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The effects of ventilation and building design factors on the risk of condensation and mould growth in dwellings

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THE EFFECTS OF VENTILATION AND BUILDING DESIGN FACTORS ON THE RISK OF CONDENSATION AND MOULD GROWTH IN DWELLINGS

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A number of publications set out procedures for assessing the risk of condensation or mould growth with given internal conditions, but little information is available on the effect of ventilation, insulation, and other building design factors on the internal temperature and humidity in dwellings. This paper sets out calculations for three typical house types assuming different heat and moisture inputs.

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THE EFFECTS OF VENTILATION AND BUILDING DESIGN FACTORS ON THE RISK OF CONDENSATION AND MOULD GROWTH IN DWELLINGS

by A G Loudon

INTRODUCTION

This paper discusses how temperature and relative humidity are controlled by adjusting the ventilation rate. When these are known, methods are available for assessing whether condensation is likely to occur on surfaces - such as windows, walls, heat bridges - or within the structure[1, 2, 3, 4, 5]. Experience at BRS has shown that mould growth is more troublesome than condensation. Mould growth can occur when the relative humidity exceeds 70 per cent for extended periods[2], and this figure has been taken as a basis for discussion of the information on temperature and humidity.

The problem of predicting temperatures and humidities is a complex one. Living habits and incomes vary, so that heat inputs and moisture inputs differ in different houses. Furthermore heat and moisture inputs are not uniform for any one house and family, and some account has to be taken of the effect of their variations. Problems are different in different rooms because heat inputs and moisture emission rates are different; kitchens, bathrooms, bedrooms and living rooms require separate consideration. There is also some mixing of air between different rooms, and heat transfer between rooms through walls and ceilings, the amount varying from one house to another.

It is not possible to consider such a wide variety of situations in this paper, but information has been derived for important aspects of the problem for different types of house. The effect of ventilation on temperature and relative humidity has been calculated for:

(a) a whole house uniformly heated, with moisture from household activities uniformly distributed through the house,

(b) a kitchen, assumed to be at a constant temperature during a period when the moisture emission rate is high,

(c) an unheated bedroom with two occupants, assumed to be in thermal equilibrium with a room downstairs maintained at 15^{o}C.

These cases are considered in turn.

Calculations have been made for different heat and moisture input rates, for houses insulated to the standard required by Building Regulations and for houses insulated to a high standard, called the 'Continental' standard, following usage adopted in a report by the National Building Agency[6], since it is widely used on the Continent.

WHOLE HOUSE UNIFORMLY HEATED

It is usual for heat inputs and temperatures to be different in different rooms - for instance for living rooms to be better heated during the evening than bedrooms. The same is true of moisture generation rates and humidities, kitchens having a high moisture input when clothes are being washed, and a high heat and moisture input when meals are being cooked. Temperatures can be fairly uniform in centrally heated houses but there are usually some differences between temperatures in different rooms.

In spite of this, however, a first estimate of the danger of mould growth can be obtained from conventional steady state calculations of mean temperatures and relative humidities for the house as a whole. It can be assumed that there is a danger of mould growth if the average relative humidity is more than 70 per cent[2].

On the other hand if the average relative humidity is less than 70 per cent, it does not follow that there is no danger of mould growth. Separate calculations have to be made for any parts of the house where humidities are expected to be above this value. Intermittent heating poses a further problem. When a family is out all day and returns to heat and prepare meals in a house whose fabric is cold, temporary condensation can occur in buildings where the mean relative humidity is below 70 per cent. On the other hand, a relative humidity above 70 per cent would always indicate a danger of mould growth. It is therefore worth while to see whether the average relative humidity exceeds 70 per cent before making more detailed calculations.

Temperatures and humidities depend on the type of house as well as its size, the degree of insulation and the ventilation rate. Thus a flat in the centre of a block is warmer than a similarly ventilated centre-terraced or detached house with the same heat input, because fewer surfaces are exposed externally. Calculations were made for these three house types, using the house plans in the NBA report[6]. Detailed results are given for the centre-terraced house shown in plan in Figure 1. This type lies between flats and detached houses in regard to the number of exposed surfaces. The house was assumed to have 5 occupants, the average for this size of house. Two standards of insulation, specified in Table 1, were assumed; the Building Regulations standard and the 'Continental' standard. Heat losses through the floor were neglected. Windows were assumed to be single glazed.

