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INTERZONE AIR MOVEMENT AND ITS EFFECT ON CONDENSATION

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SUMMARY

The work is concerned with measuring interzone air movement and investigating its effect on condensation in a traditionally built house. Air flows through a doorway between the lower and upper floors of a house were measured using a single tracer gas technique. To study the effect of the temperature difference on interzone air flows, the lower floor of the 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 employed for the measurement of interzonal air flow. The concentration of tracer gas and the temperature difference between the two floors were used to estimate the heat and mass transfer through the doorway. Results were compared with the values predicted by the existing algorithms for two zone enclosures. The doorway coefficient of discharge was found to be a function of the temperature difference between the 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.

INTRODUCTION

Interzonal air movement in houses is an important factor influencing transfer of heat between various rooms, control of indoor air quality and condensation. Considerable attention has been given to interzone heat and mass transfer via doorways and theoretical 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 [2,3,4]. 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 transfer in a traditionally built houses. Interzone air movement within the house via, for example, the doorway can create heat losses, 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 practise and as a result the concentration of indoor air contaminants, particularly water vapour is increased. The deterimental effects of condensation including deterioration of building fabric, peeling of wallpaper and mould growt,[7], have become serious and widespread problems affecting 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 usually heated to 22 °C, to other parts of the house, such as the unheated bedrooms, where condensation can occur. 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] have been developed to study energy and moisture transfer in buildings. Some of these models assume fixed values for the infiltration rate and interzone heat transfer coefficient while other models regard the building as a single uniformly mixed zone. There is an urgent need to perform experimental studies on interzone of 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 heat and mass transfer through a doorway in a traditional house. The results have been compared with those predicted by existing alogorithms for two-zone enclosures. The second section is focused on the effect of air flow patterns on interzone moisture movement. 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 mass transfer was measured using sulphur hexafluoride tracer gas while the temperature at various 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.

SECTION ONE : INTERZONE HEAT AND MASS TRANSFER VIA A DOORWAY

Figure .1 shows a schematic diagram of a house in which the downstairs and upstairs are designated zone 1 and zone 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 exchange between the two zones through a doorway in both directions (F_{12} and F_{21}). The mean temperatures for zone 1 and 2 are T_1 and T_2, respectively. The air flow rate between the two zones may be varied by heating zone 1 at different temperatures. The volumetric flow rate through a doorway is given by Shaw[3] as follow:

$$F = (C_d\ W/3)\ [g\ \Delta\rho\ H^3/\rho]^{0.5} \tag{1}$$

Since the coefficient of thermal expansion, $\beta = 1/T = \Delta\rho/(\rho\ \Delta T)$, equation 1 can be rewritten as follow:

$$F = (C_d\ W/3)\ [g\ \Delta T\ H^3/T]^{0.5} \tag{2}$$

The heat transfer rate (Q), heat transfer coefficient (h), Nusselt number (Nu), Prandtl number (Pr) and Grashof number (Gr) may be given by[9] :

$$Q = F\ \rho\ C_p\ \Delta T = (C_d\ \rho\ W\ C_p/3)\ [g\ \Delta T\ H^3/T]^{0.5}\ \Delta T \tag{3}$$

$$h = Q/(W\ H\ \Delta T) \tag{4}$$

$$Nu = h\ H/k \tag{5}$$

$$Pr = C_p\ \mu\ /k \tag{6}$$

$$Gr = \rho^2\ g\ \beta\ \Delta T\ H^3/\mu^2 \tag{7}$$

Equations 3-7 can be substituted in equation 2 to give:

$$Nu/Pr = (C_d/3)\ Gr^{0.5} \tag{8}$$

The above analysis assumed the flow of air is one-dimensional and air viscousity effects have been neglected. The effects of viscosity, the temperature distribution in each zone and the shift of the neutral plane on the air flow through the doorway are given in ref.10. 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, opening size, zone geometries and experimental conditions. Various values have been measured in previous studies but many researchers have assumed a value of 0.61.

EXPERIMENTAL TECHNIQUE

Air flow measurements were carried out using a single tracer gas technique[11]. 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[11,12,13].

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 decrease of tracer concentration in zone 1 at time t is given by:

$$V_1 \, dC_1/dt = - C_1 \, (F_{10} + F_{12}) + C_2 \, F_{21} \quad (9)$$

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

$$V_2 \, dC_2/dt = C_1 \, F_{12} - C_2 \, (F_{21} + F_{20}) \quad (10)$$

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

$$F_{01} = F_{12} + F_{10} - F_{21} \quad (11)$$

$$F_{02} = F_{20} + F_{21} - F_{12} \quad (12)$$

Mass-balance equations may be solved using the theoretical technique described in ref.14. An alternative method to estimate air flows between internal spaces was used by Sinden[15]. The method assumes a multi-zone system may be represented by a series of cells of known and constant volumes which are all connected to a cell of infinitely large volume, i.e., the outside space. The mass balance for each zone can be expressed by a series of equations which can be then solved using matrices. A similar method was used in our work with the modification of introducing the discrete time model[16].

The tracer gas technique used in this work has been validiated in the laboratory by measuring air flow between two small chambers and an independent flow meter. The agreement between the SF_6 tracer calculation of air flow and that measured with a calibrated flow meter was ± 5%.

INSTRUMENTATION

Air Flow Measurements

The air flow measurements were carried out using two highly portable microcomputer systems, Figure 2. The two systems are identical in construction and are described in detail by Riffat et. al.[17]. In essence, it consists of the following major components, a sampling and injection unit, a column, a chromatographic oven, an electron capture detector and a microcomputer and interface.

The sampling unit consists of a two-position, 6-port valve, connected to a 0.5 cm³ sampling loop. The valve can be easily rotated to position 1 or 2 using a small motor. The separation column was made by packing a 1.5 m length x 4.3 mm internal diameter nylon tube with 60-80 mesh aluminium oxide. The column was held at 35°C in a thermostaticly controlled electric oven. The electron capture detector, which uses Ni-63 radioactive cell, was made by Pye Unicom Ltd.

The system incorporates a BBC micro-computer, a parallel printer and interfaces for both analogue and digital data. The interfacing of the gas chromatograph and the sampling and injection units was accomplished by specially designed interface cards. The system is compact and can be used for unattended operation.

Temperature and Wind Speed Measurements

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.

The location of thermocouples in each zone is important if the heat flow between the two zones is to be measured accurately. Various approaches have been used by previous researchers studying natural convection between two-zone enclosures. Brown and Solvason [2] measured air temperatures as the average for vertical grids (floor to ceiling) located at a specific distant from the partition and the centre of the opening. Shaw and Whyte[3] used thermocouple grids suspended either in the rooms or in the doorway openings themselves. Other studies on natural convection in small scale models have involved different techniques[4].

All these methods are useful in simple enclosures but are impractical if measurements are to be carried out in houses. In this situation it is important to employ a simple method of temperature measurement which would be relevant to building designers. In this study temperature measurements were made at the centre of each room.

MEASUREMENTS AND RESULTS

Measurement of inter-zone mass and heat transfer 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 the living room, dining room and the kitchen. The upstairs, zone 2, has a volume of 92 m^3 and contains the 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 flows between the two zones the 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 heat and 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. To ensure that a uniform concentration had been achieved in zone 1, samples were taken at four sampling points. After a mixing period of about 30 minutes the sealing tape was removed and the communication door was opened. Samples were taken every 3 minutes for a total experimental time of 90 minutes. The SF_6 systems analysed the samples in-situ so providing instantaneous readings of gas concentration in each zone.

The air flows between the two zones were estimated from the tracer gas concentration data using the method described in section 2.

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 others 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 hours before the beginnig 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.

Figures 3 and 4 show tracer gas concentration versus time for two temperature differences. Tests were carried 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 measured using the tracer gas technique was divided by the theoretical air flow described in section 1 as follows:

$$C_d = \frac{\text{Measured Air Flow Using Tracer Gas}}{(W/3)\ [g\ \Delta T\ H^3/T]^{0.5}} \qquad (13)$$

The coefficent 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 were correlated well with:

$$C_d = 0.0835\ [\Delta T/T]^{-0.313} \qquad (14)$$

We believe that 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 will effect the coefficient of discharge.

By substituting equation 14 into equation 2, the mass flow rate between the two zones can be given in the form:

$$M = 0.0278\ \rho\ W\ (g\ H^3)^{0.5} [\Delta T/T]^{0.187} \qquad (15)$$

The mass flow rate versus $[\Delta T/T]^{0.187}$ is shown in Figure 5. It is clear from this figure that the mass flow rate increases linearly with the temperature difference.

The heat flow rate between the two zones through the doorway is given by:

$$Q = 0.0278\ \rho\ C_p\ W\ (g\ H^3)^{0.5}\ [\Delta T^{1.187}/T^{0.187}] \qquad (16)$$

The variation of heat flow rate with $[\Delta T^{1.187}/T^{0.187}]$ is shown in Figure 6. The heat losses from the lower floor through the doorway were found to be significant and temperatures up to 21 °C were achieved in the upper floor with the heating system switched off on this floor.

Equation (17) describes convection through the doorway in terms of the Nusselt number, Grashof number and Prandthl number :

$$Nu/Pr = 0.0278\,[\Delta T/T]^{-0.313} Gr^{0.5} \quad (17)$$

Figure 7 shows this correlation together with a number of previous correlations[2,3,4] describing flow through openings between two-zone enclosures. The difference between the present case and examples based upon convection between two adjacent zones is apparent. The mean inter-zone heat transfer coefficient may be calculated using the average experimental values of Pr, ρ, μ and k as follows:

$$h = 47.22\ W\,[\Delta T\ H^3]^{0.187} \quad (18)$$

TABLE 1

Experimental Conditions

Run. No.	Temperatue difference between zone 1 & 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

SECTION TWO : INTERZONE MOISTURE TRANSFER

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

(a) Temperature and moisture content of the air in each room.

(b) Temperature and moisture content of the incoming air

(c) Surface temperature and cold bridges in the room.

(d) Thermal resistance and permeablity of the construction material.

(e) Ventilation rate and interzone air movement

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[3]. 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 causing the moist air to convect to areas of lower vapour pressure, i.e., poorly heated bedrooms and the unheated roof space.

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 Figure 1. Assume the moisture release rate in zone 1 is M_{g1} and that is in zone 2 is M_{g2}.

