag{16}$$

$$d_{v2} = \frac{[F_{02}(F_{10}+F_{12}) + F_{01}F_{12}]}{(F_{10}+F_{12})(F_{20}+F_{21}) - F_{12}F_{21}}\,d_{v0} + \frac{F_{12}M_{g1} + (F_{10}+F_{12})M_{g2}}{(F_{10}+F_{12})(F_{20}+F_{21}) - F_{12}F_{21}} \tag{17}$$

The air infiltration rates from outside the house in each zone are given by eqns (7) and (8).

The air change rates in zones 1 and 2 are respectively

$$A_1 = (F_{10} + F_{12})/V_1 \qquad (18)$$

$$A_2 = (F_{20} + F_{21})/V_2 \qquad (19)$$

Substituting from eqns (7), (8), (18) and (19) into eqns (16) and (17), and simplifying, gives

$$d_{v1} = d_{v0} + \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \qquad (20)$$

$$d_{v2} = d_{v0} + \frac{F_{12}M_{g1} + A_1V_1M_{g2}}{(A_1V_1A_2V_2 - F_{12}F_{21})} \qquad (21)$$

The absolute humidities, d_{v1} and d_{v2}, are given by[16]

$$d_{v1} = 2{\cdot}17P_{v1}/T_1 \qquad (22)$$

$$d_{v2} = 2{\cdot}17P_{v2}/T_2 \qquad (23)$$

It is also assumed that

$$K_1 = \frac{F_{21}M_{g2} + A_2V_2M_{g1}}{(A_1V_1A_2V_2 - F_{12}F_{21})}$$

$$K_2 = \frac{F_{12}M_{g1} + A_1V_1M_{g2}}{(A_1V_1A_2V_2 - F_{12}F_{21})}$$

Substituting from eqn (22) and (23) into eqns (20) and (21), respectively and using K_1 and K_2 as defined above, eqns (20) and (21) become

$$P_{v1} = (T_1/T_0)P_{v0} + 0{\cdot}461K_1T_1 \qquad (24)$$

$$P_{v2} = (T_2/T_0)P_{v0} + 0{\cdot}461K_2T_2 \qquad (25)$$

3.2 Moisture movements between upstairs and downstairs

The mean internal vapour pressures for the lower and upper floors of the house were calculated using the above moisture transfer model. The external vapour pressure, at 5°C and 95% RH, was taken from BS5250 (Ref. 17) as 0·83 kPa.

Moisture generation and distribution between the two zones are important in estimating the internal vapour pressure. It is estimated that between 4 and 12 kg of moisture may be generated within the home each day.[7] In this work, three levels of moisture release rates were assumed, namely 4, 8 or 10 kg/day, and these were distributed between the two zones on the basis of occupancy and appliance use (e.g. cooker, tumble-drier and shower). Typical moisture-generation rates for various heating appliances and occupant activities are given by CIBSE[18] as shown in Table 2.

Infiltration and interzone air movements in the house were measured experimentally using a single-tracer gas technique, the derived algorithm, described in Section 1, being used to determine the mass flow rate between the two zones. The following assumptions were made for the purpose of the theoretical analysis:

(a) The lower and upper floors of the house were assumed to be heated to different temperatures. The mean internal temperatures of the lower floor were 12·5, 14·5, 16·5, 18·5, 20·5, 22·5, 24·5, 26·5 or 28·5°C and the corresponding mean temperatures of the upper floor were 12, 13·5, 15, 16·5, 18, 19·5, 21, 22·5 or 24°C. The temperature differences between the two floors were therefore 0·5, 1, 1·5, 2, 2·5, 3, 3·5, 4 and 4·5°C.

(b) The lower floor was heated to mean temperatures of 12·5, 14·5, 16·5, 18·5, 20·5, 22·5, 24·5, 26·5 or 28°C while the upper floor was kept at 12°C.