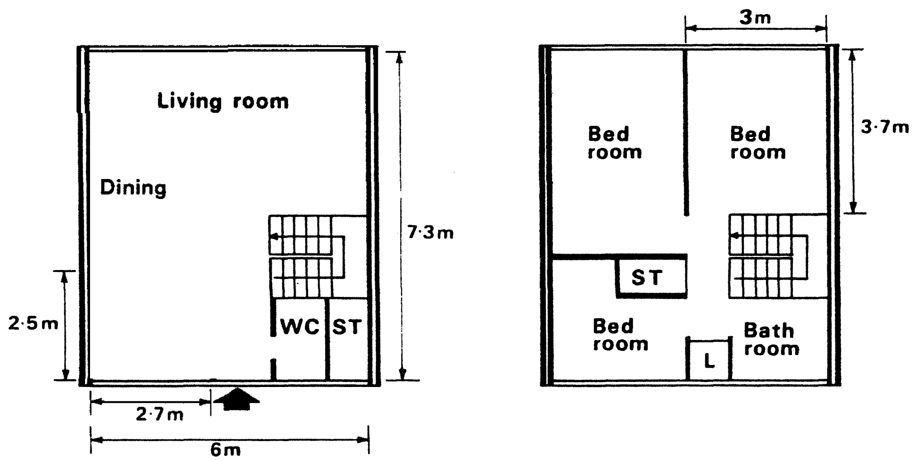

Figure 1 Plan of centre terraced house floor area - 90 m^2

TABLE 1 ASSUMED CHARACTERISTICS OF CENTRE TERRACED HOUSE

Building element	Area m^2	Thermal transmittance (W/m^2 degC)	
		(a) Building Regulations Standard	(b) Continental Standard
Floor	43	-	-
Roof	43	1.4	0.5
External walls	41	1.7	0.5
Windows & doors	19	4.5	4.5

Calculations were made for two heat emission rates, 2 and 4 kW, and for two moisture input rates, derived from the assumptions about moisture from domestic activities set out in Table 2. The lower moisture input rate, 7.2 kg/day, applies to houses where no clothes are dried indoors; the higher input rate, 14.4 kg/day, applies to houses where clothes are regularly dried indoors and a paraffin heater used for 4-5 hours per day, or equivalent amounts of moisture generated by other means.

TABLE 2 ASSUMED MOISTURE EMISSION RATES

SOURCES where moisture emission is low	Moisture emission per day (kg)	Comments
5 persons asleep for 8 hr		Typical moisture emission rates[7]
2 persons active for 16 hr	1.7	
Cooking	3.0	3 hrs cooking by gas cooker
Bathing, dish washing etc	1.0	Estimated
Daily total	7.2	
ADDITIONAL SOURCES where moisture emission is high		
Washing clothes	0.5	Estimated
Drying clothes	5.0	Measured, for 3 kg dry weight of clothes, spun dry
Paraffin heater during evening	1.7	1.7 litres paraffin, eg 4 kW for 5 hrs
Daily total	14.4	

The internal temperature and relative humidity were calculated assuming an external temperature of 0°C and relative humidity of 90 per cent (ie moisture content 0.0034 kg moisture per kg of dry air). The mean internal temperature $\bar{t}_i$ was calculated from the steady-state equation:

$$\bar{q} = (\Sigma AU + sV)\ (\bar{t}_i - \bar{t}_o) \quad \text{.......... (1)}$$

where $\bar{q}$ = mean rate of heat input

ΣAU = sum of areas and U values of building elements (walls and roof) exposed to outside air

s = thermal capacity of air per unit volume

v = volumetric rate of air exchange with outside; this is equal to the product of the air change rate n and the volume of the house or room considered

$\bar{t}_i$, $\bar{t}_o$ = mean inside and outside temperatures.

The mean moisture content of the internal air, $\bar{g}_i$, was then found from the equation:

$$G = P\,V(\bar{g}_i - \bar{g}_o) \quad \text{.......... (2)}$$

where G = mean rate of moisture emission

P = density of air

V = volumetric rate of air exchange

$\bar{g}_i$, $\bar{g}_o$ = mean inside and outside moisture contents (mass of water per unit mass of dry air).

The relative humidity was found from the moisture content and temperature using a psychrometric chart.

It is interesting to examine the curves in Figures 2 and 3, which show calculated mean temperatures and relative humidities plotted against ventilation rates for the two standards of insulation, first considering a heat input of 4 kW. For normal insulation (Building Regulations standard) and a ventilation rate of 0.5 to 1.0 air changes/h, a mean temperature of about 15°C is obtained with a relative humidity below 70 per cent. This temperature meets the standards proposed by the 'Parker Morris' report[8], which recommends that living rooms should be capable of being kept at 18.3°C (65°F) and kitchen and circulation spaces at 12.8°C (55°F). If bedrooms are also assumed to be at 12.8°C, the mean house temperature is 15°C. If the ventilation rate is raised to 2.5 air changes/h, the house is uncomfortably cool (10°C) and the relative humidity is not significantly reduced. If the house is insulated to the 'Continental' standard, a heat input of 4 kW is more than enough to maintain comfortable temperatures with a ventilation rate of 0.5 to 1.0 air changes/h (see Figure 3).