A Two-Zone Moisture Transfer Model

The amount of moisture transfer in each zone can be calculated by applying equations describing conservation of mass:

The rate of moisture increase in zone 1 is given by:

$$d(d_{v1})/dt = F_{01}\ d_{v0} + F_{21}\ d_{v2} - F_{10}\ d_{v1} - F_{12}d_{v1} + M_{g1} \qquad (19)$$

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

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

Assuming a steady-state moisture transfer in the two zones, equations 19 and 20 become:

$$F_{01}\ d_{v0} + F_{21}\ d_{v2} - F_{10}\ d_{v1} - F_{12}d_{v1} + M_{g1} = 0 \qquad (21)$$

$$F_{02}\ d_{v0} + F_{12}\ d_{v1} - F_{20}\ d_{v2} - F_{21}d_{v2} + M_{g2} = 0 \qquad (22)$$

Re-arranging equations 21 and 22 for d_{v1} and d_{v2},, substituting for d_{v2} from equation 21 into equation 22 and substituting for d_{v1} from equation 22 into equation 21, the following equations are obtained:

$$d_{v1} = \frac{(F_{01}(F_{20} + F_{21}) + F_{02}\ F_{21})d_{v0}}{((F_{10} + F_{12}) - F_{12}\ F_{21})} + \frac{F_{21}\ M_{g2} + (F_{20}+F_{21})\ M_{g1}}{((F_{10} + F_{12}) - F_{12}\ F_{21})} \qquad (23)$$

$$d_{v2} = \frac{(F_{02}(F10 + F12) + F_{01}\ F_{12})d_{v0}}{((F_{10} + F_{12}) - F_{12}\ F_{21})} + \frac{F_{12}\ M_{g1} + (F10+F_{12})M_{g2}}{((F_{10} + F_{12}) - F_{12}\ F_{21})} \qquad (24)$$

The air infiltration rates from outside the house in each zone are given by:

$$F_{01} = F_{12} + F_{10} - F_{21} \qquad \text{(equation 11)}$$

$$F_{02} = F_{20} + F_{21} - F_{12} \qquad \text{(equation 12)}$$

and the air change rates in zone 1 and 2 are :

$$A_1 = (F_{10} + F_{12})/V_1 \qquad (25)$$

$$A_2 = (F_{20} + F_{21})/V_2 \qquad (26)$$

Substituting equations 11, 12, 25 and 26 into equations 23 and 24, and simplifing :

$$d_{v1} = d_{vo} + \frac{F_{21}\ M_{g2} + A_2\ V_2\ M_{g1}}{(A_1 V_1\ A_2\ V_2 - F_{12}\ F_{21})} \tag{27}$$

$$d_{v2} = d_{vo} + \frac{F_{12}\ M_{g1} + A_1\ V_1\ M_{g2}}{(A_1 V_1\ A_2\ V_2 - F_{12}\ F_{21})} \tag{28}$$

The absolute humidities, d_{v1} and d_{v2}, are given by[18]:

$$d_{v1} = 2.17\ P_{v1}/T1 \tag{29}$$

$$d_{v2} = 2.17\ P_{v2}/T2 \tag{30}$$

It is also assumed:

$$K_1 = \frac{F_{21}\ M_{g2} + A_2\ V_2\ M_{g1}}{(A_1 V_1\ A_2\ V_2 - F_{12}\ F_{21})}$$

$$K_2 = \frac{F_{12}\ M_{g1} + A_1\ V_1\ M_{g2}}{(A_1 V_1\ A_2\ V_2 - F_{12}\ F_{21})}$$

Substituting equation 29 and 30 into equations 27 and 28, respectively and using K_1 and K_2 as defined above, equations 27 and 28 become:

$$P_{v1} = (T_1/T_o)\ P_{vo} + 0.461\ K_1\ T_1 \tag{31}$$

$$P_{v2} = (T_2/T_o)\ P_{vo} + 0.461\ K_2\ T_2 \tag{32}$$

Moisture Movement 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% relative humidity, was taken from the BS5250 (ref. 19) as 830 N/m^2.

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 4, 8 and 10 kg/day and these were distributed between the two zones on the basis of occupancy and appliance use (e.g., cooker, tumble drier, shower). Typical moisture generation rates for various heating appliances and occupant activities are given by CIBSE[20] as shown in Table 2.

Infiltration and interzone air movement in the house were measured experimentally using a single tracer gas technique. The derived algorithm described in section 1 was used to determine the mass flow between the two zones. The following assumptions were used in this analysis:

(a) The lower and upper floors of the house were heated to various 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 and 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 and 24 °C. The temperature difference 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 and 28 °C while the upper floor was kept at 12 °C.

Analysis of the Results for Case (a):

The internal vapour pressures were calculated using mean internal temperatures, amount of moisture generated in each zone, air change rates and interzone air flow. The variation of vapour pressure with temperature for zones 1 and 2 is shown in Figure 8. For a given moisture release rate, the vapour pressure is directly proportional to the mean internal temperature. The mean internal vapour pressure and saturated vapour pressure were used to estimate the mean relative humidity. Figures 9 and 10 show the variation of relative humidity with temperature for the lower floor and upper floor of the house, respectively. The effect of variations in moisture release rate is clearly shown in these figures. Relative humidities in the range 75-100% are obtained in zone 1, for an air change of 0.7 h^{-1}, at a temperature of about 12 °C. It is recommended[2] that 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 relative humidity in zone 2 is found to be high when the temperature is low and the moisture release rate is large.

The relative humidity difference between the upper and lower floors versus the temperature difference between the two floors is presented in Figure 11. The relative humidity difference, RH2-RH1, 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.

The effects of interzone air flow on the relative humidity in the lower and upper zones are shown in Figures 12 and 13. These figures show that for zone 1, the condition including interzone air flow results a relative humidity about 8% lower than that for the condition with no interzone air flow. In case of zone 2, the relative humdity for the condition with interzone air flow is about 10% higher than that for the condition with no interzone air flow.

Analysis of Results for Case (b):

This assumption is valid when only the lower floor of the house is provided with heating. The estimated relative humidity for the upper floor is about 92% for a mean internal temperature 12 °C and a moisture release rate of 2.64 kg/day. This high relative humidity would lead to severe condensation and mould growth.

The variation of RH_2-RH_1 with temperature difference is shown in Figure 14. 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 the cooking periods. Even so, relative humidity differences in the range 35-45% may exist if the lower floor is heated to about 22 while the upper floor is held at 12 °C.

The effect of interzonal air flow on the relative humidity in zone 2 is shown in Figure 15. If the interzone air flows F_{12} and F_{21} are included the calculated RH_2 is about 10% higher than that for the condition with no interzone air flow. This figure is based upon specific values of air of air change rate, interzone air flow and moisture release rate and could be higher or lower if different values were used.

KITCHEN EXTRACT FANS

Installation of kitchen extract fans 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 a 150 mm (extract rate about 290 m^3/h) fan 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 16 displays a schematic 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 slight effect on interzone air flow. With the extract fan in operation F_{12} and F_{21} were found 96 and 125 m^3/h compared to 105 and 97 m^3/h with extract fan switched off.

Figure 17 shows the interzonal air flow for the second test. The limit of the extract fan is clearly shown 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. The two tests indicate that the use of a 290 m^3 capacity fan does not prevent moisture movement to other rooms. Calculations were carried out to establish the minimum extract rate fan 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 relative humidity in a zone does not exceed the range 60-70% (ref. 22). 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[23]. As alternative, extract fans controlled by a humidisat 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[23].

TABLE 2
Source of Moisture Within Building

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 to 3.0 kg per day
Dish washing (3 meals)	0.15 to 0.45 kg per day
Clothes washing	0.5 to 1.8 kg per day
Cloth drying indoor	5.0 to 14 kg per day
Baths and showers	0.75 to 1.5 kg per day
Floor washing	1.0 to 1.5 kg per 10 m^2
Indoor Plants	up to 0.8 kg per 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	4000 kg in one year for medium sized office building

From Section A.10 of the CIBSE Guide.

CONCLUSIONS AND RECOMMENDATIONS

1. The experimental results indicate that the coefficient C is dependent on the temperature difference. Further experimental work is required to study the effects of geometry of the house and size of the doorway on the value of C.
2. The use of the SF_6 systems and thermocouples to measure temperatures at the centre of each room has proved to be a simple and practical approach for measuring heat and mass transfer between the two floors of the house. However, the accuracy of interzone air flow measurements could be improved by using multiple tracer gas technques [17,24].
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 transfer 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 significanthly 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 manully operated kitchen extract fan was found to be ineffective in reducing air flow from the lower floor to the upper floor of the house. Further work is required to establish the optimum extract rate of a fan for prevention of condensation in the kitchen and reduction of moisture movement to the rest of the house.
6. Work is now underway at PCL to establish a four-zone moisture transfer model. Moisture generation in various zones will be simulated using humidifers and the new multi-tracer gas system will be used to estimate the interzonal air movement.

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NOMENCLATURE

C_d	Coefficient of discharge (dimensionless)
W	Width of the opening (m)
H	Height of the opening (m)
g	Acceleration due to gravity (m/s^2)
T_1	Average value of air temperature in zone 1 (°C or K)
T_2	Average value of air temperature in zone 2 (°C or K)
T	Mean absolute temperature of the two zones (°C or K)
ΔT	Average temperature difference between the two zones (°C or K)
F	The volumetric flow rate (m^3/h)
M	Interzone mass flow rate (kg/s)
Q	Heat transfer rate (kW)
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (kW/m K)
Nu	Nusselt number (dimensionless)
Pr	Prandtl number (dimensionless)
Gr	Grashof number (dimensionless)
V_1	Interior volume of zone 1 (m^3).
V_2	Interior volume of zone 2 (m^3)
C_1	Concentrations of the tracer at time t in zone 1 (arbitrary units)
C_2	Concentration of the tracer at time t in zone 2 (arbitrary units)
C_p	Specific heat of air (KJ/kg K)
M_{g1}	Moisture release rate in zone 1 (kg/day)
M_{g2}	Moisture release rate in zone 2 (kg/day)
d_{va}	Ambient absolute humidity (g/m^3)
d_{v1}	Absolute humdity for zone 1 (g/m^3)
d_{v2}	Absolute humdity for zone 2 (g/m^3)
RH_1	Relative humidity in zone 1
RH_2	Relative humidity in zone 2
P_{v1}	Vapour pressure in zone 1 (N/m^2)

P_{v2} Vapour pressure in zone 2 (N/m^2)
A_1 Air change rate per hour in zone 1
A_2 Air change rate per hour in zone 2
K_1 Constant equation 31
K_2 Constant equation 32
μ Dynamic viscosity (kg/m s)
ρ Average air density (kg/m^3)
$\Delta\rho$ Air density difference between the two zones (kg/m^3)
β Coefficient of thermal expansion (K^{-1})