TABLE 2
Sources of Moisture Within Buildings

Source	*Amount of moisture*
Combustion in flueless room heaters/cookers	
Paraffin	0·1 kg/h per kW
Natural gas	0·16 kg/h per kW
Butane	0·12 kg/h per kW
Propane	0·13 kg/h per kW
Household activities	
Cooking (3 meals)	0·9–3·0 kg/day
Dish washing (3 meals)	0·15–0·45 kg/day
Clothes washing	0·5 to 1·8 kg/day
Clothes drying indoors	5·0 to 14 kg/day
Baths and showers	0·75 to 1·5 kg/day
Floor washing	1·0 to 1·5 kg/10 m^2
Indoor plants	up to 0·8 kg/day
Perspiration and respiration of building occupants	0·04 to 0·1 kg/h per person
Direct penetration of rain, groundwater or moist ambient air	Variable
'Drying out' of water used in construction of building	4 000 kg in 1 year for medium-sized office building

From Section A.10 of the CIBSE Guide.[18]

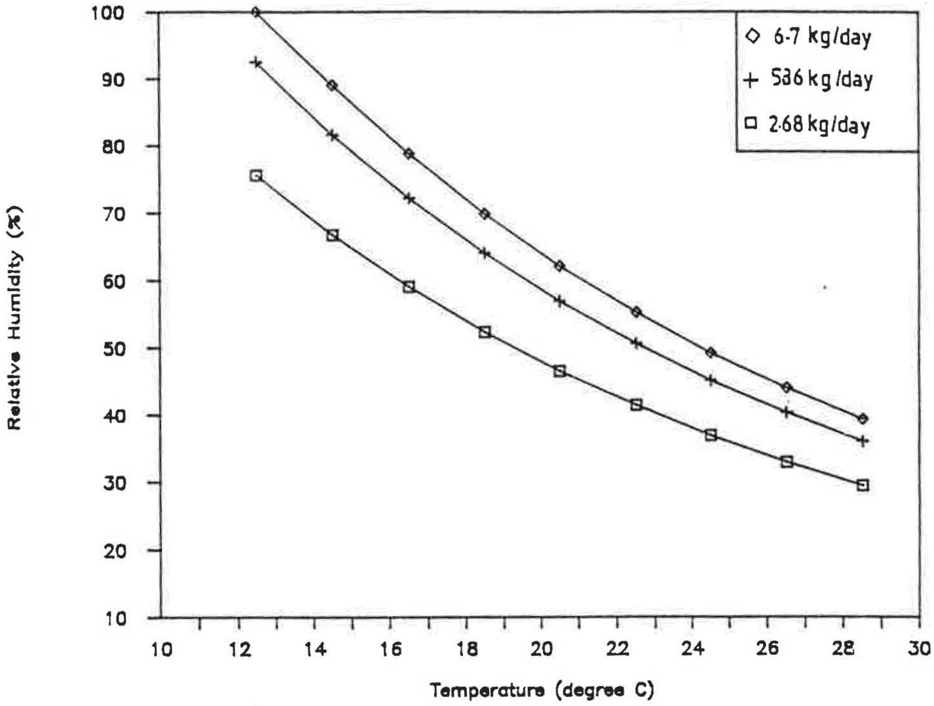

Fig. 6. The variation of relative humidity with temperature for zone 1; moisture release rate = 2·68, 5·36 or 6·7 kg/day (case a).

3.2.1 Analysis of results for case (a)

The internal vapour pressures were calculated using the mean internal temperatures, the amount of moisture generated in each zone, the air change rates and the interzone air flow. The mean internal vapour pressure and saturated vapour pressure were used to estimate the mean RH. Figures 6 and 7 show the variation of RH with temperature for the lower floor and upper floor of the house, respectively. The effects of variations in moisture release rate are clearly shown in these figures. Relative humidities in the range 75–100% are obtained in zone 1, for an air change of $0{\cdot}7\,h^{-1}$ and a temperature of about 12°C. It is recommended[19] that the RH should be less than 70% to prevent mould growth, which implies temperatures in the range 14·5–18·5°C are required. Similarly, the RH in zone 2 is found to be high when the temperature is low and the moisture release rate is large.