However some families cannot, or do not choose to, pay for a heat input of 4 kW and the graphs illustrate what happens when they cannot afford to provide more than 2 kW. With normal insulation, a mean temperature of 9°C is achieved with 0.5 air changes/h, which is the ventilation rate required to meet the hygienic requirements of 0.6 l/s per person. Such temperatures are not uncommon in Local Authority houses. The graphs show that even with the lower moisture input (7.2 kg/day) the mean relative humidity is 85 per cent under these conditions - well above the limit of 70 per cent. With the higher moisture input, the relative humidity is 100 per cent and moisture is continuously deposited by condensation.

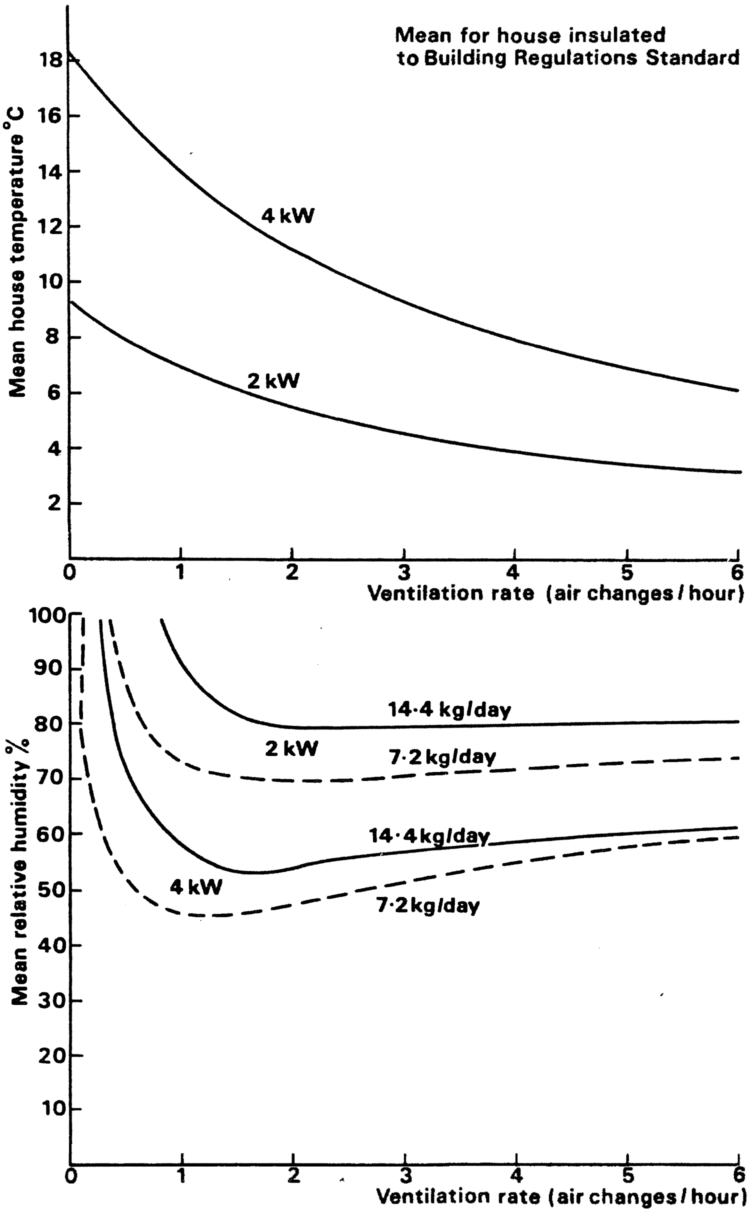

Figure 2 Effect of ventilation on temperature and relative humidity

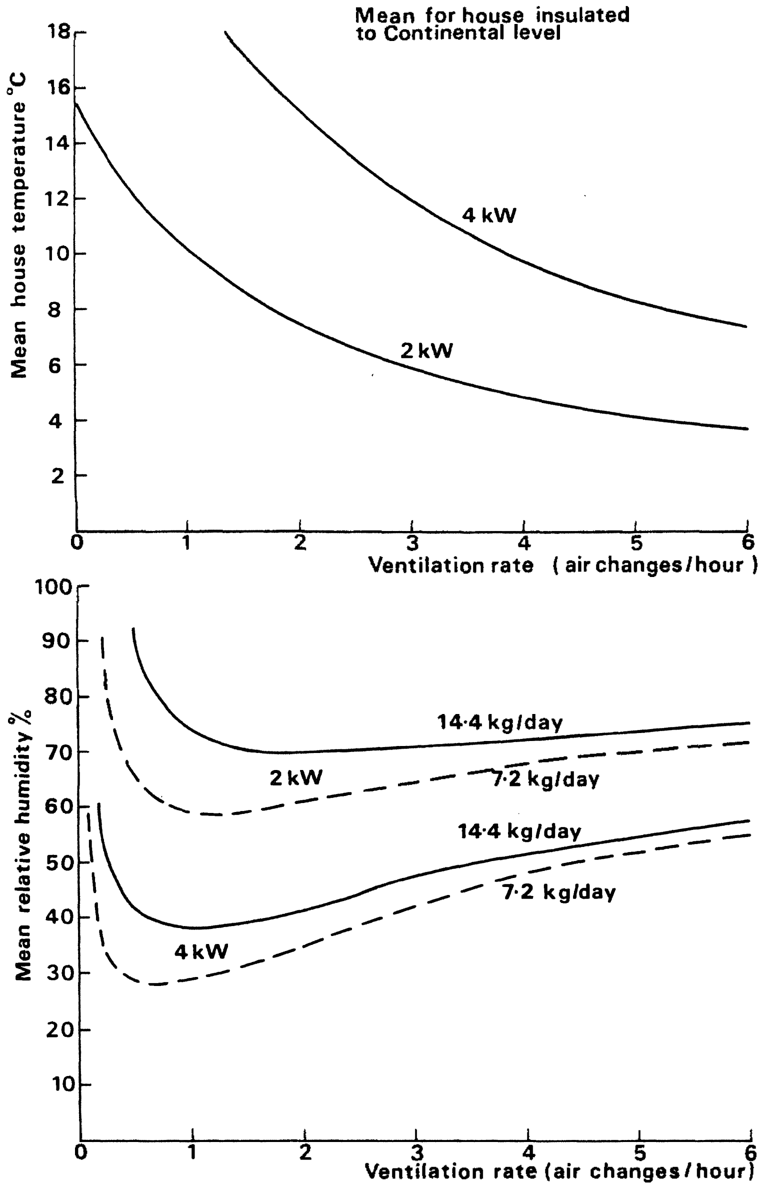

Figure 3 Effect of ventilation on temperature and relative humidity

Moreover, the relative humidity cannot be brought below 70 per cent by increasing the ventilation rate which merely reduces the temperature to the low value of 5.5°C with 2 air changes/hr.

A high standard of insulation can be very valuable when the heat input is low. Figure 3 shows that insulation to the Continental standard reduces the relative humidity to an acceptable level even when the rate of heat input is only 2 kW. A mean temperature of 12°C is obtained with a ventilation rate of 0.5 air changes/h, and a moisture input of 7.2 kg/day gives a mean relative humidity below 70 per cent. While not ideal, this condition would be acceptable to many people.

Calculations were also made for a detached house with the same floor plan as the centre-terraced house (see Figure 1), but with side walls exposed, and for a centre flat of area 70 m^2. For the detached house 'normally insulated', calculations indicate that the heat input has to be 7 kW to give a mean temperature of 15°C with 1 air change/h; 4 kW suffices with Continental standards of insulation. Relative humidities, as before, are well below 70 per cent. A heat input of 2 kW is inadequate; it gives a temperature of only 5.5°C with 0.5 air changes/h in the normally insulated house, and 10°C with Continental standards of insulation; relative humidities are above 70 per cent in both cases. For the centre flat, normally insulated, a heat input of only 2.5 kW provides a temperature of 15°C and a relative humidity below 70 per cent at 0.7 air changes/h, and less than 2 kW is needed to give these conditions with Continental standards of insulation.