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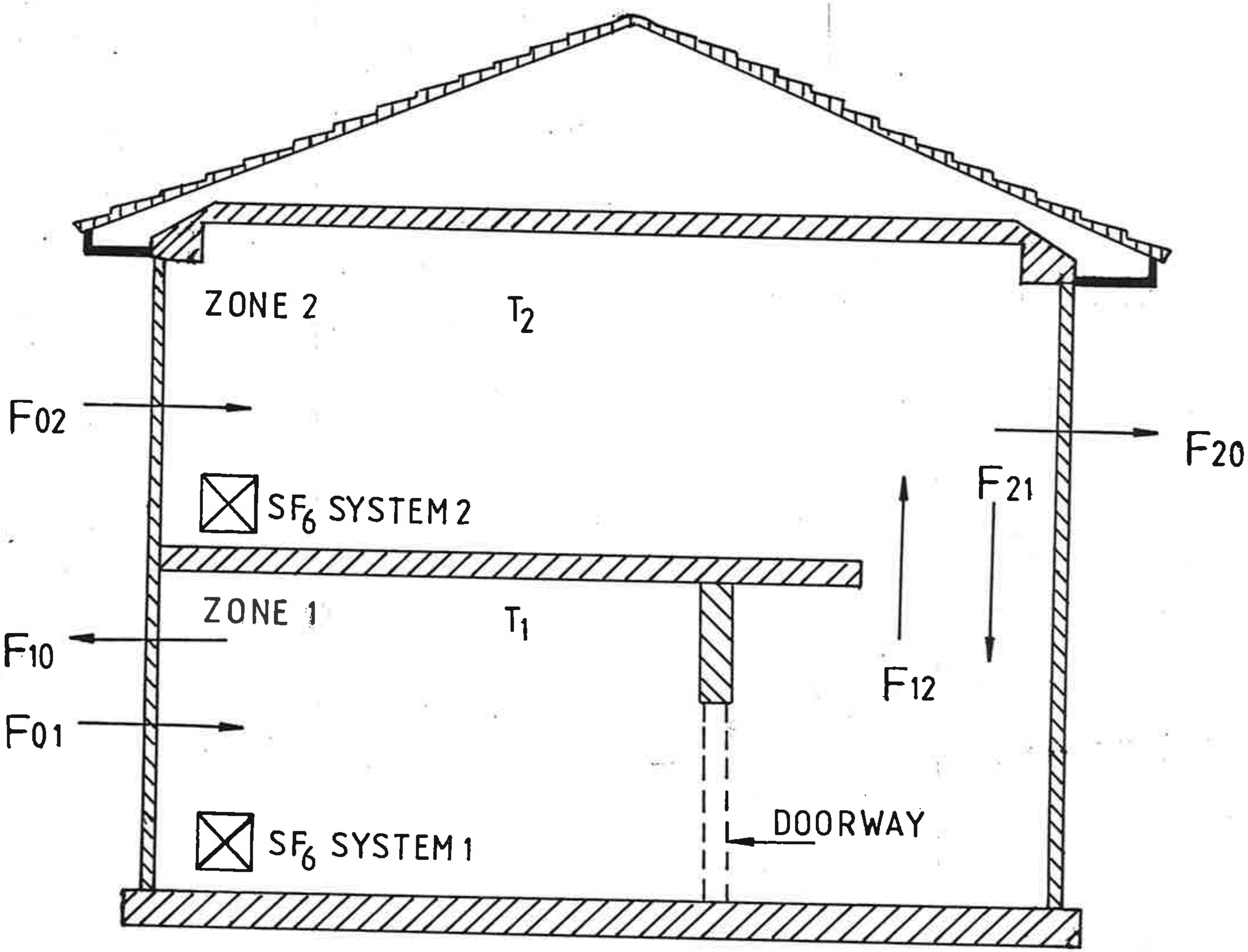
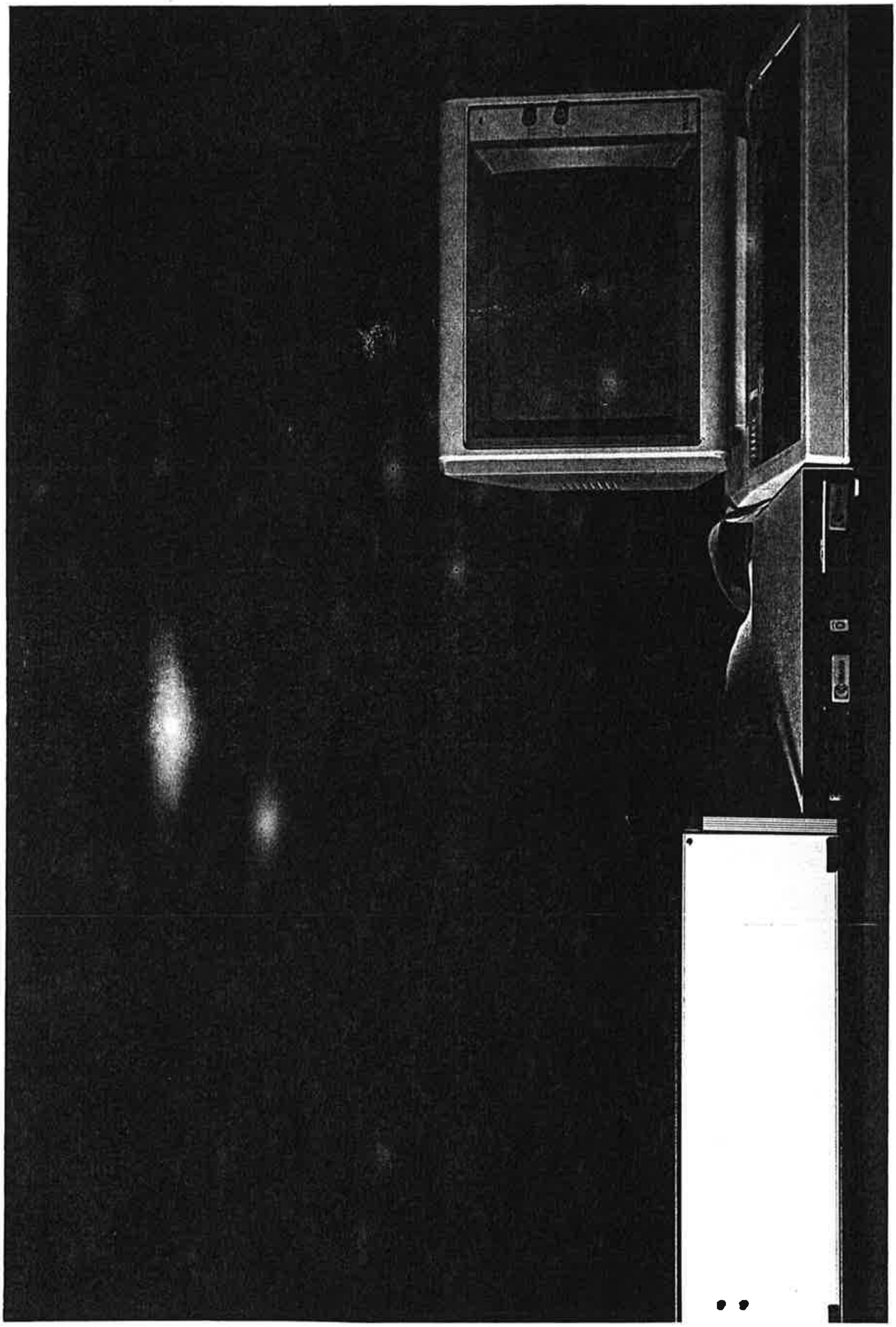
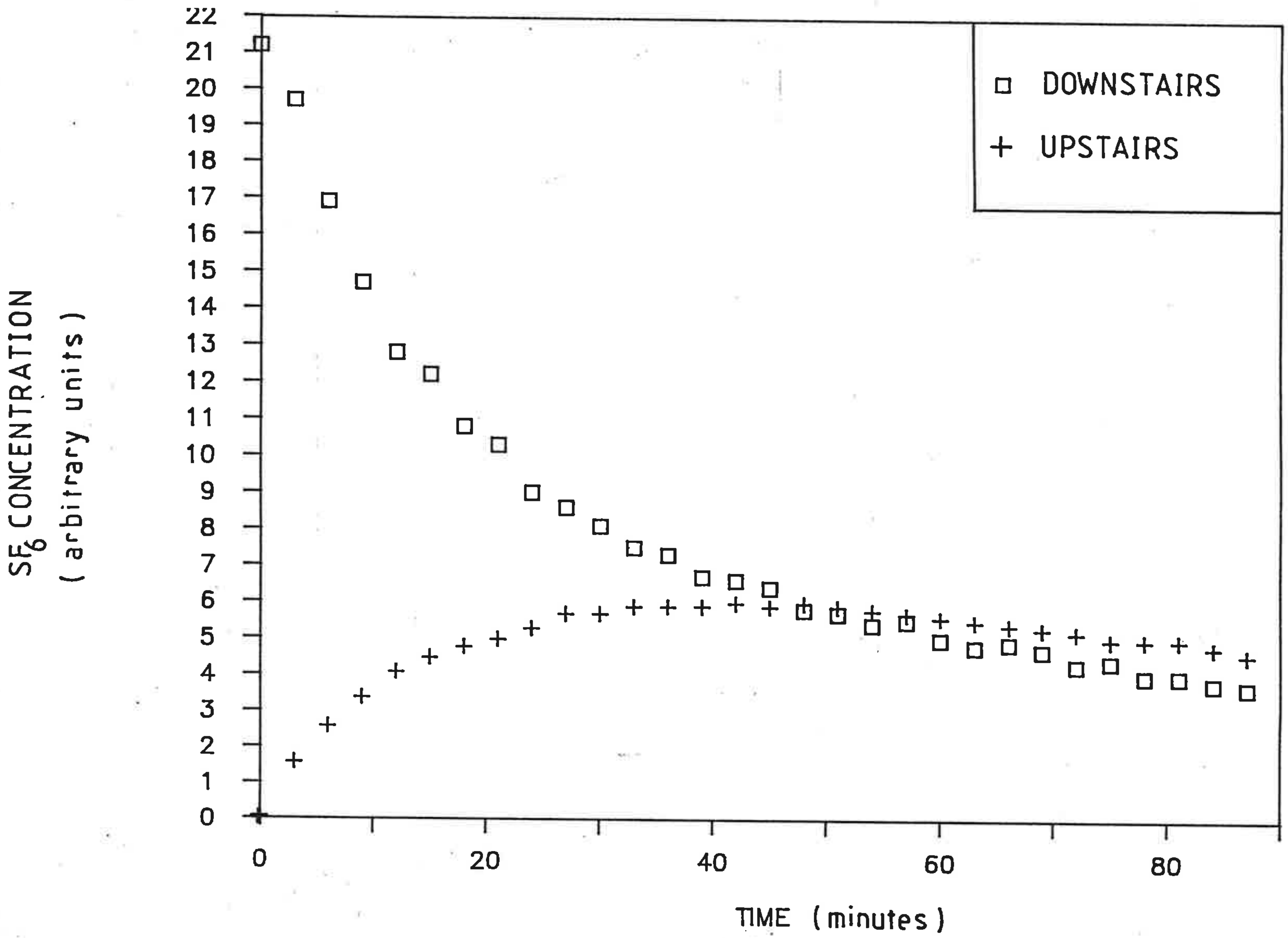
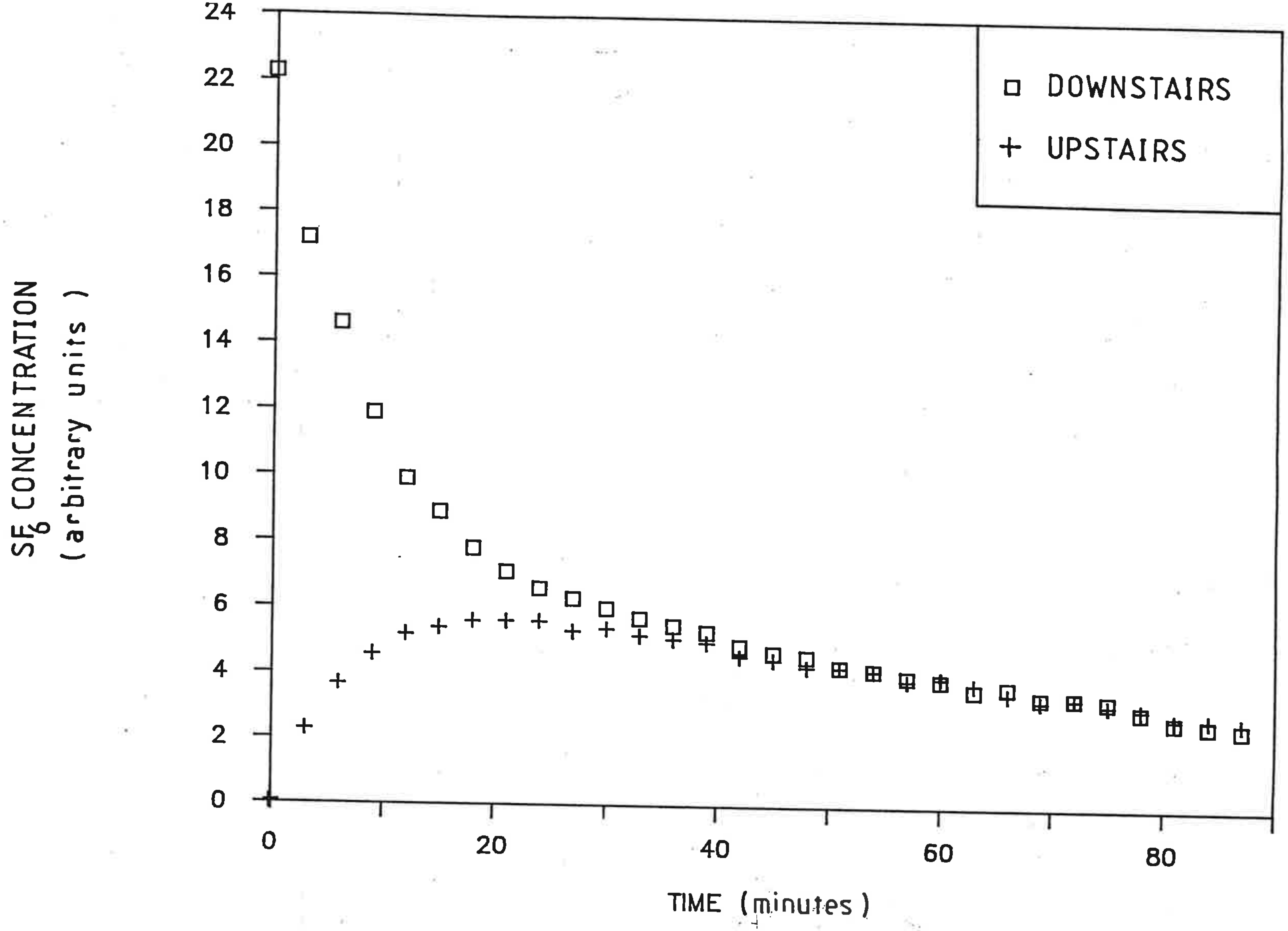
FIGURES