The RH difference between the upper and lower floors vs the temperature difference between the two floors is presented in Fig. 8. The RH difference, $RH_2 - RH_1$, is found to increase from about 0·5% to about 9·5% (depending on the moisture release rate) as the temperature difference is increased from 0·5 to 4·5°C.

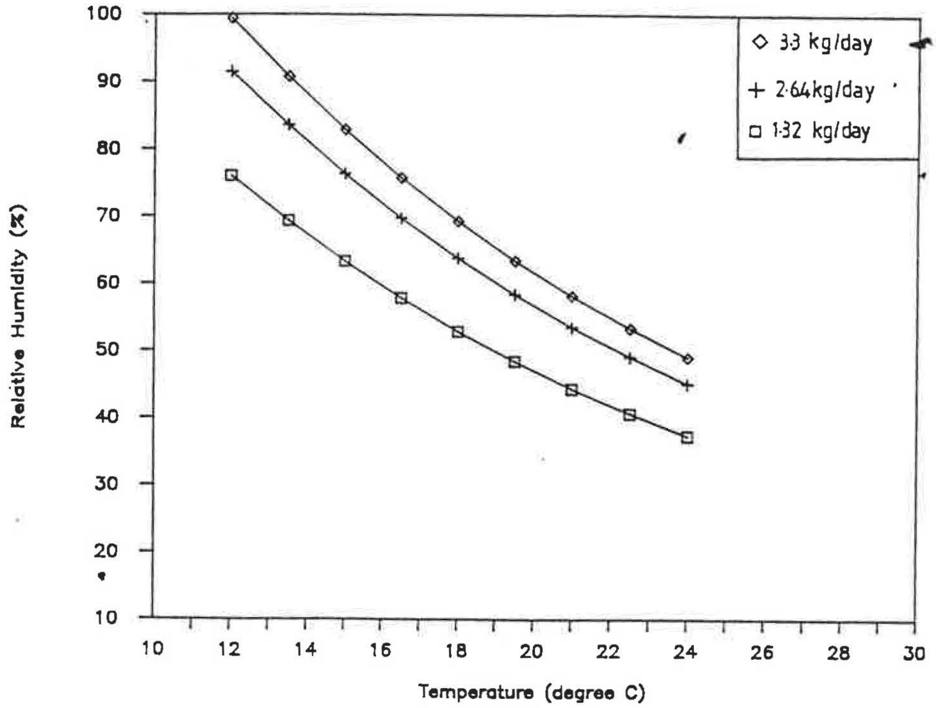

Fig. 7. The variation of relative humidity with temperature for zone 2; moisture release rate = 1·32, 2·64 or 3·3 kg/day (case a).

The effects of interzone air flows on the RH in the lower and upper zones are shown in Fig. 9 and 10. These figures show that for zone 1, the condition including interzone air flow results in an RH about 8% lower than that for the condition with no interzone air flow. In the case of zone 2, the RH for the condition with interzone air flow is about 10% higher than that for the condition with no interzone air flow.

3.2.2 Analysis of results for case (b)

This assumption is valid when only the lower floor of the house is provided with heating. The estimated RH for the upper floor is about 92% for a mean internal temperature of 12°C and a moisture release rate of 2·64 kg/day. This high RH would lead to condensation and mould growth.

The variation of $RH_2 - RH_1$ with temperature difference is shown in Fig. 11. Relative humidity differences in the range 45–60% may be reached for a temperature difference of 16·5°C. This situation is likely to occur when the kitchen reaches high temperatures during cooking periods. Even so, RH differences in the range 35–45% may exist if the lower floor is heated to about 22°C while the upper floor is held at 12°C.