These calculations apply, of course, only to buildings which conform to the assumptions made, and separate calculations have to be made for other house designs, and other circumstances. Thus losses through ground floors affect results for ground floor flats or centre-terraced houses; and flats and terraced houses lose heat through end walls, and top floor flats lose heat through the roof. Again, calculations should be modified to allow for the fact that the heat input to living areas is generally higher than to other parts of the house; this could be done by basing the calculations on the mean heat input to the cooler parts of the house.

It is also necessary to adjust assumptions about average moisture input rates to the circumstances of the houses considered. For instance the moisture inputs to the house as a whole are reduced if a kitchen or bathroom extract fan is fitted to remove moisture directly from these rooms. Though this reduces condensation and mould growth, however, it does not necessarily eliminate it. It is necessary to allow for moisture generated by drying clothes, washing floors etc as well as that generated by the occupants, and to recalculate the relative humidity.

Charts of the type shown in Figure 2 and 3 could be useful to designers. They could be drawn up for different house types and different methods of using houses. Field studies might be needed to establish soundly based assumptions about the range of heat and moisture inputs actually used in buildings.

Such charts could be used directly to indicate whether relative humidities could be kept low enough by suitable ventilation, and provide guidance on the necessary ventilation rates where this is possible. If reliance is placed on natural ventilation, either through openable windows or other ventilation openings, guidance on the apertures required can be obtained by reference to Dick's investigations of the principles of natural ventilation[9].