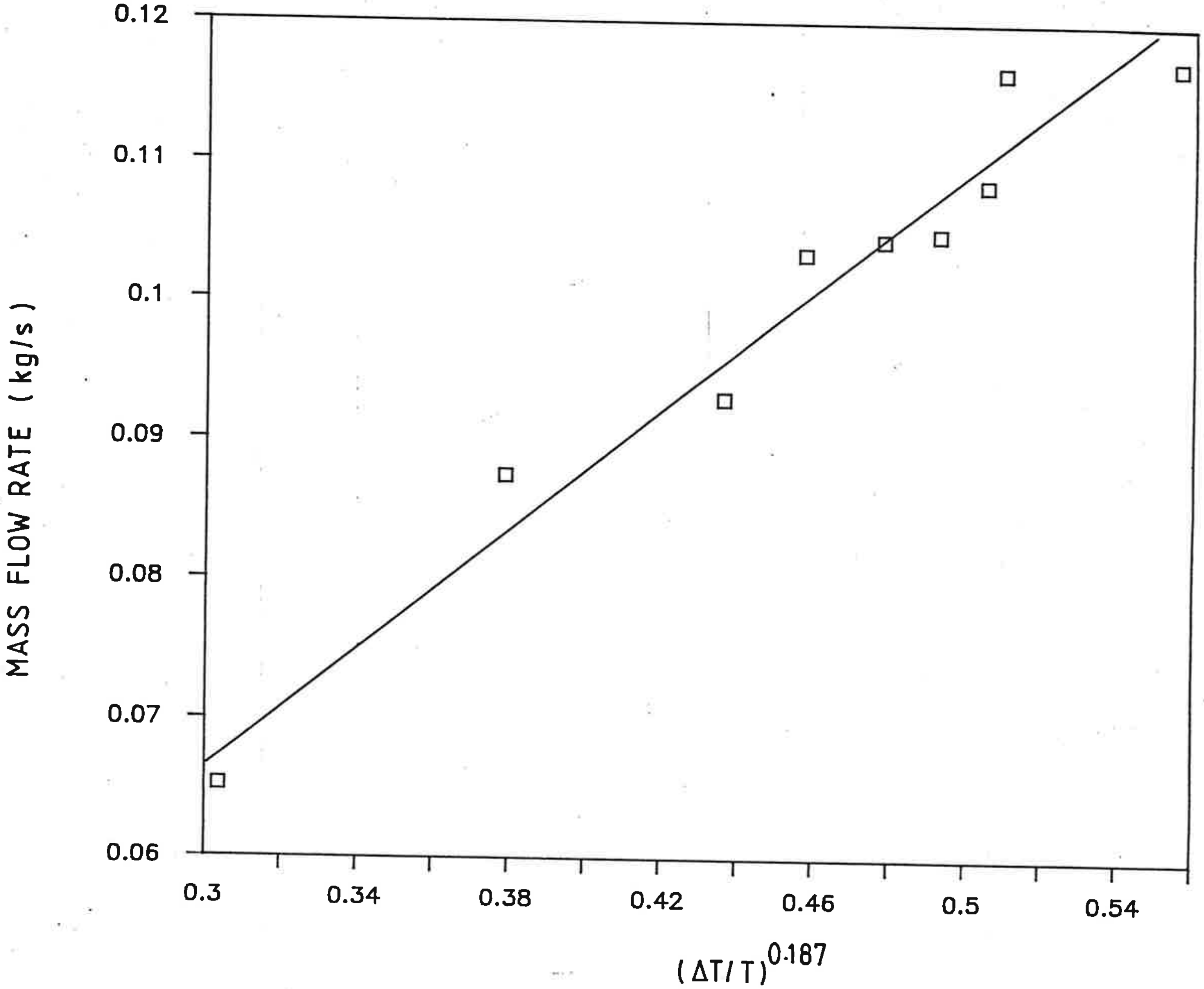

ZONE 2
T_2
F_{02}
F_{20}
F_{21}
SF_6 SYSTEM 2
ZONE 1
T_1
F_{10}
F_{12}
F_{01}
DOORWAY
SF_6 SYSTEM 1

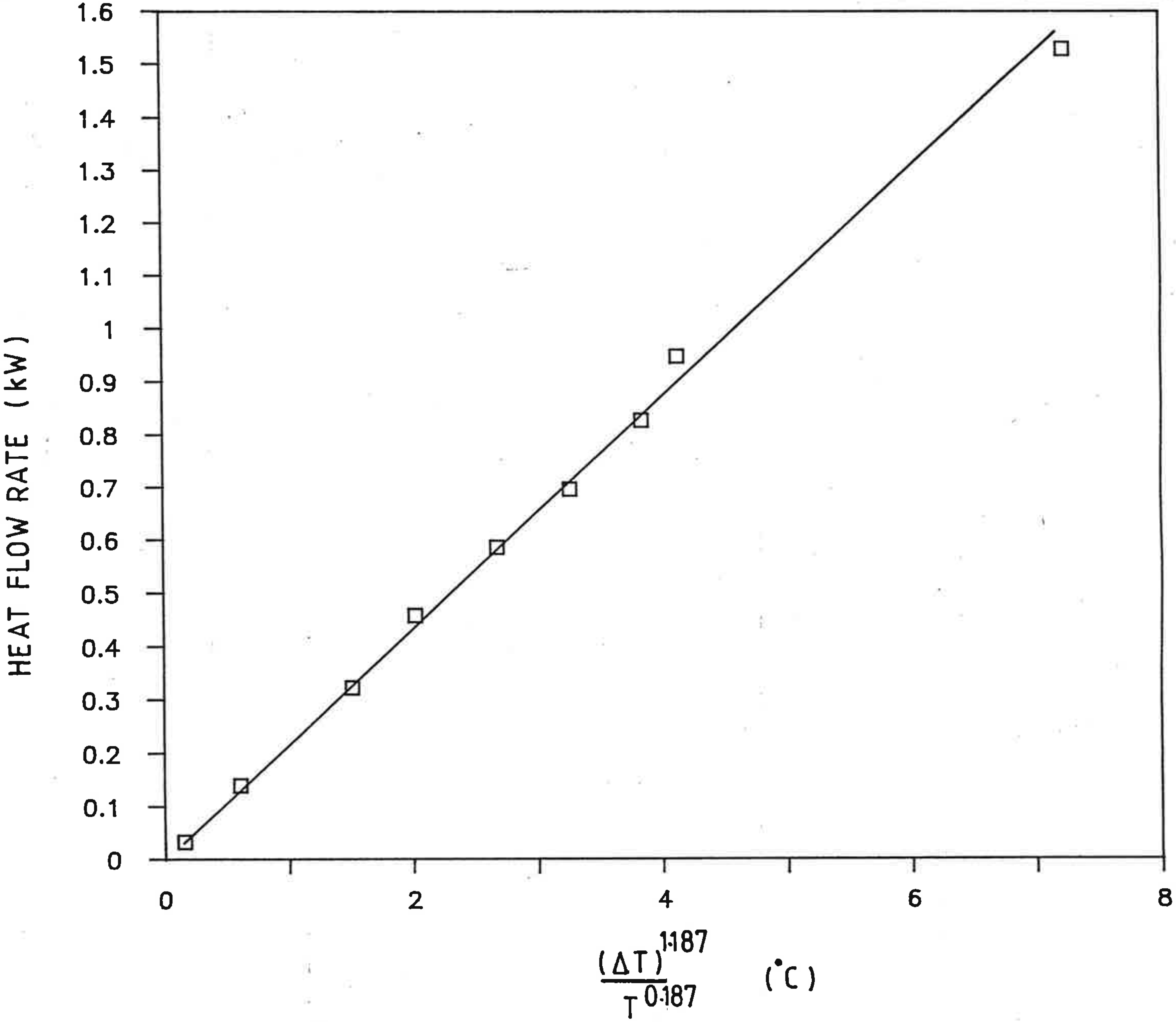


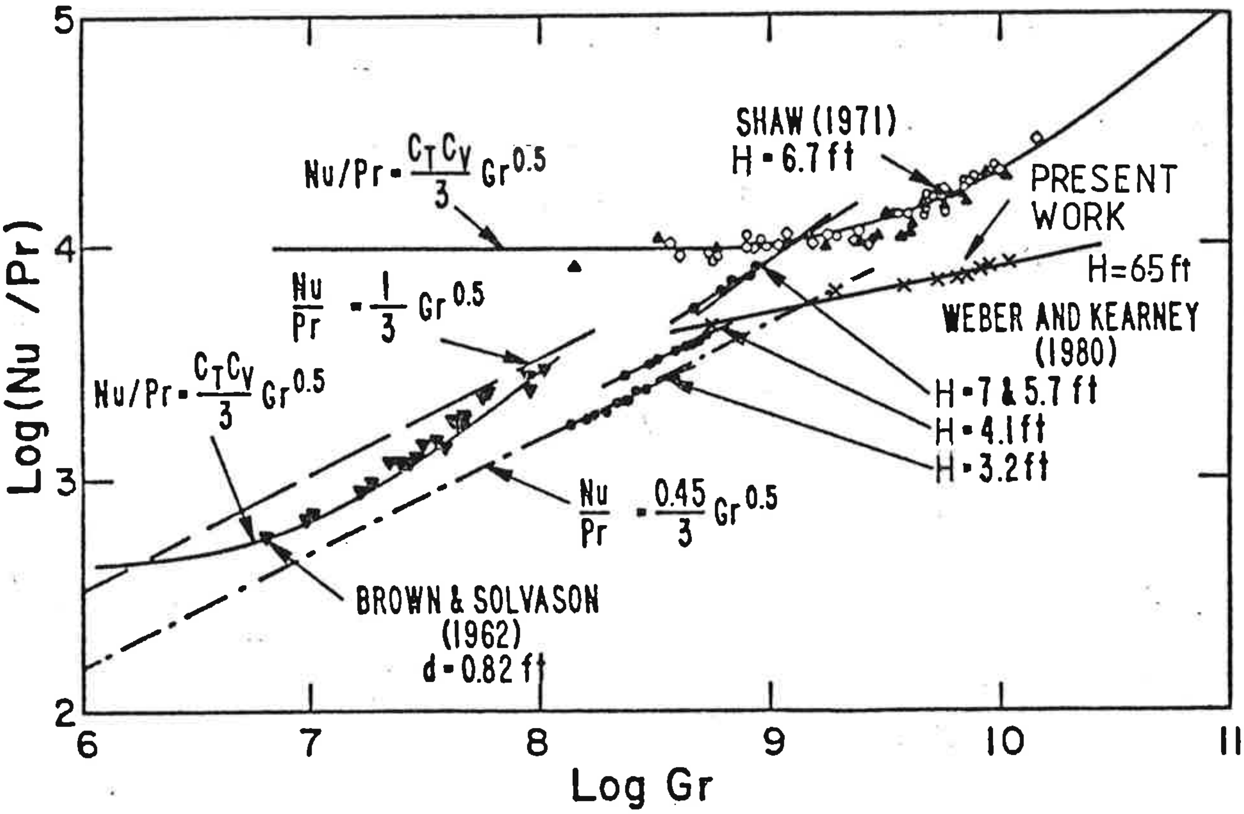


SF6 CONCENTRATION
(arbitrary units)
TIME (minutes)
DOWNSTAIRS
UPSTAIRS
0
20
40
60
80
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

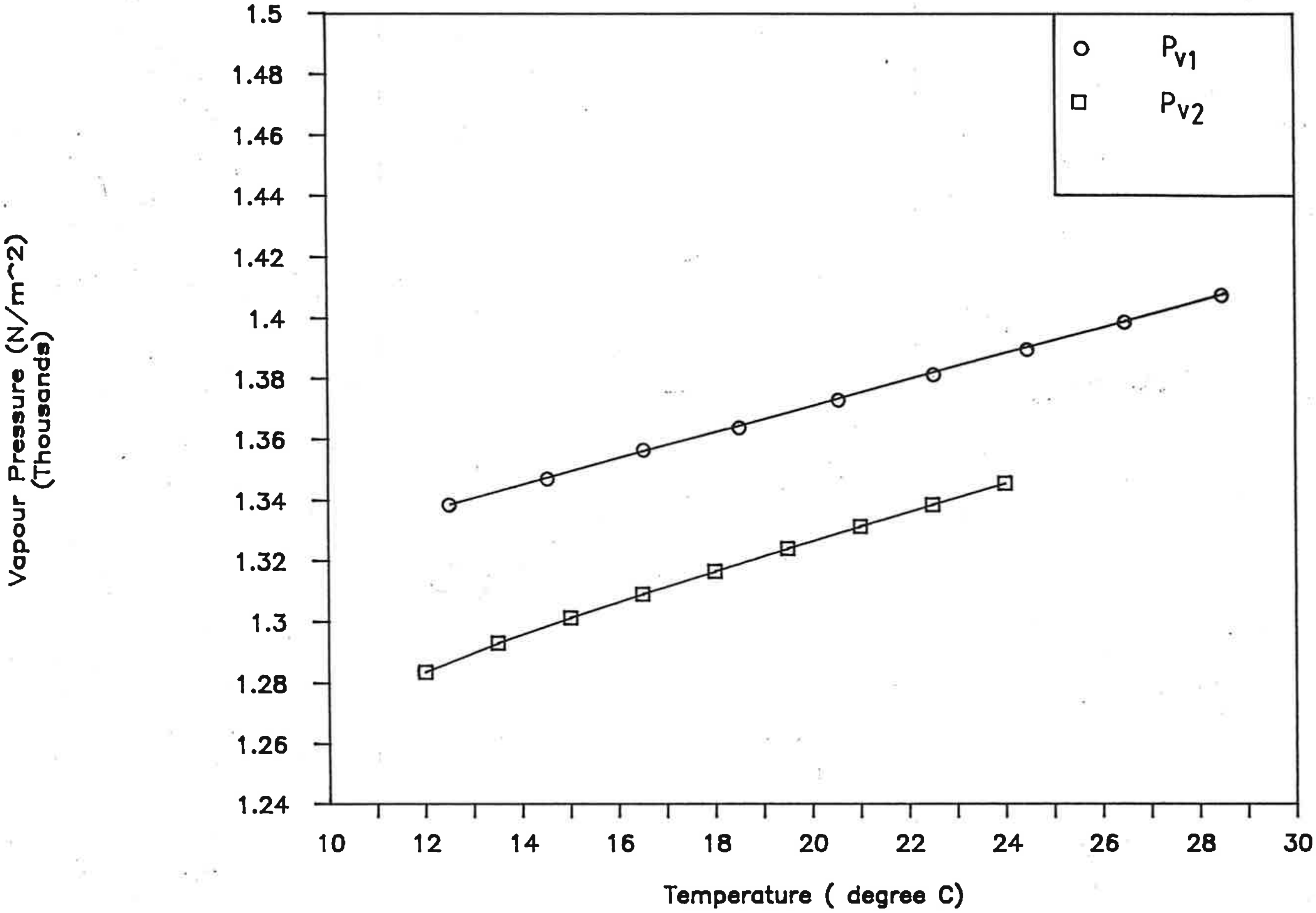