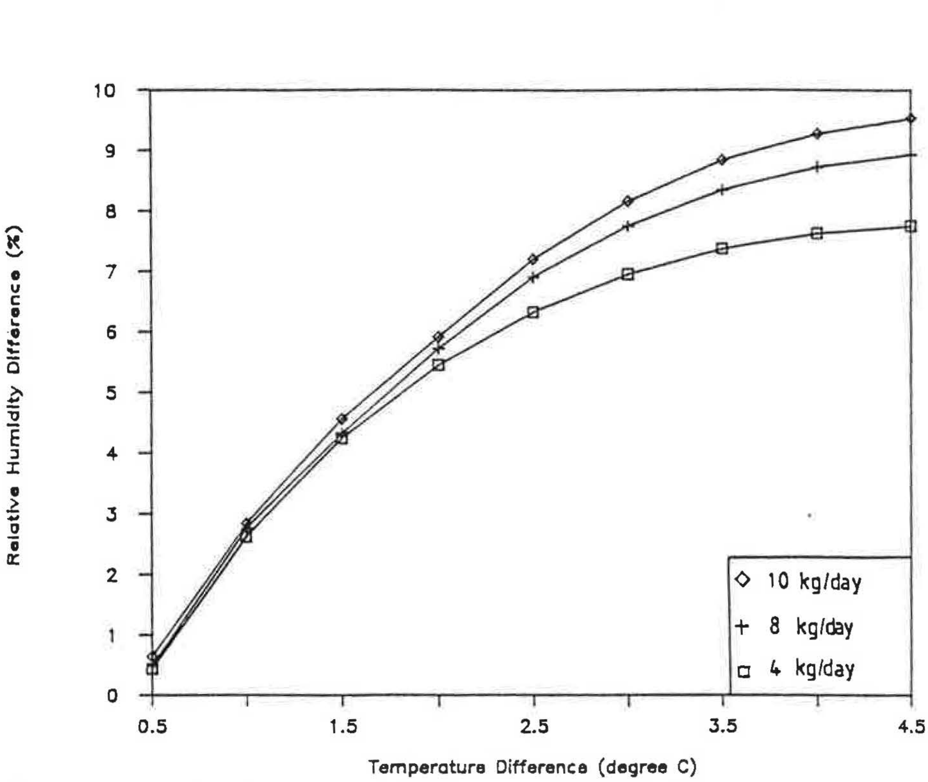

Fig. 8. The variation of $RH_2 - RH_1$ with temperature; total moisture release rate of 4, 8 or 10 kg/day (case a).

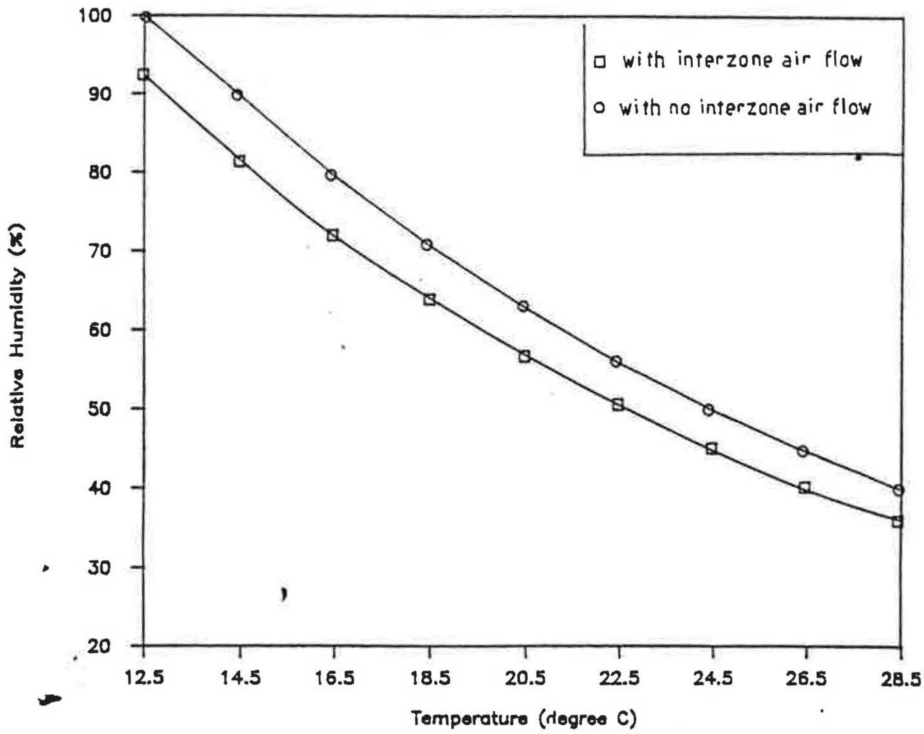

Fig. 9. The effect of interzone air flow on the relative humidity in zone 1; total moisture release rate = 8 kg/day (case a).