The charts in Figures 2, 3, 5, 6 and 7 have the deficiency that they are based on steady-state calculations and do not take account of the effect of diurnal variations in heat and moisture emission rates. Ideally temperature and humidity variations should be calculated and an assessment made of the periods when condensation is likely to occur. This has not been considered in detail, but the admittance procedure developed by Danter[10] provides a means of assessing the temperature variations resulting from heat input variations, and it might be adopted in future research in this field.

As an illustration Figure 4 compares measured temperature variations in an unoccupied flat with values calculated by the admittance procedure. Heat inputs were varied experimentally to correspond with an assumed typical pattern of heat input variations arising from cooking of meals, use of domestic hot water, and adjustment of the warm air heating system. Although agreement is not very close, partly because heat input variations were not recorded precisely, the predicted temperature swings are of the same order of magnitude as the measured values.

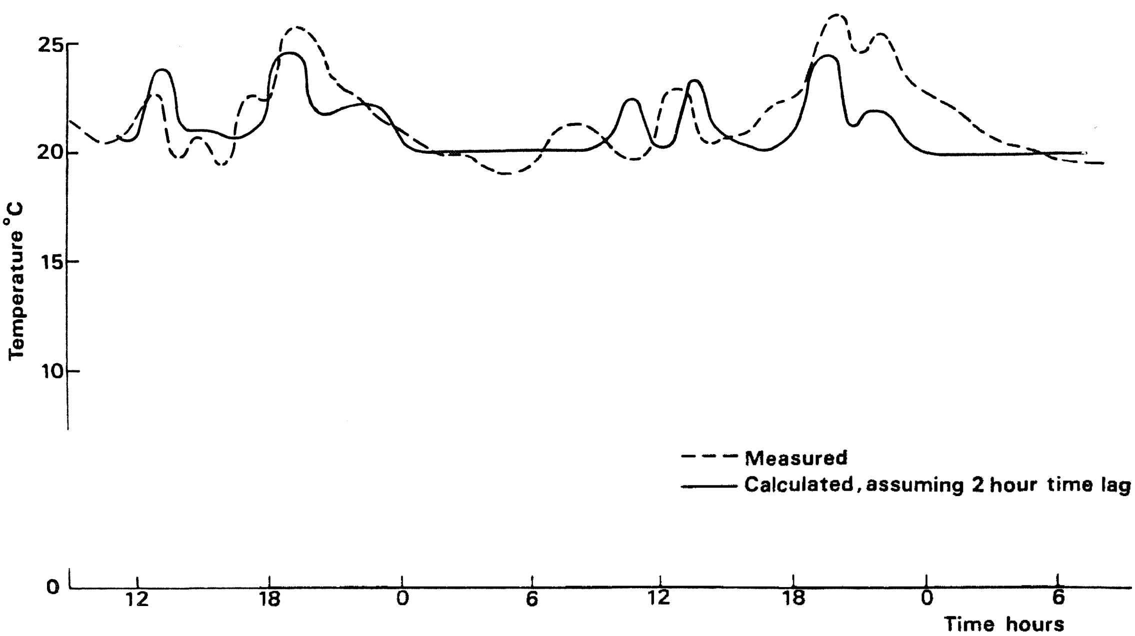

Figure 4 Comparison of measured and calculated temperatures in an unoccupied flat

In this case diurnal temperature variations were much less than the mean temperature difference between inside and outside, and the accuracy of the prediction of temperature variations was quite adequate.

As a conservative design assumption, it can be assumed that there is no storage of moisture in walls or furnishings when calculating the variations in the moisture content of the internal air. Though absorbent finishes can alleviate temporary condensation, one cannot rely on these being present. In kitchens, non-absorbent washable wall-papers or gloss painted finishes are common. Timber is generally treated and is therefore non-absorbent, and furnishing fabrics are commonly of non-absorbent man-made fibres.