DOWNSTAIRS
UPSTAIRS
SF6 CONCENTRATION (arbitrary units)
TIME (minutes)
0
2
4
6
8
10
12
14
16
18
20
22
24
0
20
40
60
80

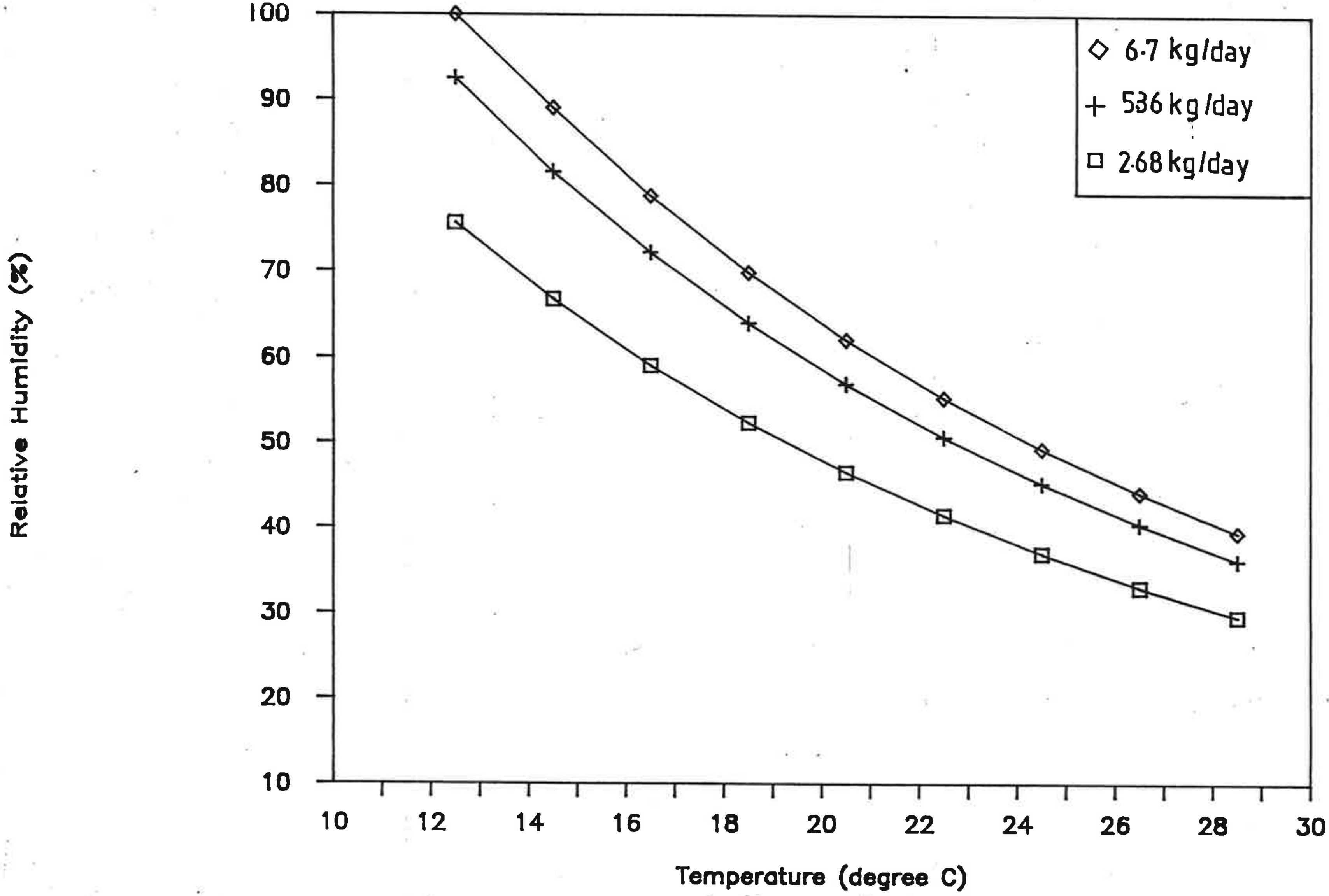

0.12
0.11
0.1
0.09
0.08
0.07
0.06
MASS FLOW RATE (kg/s)
0.3
0.34
0.38
0.42
0.46
0.5
0.54
(ΔT/ T)^0.187


HEAT FLOW RATE (kW)
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
$\frac{(\Delta T)^{1.187}}{T^{0.187}}$ (°C)