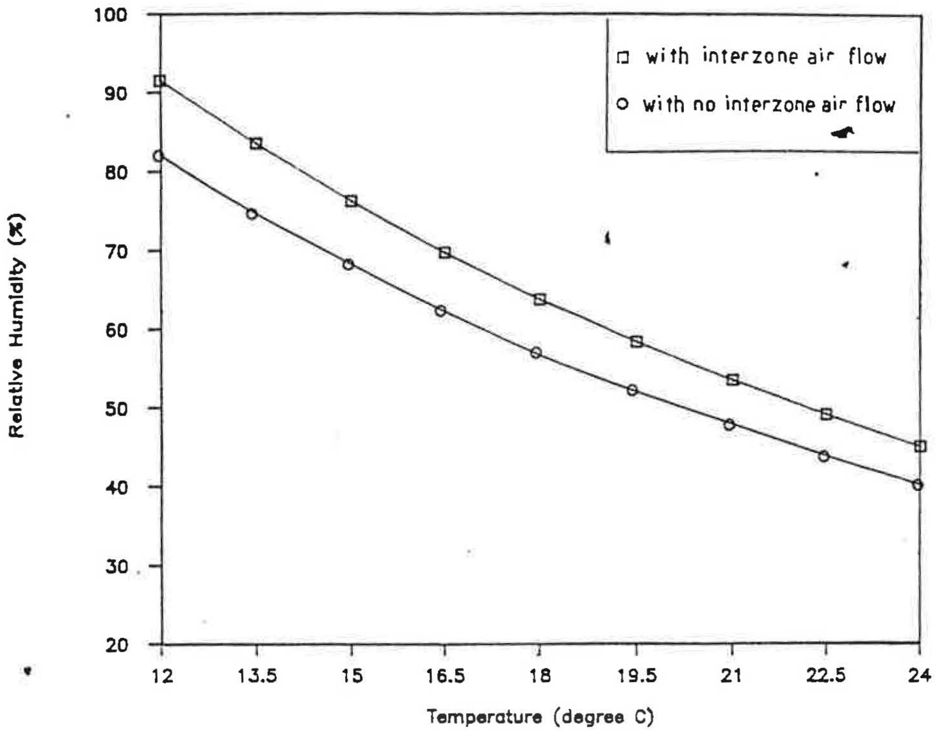

Fig. 10. The effect of interzone air flow on the relative humidity in zone 2; total moisture release rate = 8 kg/day (case a).