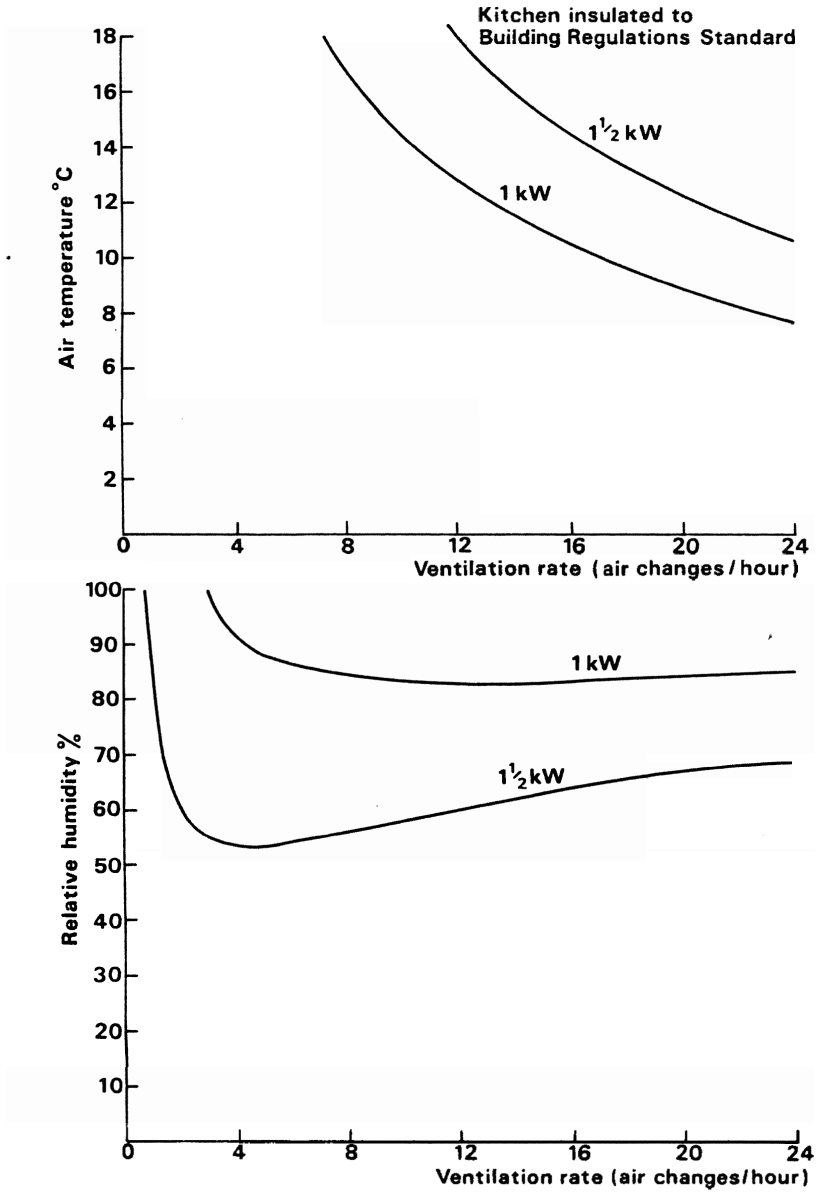

Figure 5 Effect of ventilation on temperature and relative humidity

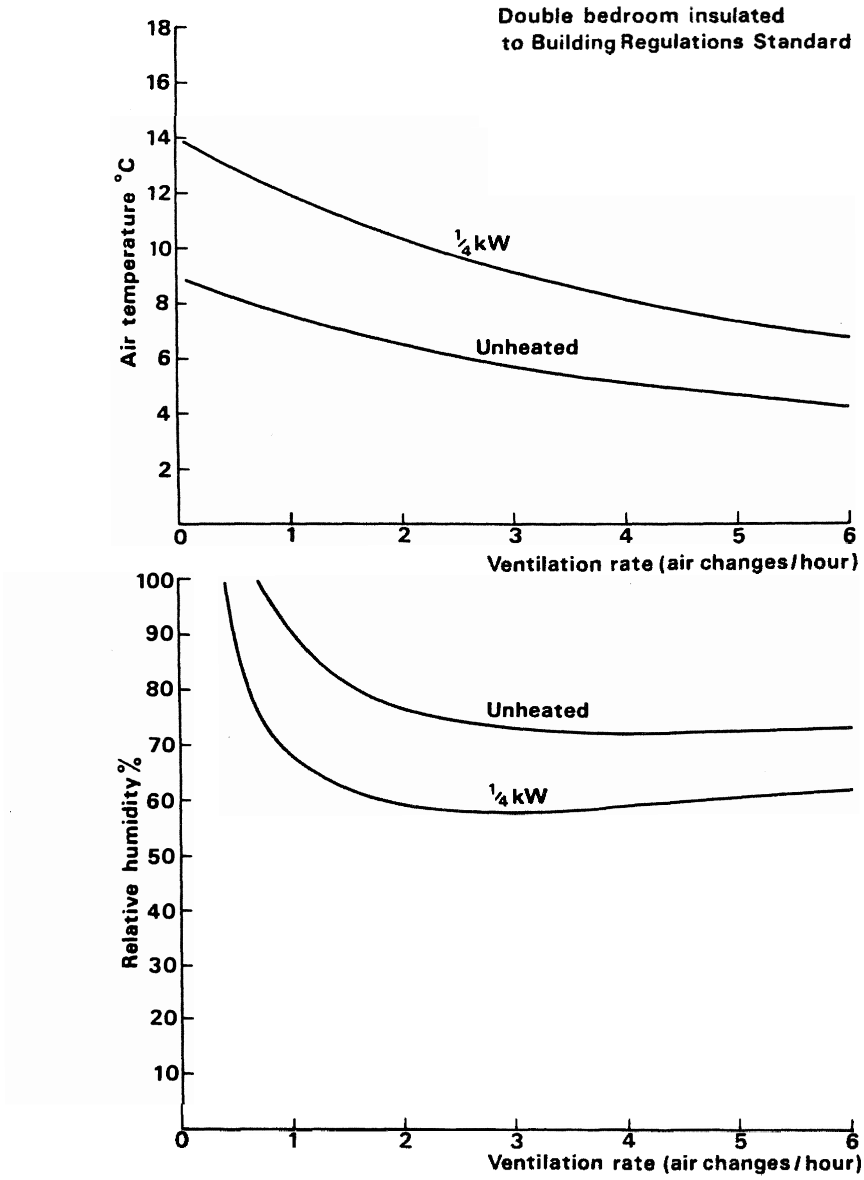

Figure 6 Effect of ventilation on temperature and relative humidity

KITCHENS

Normally the kitchen is the room in which most moisture is generated, and it is clearly better to remove this by ventilating the kitchen to outside, rather than allow it to permeate the house. If this is done, the requirements for avoiding condensation in the rest of the house are eased. The ventilation requirements for the kitchen itself need to be assessed.

It is only when moisture is being freely emitted that a high ventilation rate is needed. When meals are being cooked and the moisture input is greatest, there is also an additional heat input. Moreover the housewife here is likely to adjust the ventilation to keep the room comfortable while cooking meals. Steady-state calculations have been made on the assumption that the additional heat input just balances the additional heat loss by ventilation.

Calculations were made for the kitchen shown in plan in Figure 1, 2.4 x 2.7 x 2.3 m high, assuming a moisture input rate of 0.3 g/s (1 kg per hour) for gas cooking and heat input rates of 1.0 and 1.5 kW. The results, shown in Figure 5, indicate that the relative humidity cannot be kept much below 85 per cent with a heat input of 1 kW whatever the ventilation rate. This humidity is excessive, not because of mould growth (the kitchen dries out later) but because it causes condensation on the walls as well as the windows. With a heat input of 1.5 kW, however, the relative humidity is kept below 70 per cent and in this situation no condensation forms on the walls, with any reasonable ventilation rate.

There are some practical difficulties in providing the ventilation by 'natural' means. There is of course no difficulty when the kitchen windows are on the leeward side of the house; ventilation is achieved by opening the windows and (internal) door. However when the kitchen windows are on the windward side, moist air is blown into the house. A more elaborate system is therefore needed to obtain reliable extraction of moisture by natural ventilation. For instance it might be possible to fit a self-closing kitchen door, an outlet duct and inlet grille. The system would have to be designed to operate in calm weather by using the 'stack pressure' due to the inside to outside temperature difference.

Difficulties in designing a reliable natural ventilation system make mechanical ventilation attractive. An extract fan can be fitted in the window or outer wall and switched on when moisture is produced. The fans sold for small kitchens normally have a flow rate of about 80 l/s, giving a ventilation rate of about 18 air changes/h, which is high enough to keep the relative humidity at an acceptable level (see Figure 5).