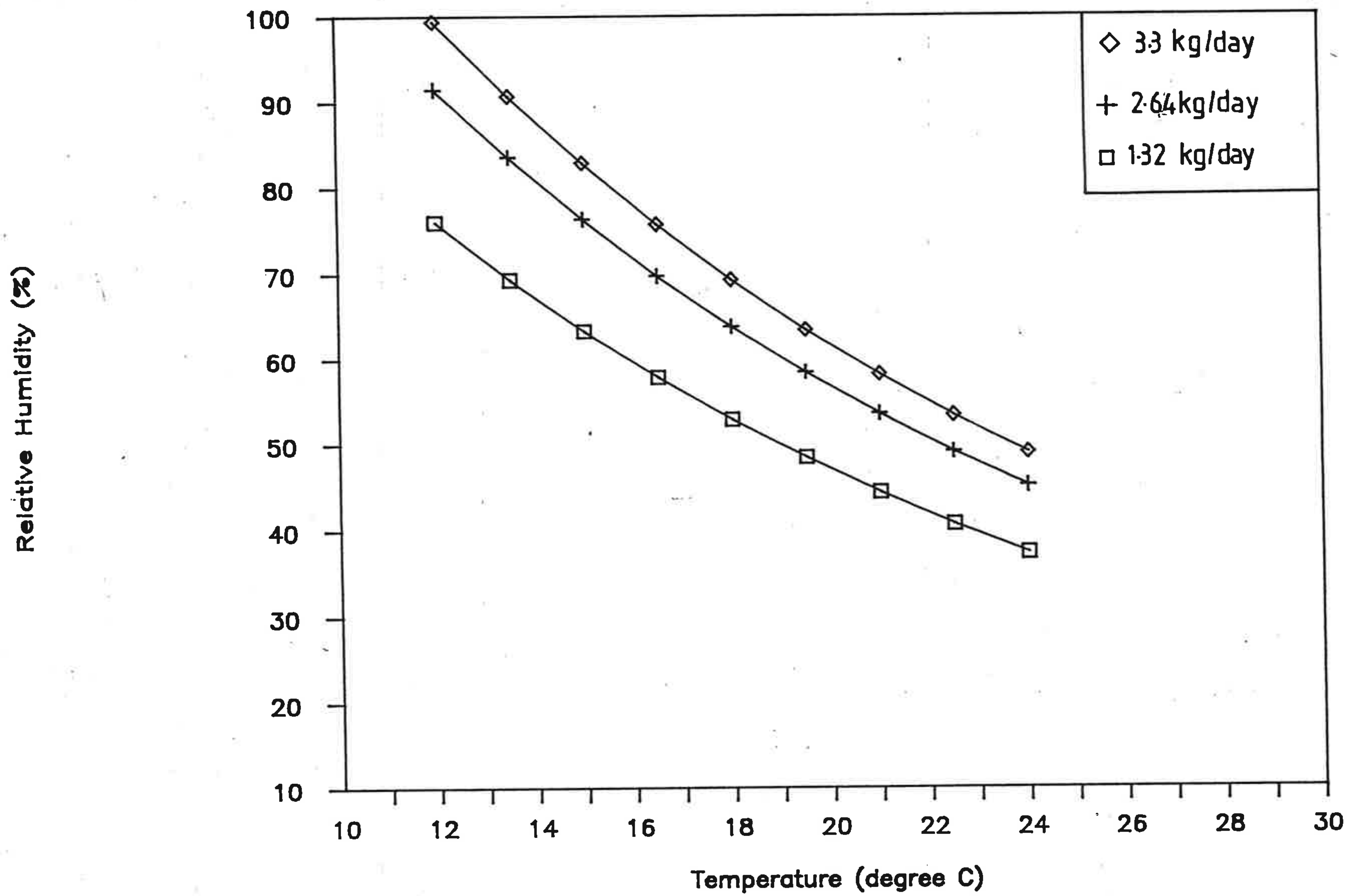
5
4
3
2
6
7
8
9
10
11
Log Gr
Log(Nu /Pr)
SHAW (1971)
H = 6.7 ft
PRESENT
WORK
H=65 ft
WEBER AND KEARNEY
(1980)
H = 7 & 5.7 ft
H = 4.1 ft
H = 3.2 ft
BROWN & SOLVASON
(1962)
d = 0.82 ft

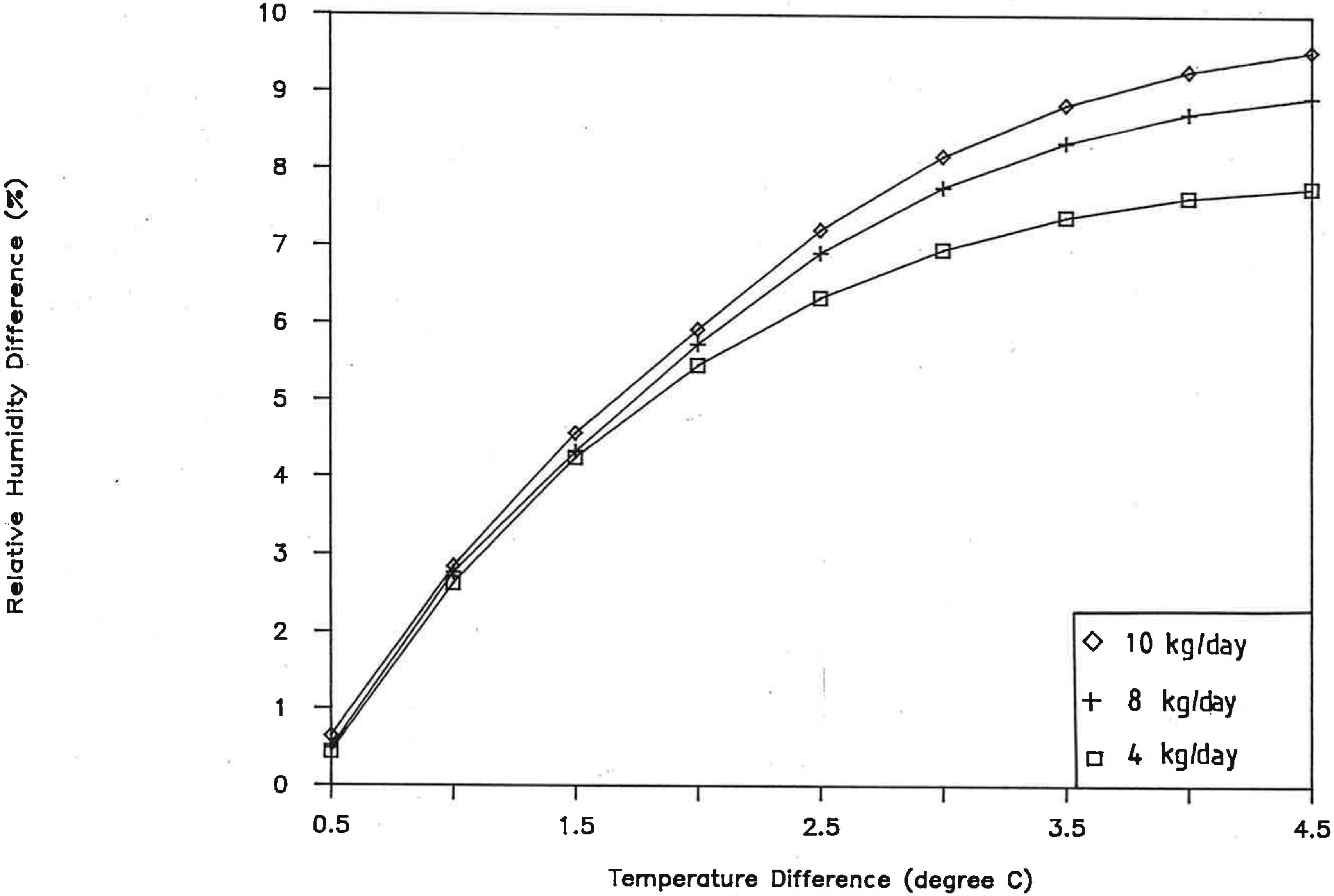

Vapour Pressure (N/m^2)
(Thousands)
1.5
1.48
1.46
1.44
1.42
1.4
1.38
1.36
1.34
1.32
1.3
1.28
1.26
1.24
10
12
14
16
18
20
22
24
26
28
30
Temperature (degree C)
P_{v1}
P_{v2}