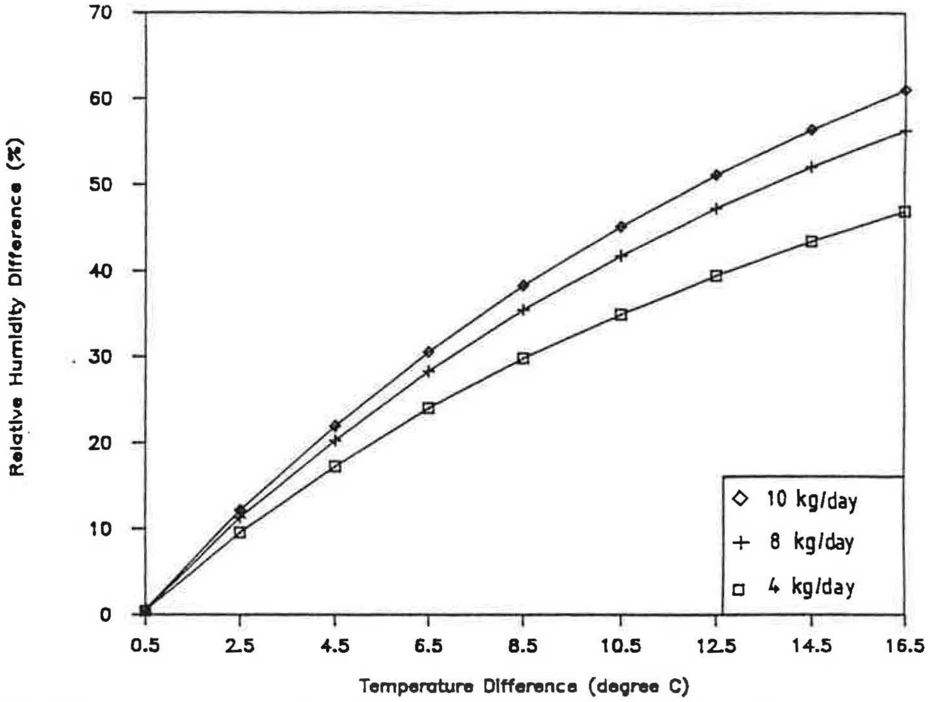

Fig. 11. The variation of $RH_2 - RH_1$ with temperature; total moisture release rates of 4, 8 or 10 kg/day (case b).

The effect of interzonal air flow on the RH in zone 2 has been calculated. If the interzone air flows F_{12} and F_{21} are included, the calculated RH_2 is about 10% higher than for the condition with no interzone air flow.

3.3 Kitchen extract fans

Installation of a kitchen extract fan is widely recommended as a remedial measure to limit condensation in houses. The purpose of using a fan is to remove moisture-laden air from the zone in which water vapour is generated and also to minimise the flow of warm moist air from the lower floor to the upper floor of the house where condensation normally occurs. Most houses nowadays are provided with extract fans, and it is generally assumed that the use of a 150 mm fan (extract rate about 290 m^3/h) is effective in preventing migration of moisture from the kitchen to the rest of the house. There is lack of theoretical and experimental evidence to support this assumption and the effectiveness of kitchen extract fans can only be determined by a more rigorous investigation.

To study the effect of a manually controlled kitchen extract fan on the air flow patterns in the house, two different tests were conducted. In the first test the central-heating system was switched off while in the second test only the lower floor was heated. Figure 12 is a schematic diagram of interzonal air flow for the first test. The use of an extract fan increases F_{10} from 59 to 231 m^3/h but has only a slight effect on interzone air flow. With the extract

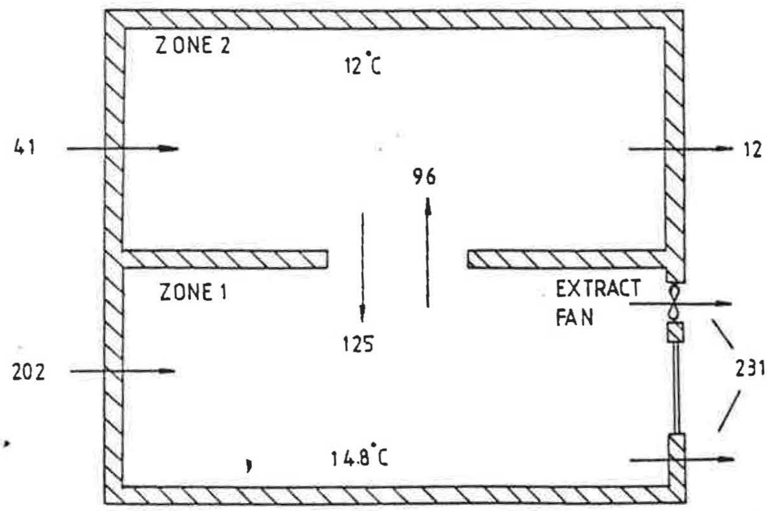

Fig. 12. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system switched off (units m^3/h).

fan in operation, F_{12} and F_{21} were found to be 96 and 125 m^3/h, compared with 105 and 97 m^3/h with the extract fan switched off.