Use of an extract fan has its dangers when the kitchen contains a boiler unless the flue is sealed from the room (eg a balanced flue). If the room is well sealed - with doors and windows weatherstripped and no air bricks - the suction due to the fan may draw combustion products into the room, and there is a danger of carbon monoxide poisoning if combustion is incomplete. One way to avoid this danger is to fit a fan in an internal wall to blow air into the kitchen, but this is ineffective if the kitchen door is opened. An extract fan can be used safely if the air inlets are adequate. A more foolproof system is to fit a 'two-way' fan, which blows in as much air as it extracts.

BEDROOMS

The mean house temperatures plotted in Figures 2 and 3 were derived on the assumption that heat and moisture are uniformly distributed through the house. In practice, however, bedrooms are often unheated and it is useful to calculate whether the moisture emitted by the occupants is sufficient to keep the relative humidity above 70 per cent at night.

Calculations were made for a double bedroom 3.7 m x 3 m x 2.3 m high with 25 per cent glass in the outer wall (Figure 1). The occupants were each assumed to emit 0.01 g of moisture/sec (0.04 kg/h - see Table 2). Though the room was nominally unheated, account was taken of heat gain by conduction through a wood joist floor from downstairs rooms at 15°C and of a heat emission of 90 W from each occupant. It was assumed that no air infiltrated to the bedroom from the rest of the house.

Calculated temperatures in the house insulated to Building Regulations standard are shown in Figure 6. The temperature is only 6°C with 2.5 air changes/h and the relative humidity does not fall below 70 per cent whatever the ventilation rate. Thus there is a danger of mould in an unheated bedroom if the house is normally insulated. A heat input of 0.25 W is sufficient to raise the temperature to 10°C with 2.5 air changes/h and to reduce the relative humidity to 60 per cent. Figure 7 shows that the temperature in a similar house insulated to Continental standards is 8°C and the relative humidity is only 65 per cent at 2.5 air changes/h. If the house plan is different and the bedroom receives less heat from downstairs, the temperature in the bedroom is of course much lower, with a correspondingly higher relative humidity. For instance in a detached house with two bedroom walls exposed, temperatures are lower than in the centre terraced house or the flat.