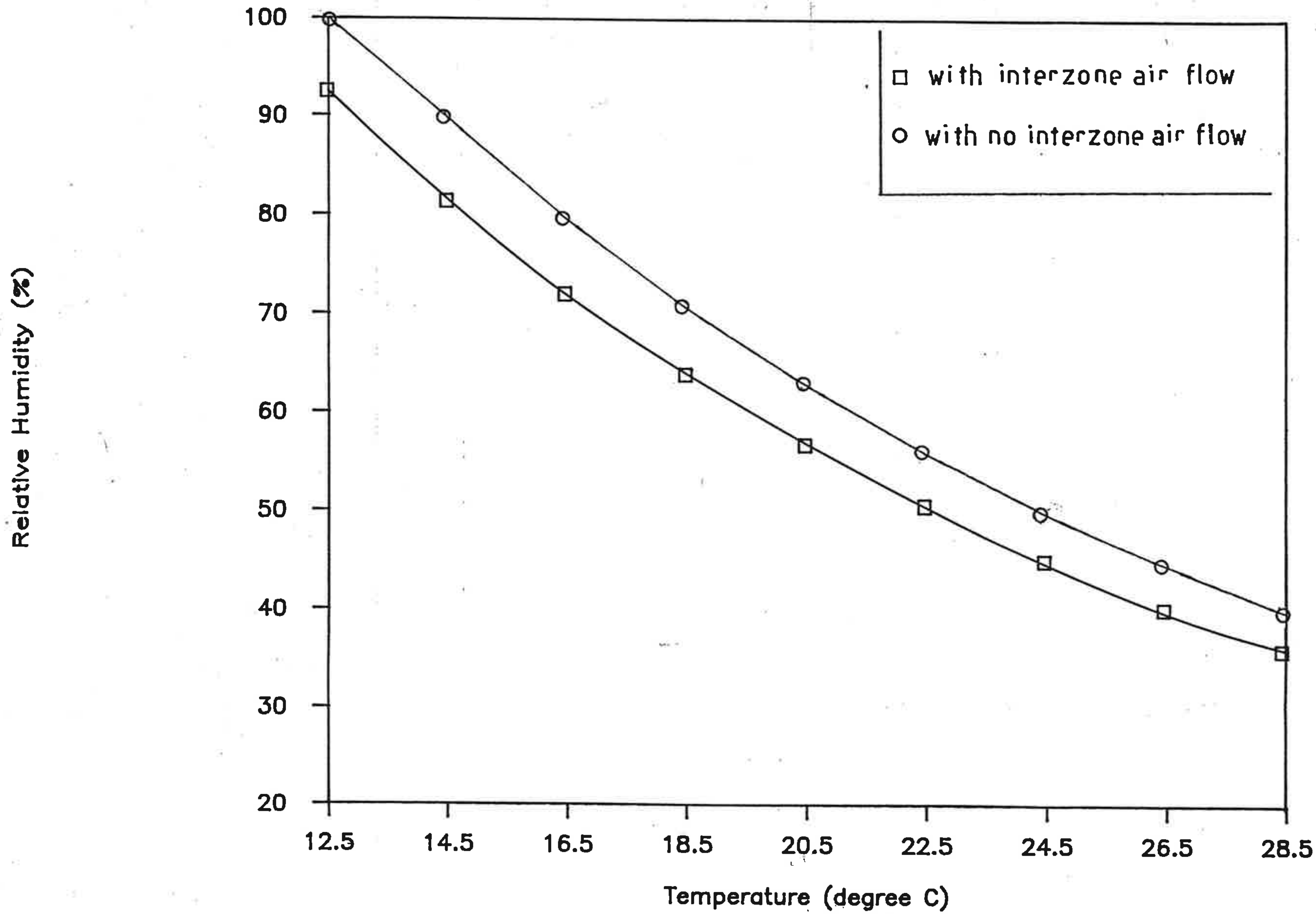


6·7 kg/day
5·36 kg/day
2·68 kg/day
100
90
80
70
60
50
40
30
20
10
10
12
14
16
18
20
22
24
26
28
30
Relative Humidity (%)
Temperature (degree C)

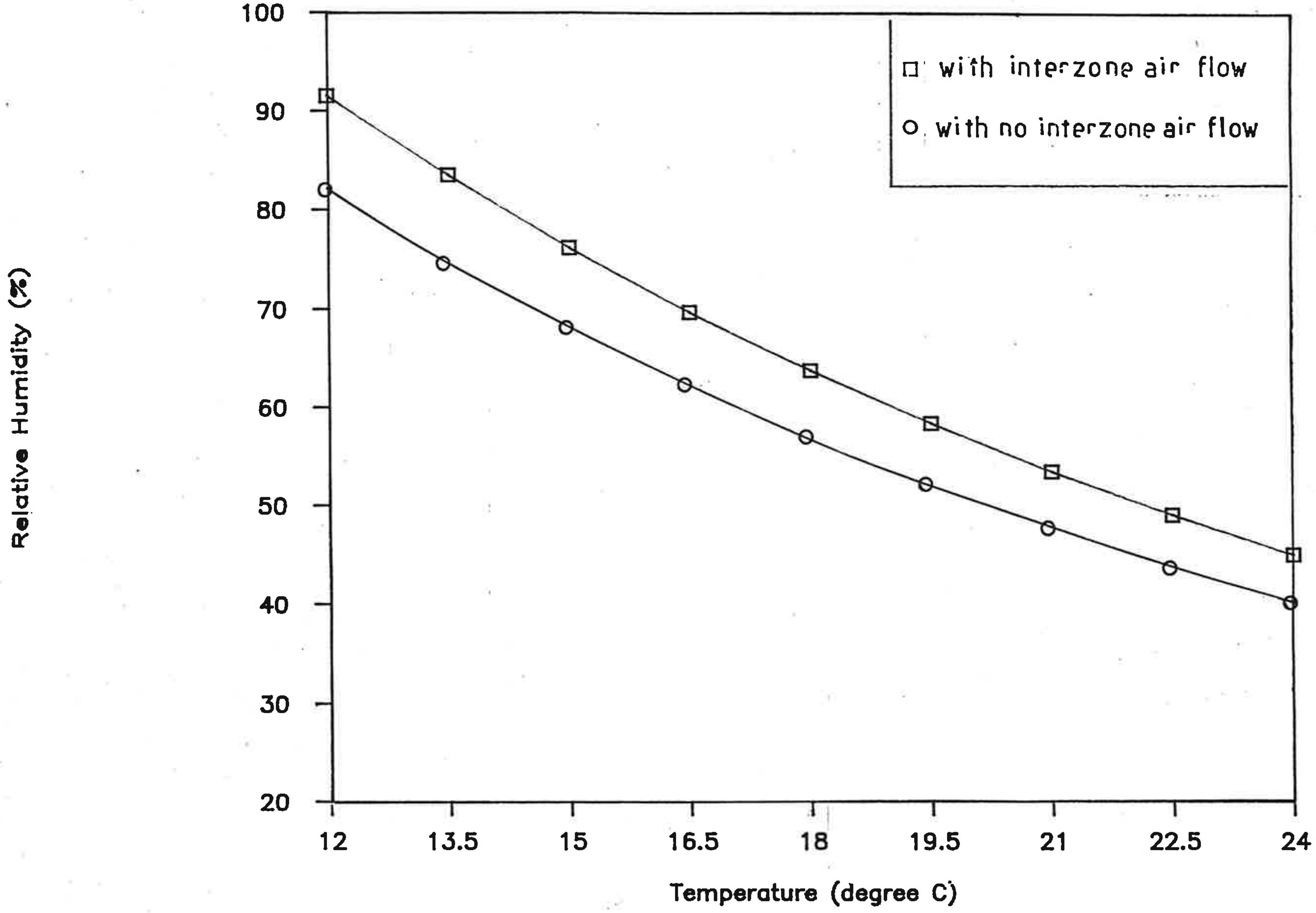
25


100
90
80
70
60
50
40
30
20
10
Relative Humidity (%)
10
12
14
16
18
20
22
24
26
28
30
Temperature (degree C)
3·3 kg/day
2·64kg/day
1·32 kg/day

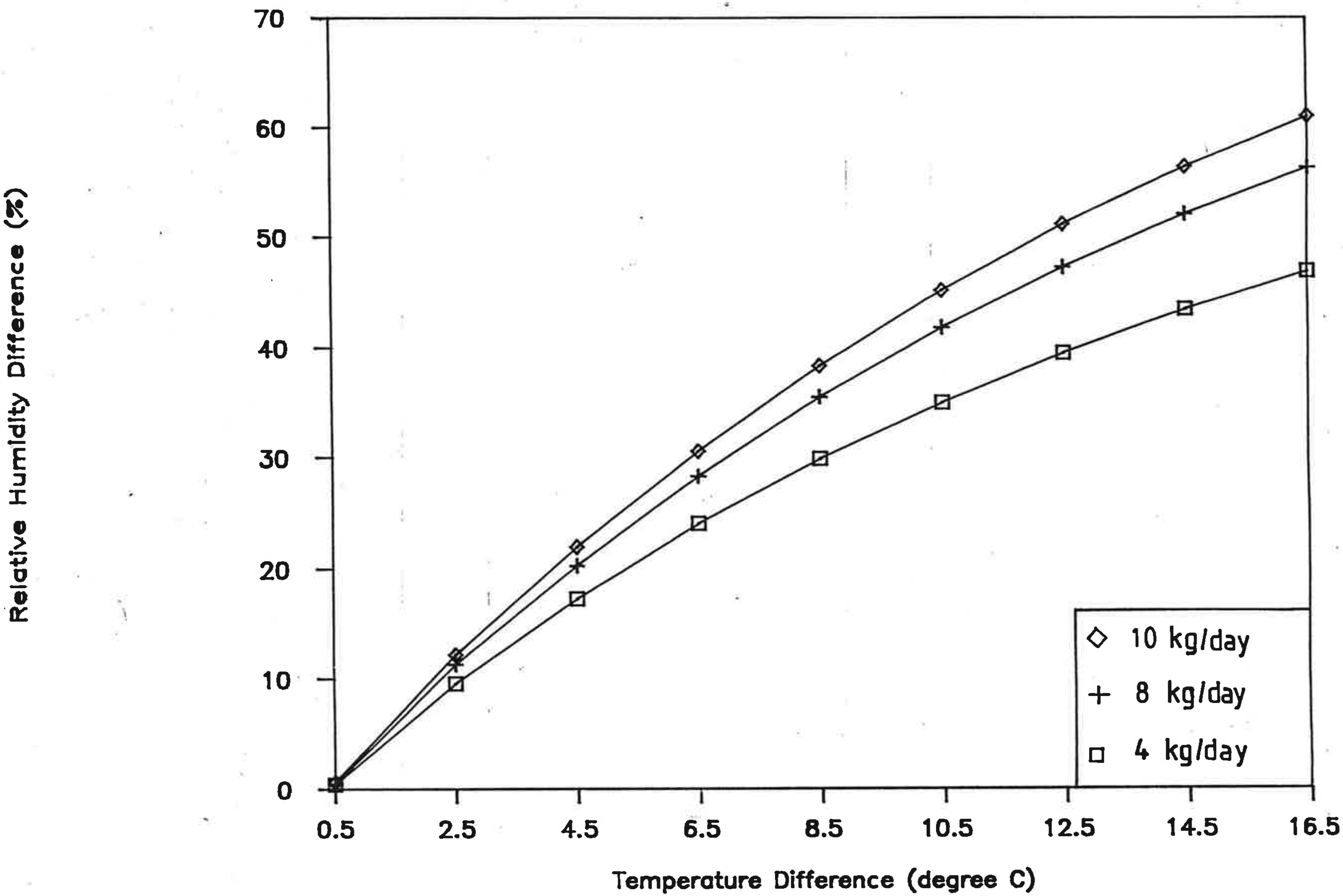

Relative Humidity Difference (%)
0
1
2
3
4
5
6
7
8
9
10
0.5
1.5
2.5
3.5
4.5
Temperature Difference (degree C)
10 kg/day
8 kg/day
4 kg/day