Figure 13 shows the interzonal air flow for the second test. The limitations of the extract fan are clearly indicated in this figure. For a temperature difference of about 5·6°C, F_{12} was increased from 96 to 180 m^3/h while F_{10} was reduced from 231 to 121 m^3/h. The two tests indicate that the use of a 290 m^3/h capacity fan does not prevent moisture movement to other rooms. Calculations were carried out to establish the minimum extract rate which would limit condensation in the kitchen and prevent air flow from the lower floor to the upper floor of the house. Condensation may be avoided if the RH in a zone does not exceed 70% (Ref. 20). Using an RH of 60% and a total moisture release rate of 8 kg/day, the fan extraction rate should be about 600 m^3/h. This represents more than twice the rate which is recommended by the BS5250. The effectiveness of an extract fan depends on whether kitchen doors to the rest of the house are open or closed and also on the local wind speed and direction. The location of the fan in the kitchen is important, and ideally it should be positioned close to the cooker and at a high level.

Installation of manually controlled fans has been found ineffective as a remedial measure to limit condensation, as these fans have small extract rates and are under-used by the occupants.[21] As an alternative, extract fans controlled by a humidistat have been used in a number of houses. These fans were found to be more effective in reducing condensation in the kitchen, but as they had small extract rates, they were ineffective in reducing moisture movement to the rest of the house.

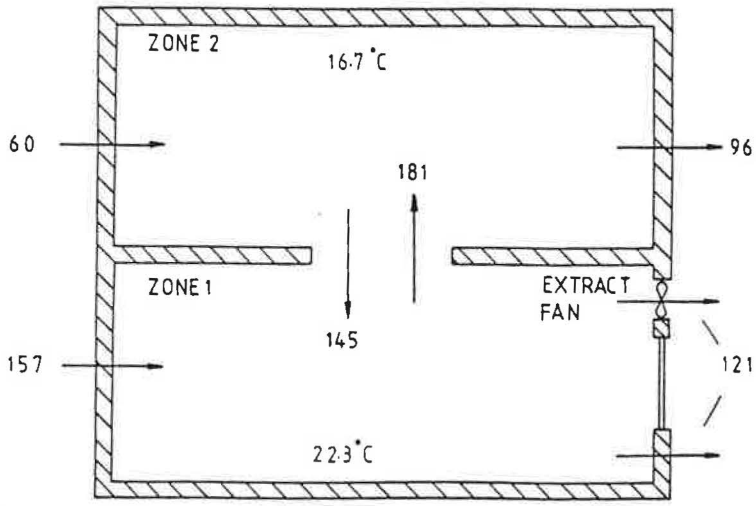

Fig. 13. The effect of a kitchen extract fan on air flow patterns in the house, with central heating system in zone 1 switched on (units m^3/h).

CONCLUSIONS AND RECOMMENDATIONS

(1) The experimental results indicate that the coefficient of discharge C_d is dependent on the temperature difference. Further experimental work is required to study the effects of the geometry of the house and the size of the doorway on the value of C_d.

(2) The use of the SF_6 systems has proved to be a simple and practical approach for measuring interzone air movement between the two floors of the house. However, for multi-zone measurements in large buildings, the use of a multi-tracer gas technique[15,22] is preferable as it would reduce the time required to make the measurements and may lead to greater experimental accuracy.

(3) Tests are also required to establish correlations for traditionally built houses under a variety of boundary conditions. Limited studies of interzone heat and mass transfers under combined natural and forced convection have been carried out and the subject requires further investigation.

(4) The mass flow rate between the lower and upper floors was found to increase significantly with increasing temperature difference. The effect of interzone air flows on moisture transfer was found to be significant and therefore should be included in condensation models.

(5) The use of a manually operated kitchen extract fan was found to be ineffective in reducing air flows from the lower floor to the upper floor of the house. Further work is required to establish the optimal extract rate of a fan for prevention of condensation in the kitchen and for reduction of moisture movement to the rest of the house.

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