CONCLUSIONS

Mean temperatures and relative humidities have been calculated for different house types, assuming an outside temperature of 0°C, a relative humidity of 90 per cent, various heat and moisture inputs, and a range of ventilation rates. The calculations indicate that there is a certain critical minimum amount of heat needed to give a relative humidity less than 70 per cent, and thus avoid the danger of mould growth. This critical amount of heat depends both on the house type and the degree of insulation. It is less in a centre-terraced than a detached house, and less in a centre flat than a centre-terraced house, because of differences in the number of exposed surfaces, and in each case improved insulation reduces the heat requirement. As well as supplying heat, it is necessary to provide a certain minimum amount of ventilation, but this minimum amount is shown to be much the same as is required for hygienic purposes, ie 0.5 to 1.0 air changes/h for the house as a whole.

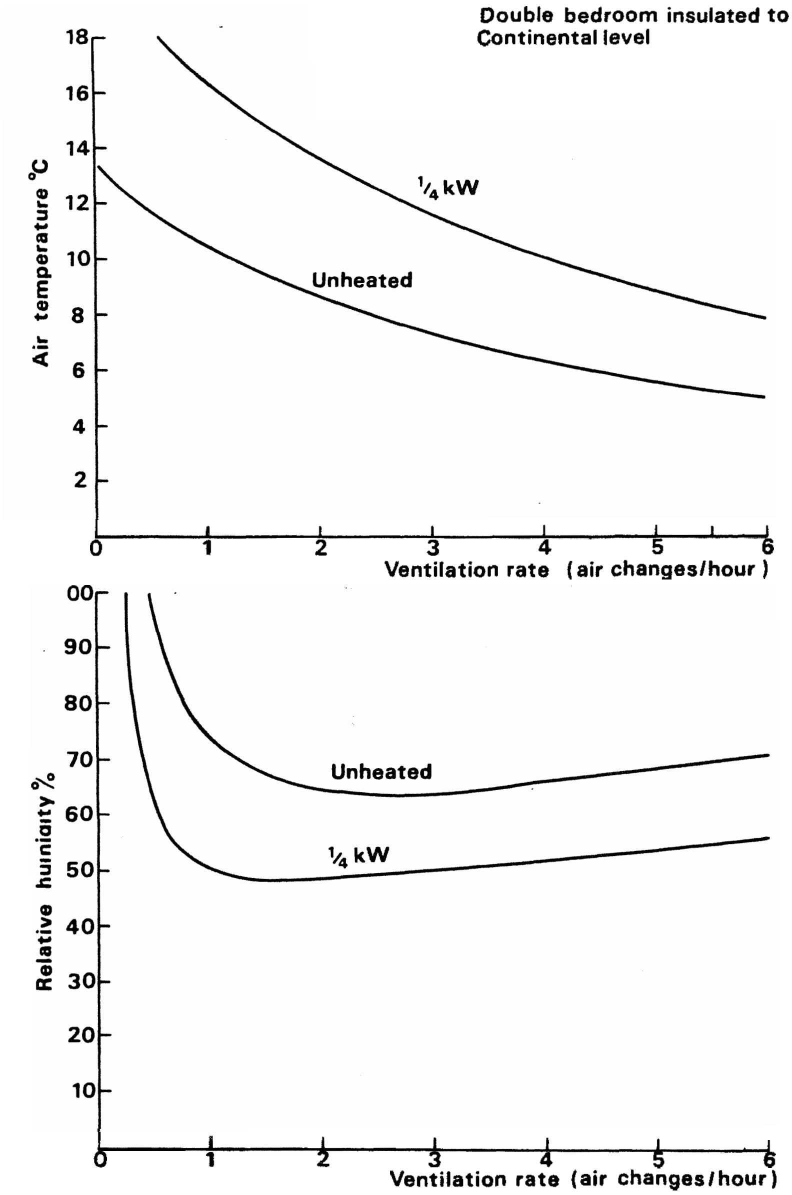

Figure 7 Effect of ventilation on temperature and relative humidity

The graphs of temperature and humidity allow the risk of condensation on different surfaces, such as walls and windows, to be assessed. Averages for the whole house can give a first warning of condensation danger, and more detail can be obtained from separate calculations for the kitchen and for a bedroom. Calculations for the kitchen show that a high ventilation rate is needed while meals are being cooked, together with a certain minimum heat input. In bedrooms, it is shown that the relative humidity cannot be kept below 70 per cent in a normally insulated unheated bedroom, whatever the ventilation rate, with the assumed external conditions. If the bedroom is insulated to the 'Continental' standard however, the heat transmitted through a wood joist floor is sufficient to reduce the relative humidity below 70 per cent.

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