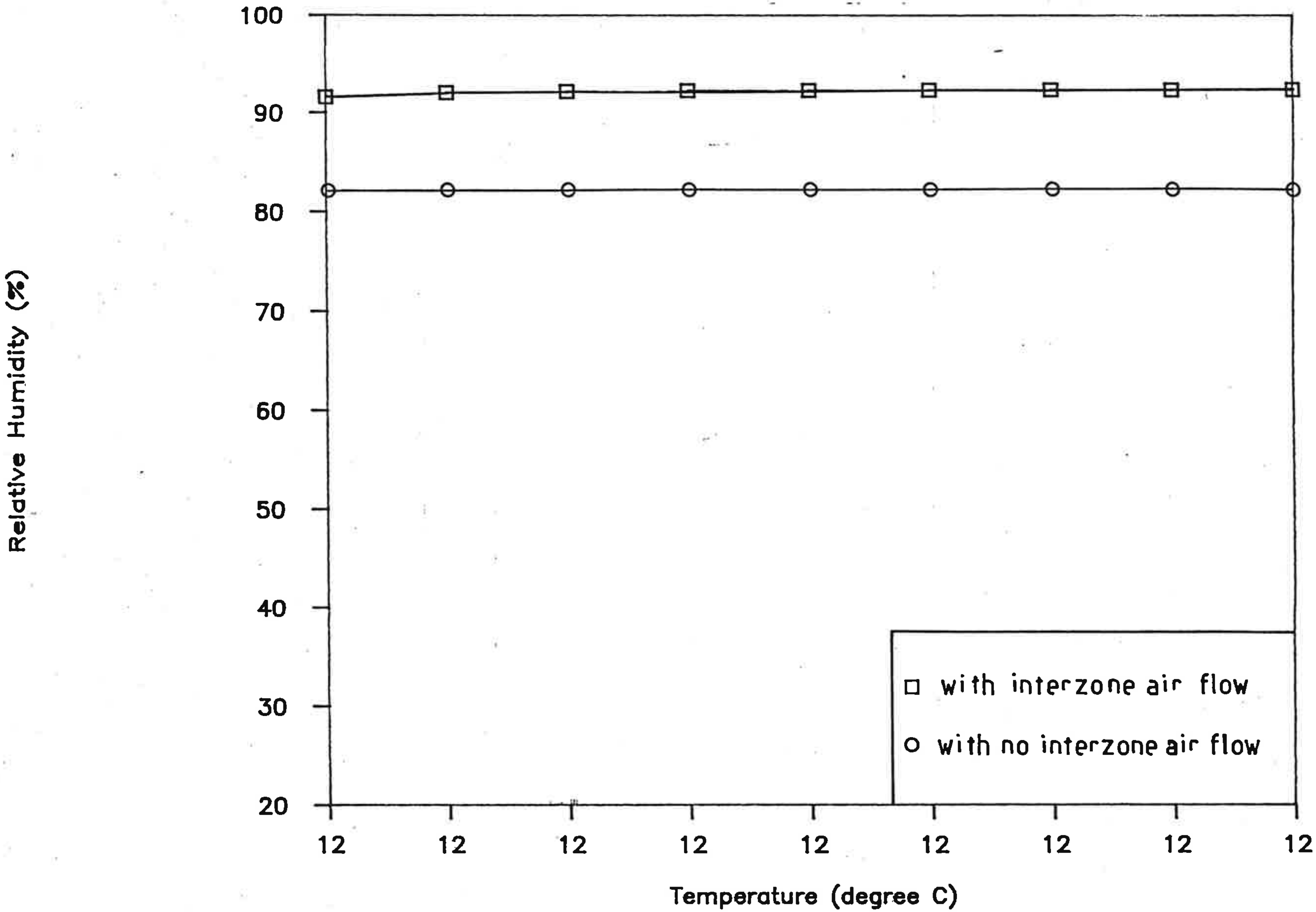


100
90
80
70
60
50
40
30
20
Relative Humidity (%)
12.5
14.5
16.5
18.5
20.5
22.5
24.5
26.5
28.5
Temperature (degree C)
with interzone air flow
with no interzone air flow

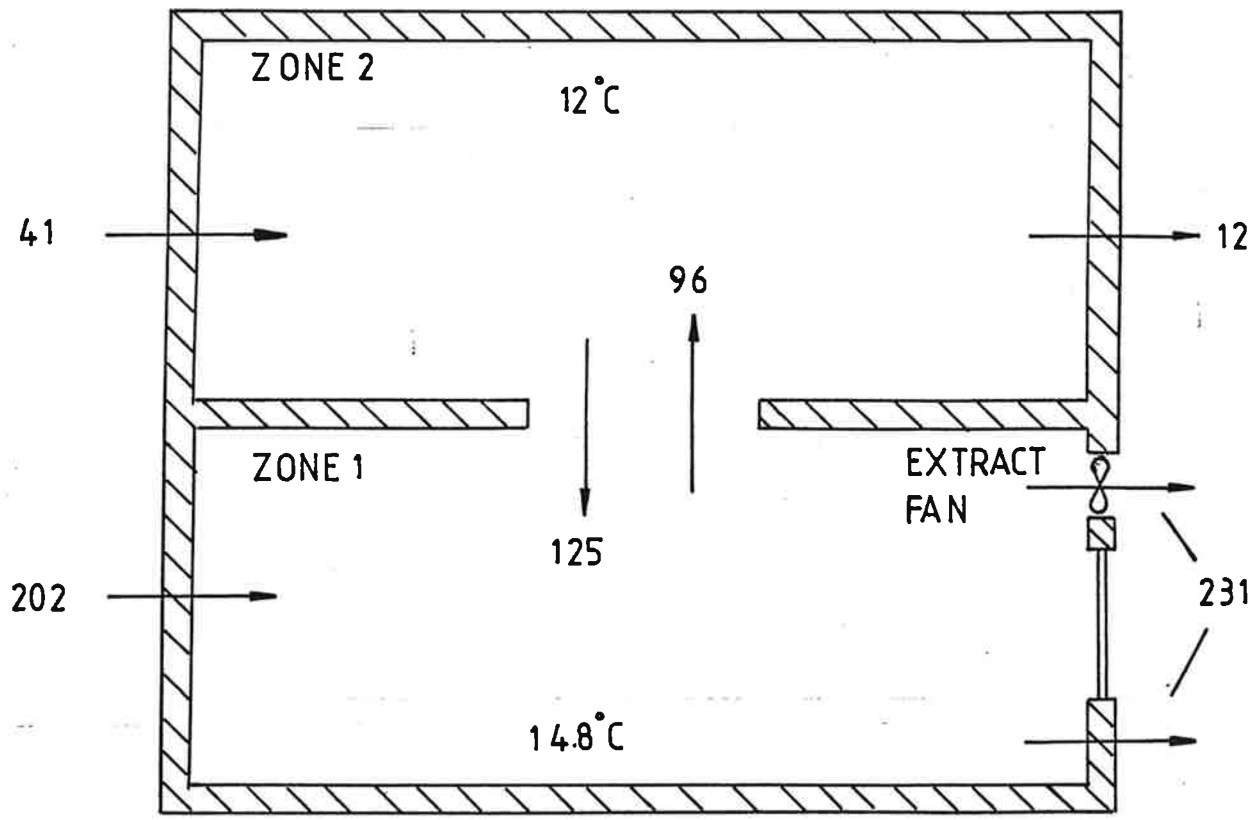


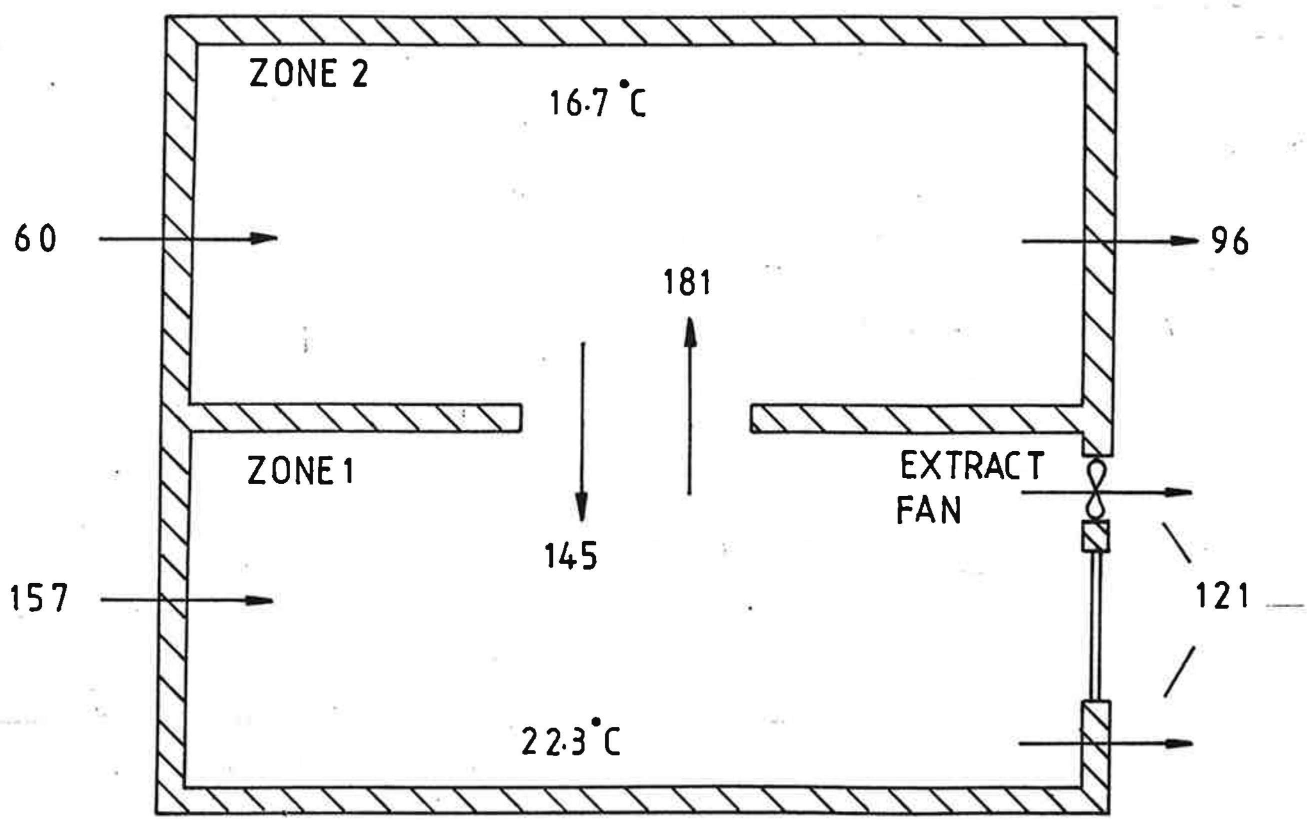
with interzone air flow
with no interzone air flow
Relative Humidity (%)
100
90
80
70
60
50
40
30
20
12
13.5
15
16.5
18
19.5
21
22.5
24
Temperature (degree C)


70
60
50
40
30
20
10
0
Relative Humidity Difference (%)
0.5
2.5
4.5
6.5
8.5
10.5
12.5
14.5
16.5
Temperature Difference (degree C)
10 kg/day
8 kg/day
4 kg/day



Relative Humidity (%)
100
90
80
70
60
50
40
30
20
12
12
12
12
12
12
12
12
12
Temperature (degree C)
with interzone air flow
with no interzone air flow


ZONE 2
12°C
41
12
96
ZONE 1
EXTRACT
FAN
125
202
231
14.8°C


ZONE 2
16·7 °C
60
96
181
ZONE 1
145
EXTRACT
FAN
157
121
22·3 °C