ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

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AVOIDING CONDENSATION AND MOULD GROWTH IN EXISTING HOUSING WITH THE MINIMUM ENERGY INPUT

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SYNOPSIS

Detailed studies of public sector modernisation programmes have shown that the principal problem resulting from lack of thermal insulation and inappropriate methods of heating and ventilation is condensation and mould growth. The traditional solution in the UK has been to install permanent 'uncontrolled' ventilation openings in the external walls of the affected rooms and encourage the occupiers to increase the heat input. This is not an energy efficient solution to the problem.

Assuming typical values for moisture emission, external temperature and relative humidity, and adopting the coarse criterion of limiting the relative humidity of the room air to 70%, it is possible to show, for dwellings with particular heat loss characteristics, the optimum air change rate at which the heat input necessary to prevent the RH rising above 70% is at a minimum.

However, the average internal temperatures which result from this minimum heat input are too low to be considered comfortable and it is necessary to consider the implications of air change rates less than the optimum.

Under these circumstances, the thermal insulation characteristics of the enclosing walls etc. become important, particularly in the corners of exposed rooms where the surface temperature will be less than the remainder of the room. Given the same typical moisture emission a wall U value of 1.0 W/m^2K is enough to avoid surface condensation in the corners of rooms.

LIST OF SYMBOLS

R = Thermal resistance of building element (m^2K/W)

U = Thermal transmittance value (W/m^2K)

T_R = Room air temperature (^oC)

T_S = Surface temperature (^oC)

T_E = External air temperature (^oC)

R_{si} = Internal surface resistance (m^2K/W)

1. CONDENSATION IN EXISTING HOUSING

Detailed studies of public sector modernisation programmes, particularly those for Local Authorities and Housing Associations (ie. private organisations receiving subsidy in order to sponsor housing for rent) have shown that in many cases insufficient emphasis had been put on incorporating, as part of the renovation work, recommended energy conservation measures. The standard of thermal performance of these dwellings was therefore substantially less than new dwellings offering the same accommodation.

As a result there were frequent reports of condensation and mould growth in dwellings, often within a few months of occupation.

The poor thermal characteristics of these existing dwellings can be attributed, not only to their general lack of thermal insulation, but also to their physical characteristics (shape and size).

1.1 Typical dwelling types

The types of dwelling found in this type of housing rehabilitation range from flats and maisonettes which result from the conversion of large 4 storey city mansions, to family units in small two storey houses. The variation in area and volume is considerable.

It is common for there to be an addition to the main terrace of the building. These "back additions" accommodate Kitchens, Bathrooms, and Bedrooms and are sometimes, but not always, back to back. In all cases their enclosing wall area is high in relation to their volume. In the large city conversions, the basement often accommodates Bedrooms and the roof space a small flat.

The main features of each location, insofar as they relate to thermal performance, are as follows:

Basements

* Windows on the road side are often large but derive no benefit from solar gain.
* There is no convective heat gain from below.
* Internal temperatures can be raised only by means of an applied heat source. Internal heat gain is negligible.
* Floor to ceiling heights are between 2.4 and 2.5 metres.

The main terrace

- In large city flat conversions, ground floor rooms (usually Living Rooms, Dining Rooms or Dining/Kitchens) have high ceilings, in the order of 3 metres.

- Where Bedrooms are above Living Rooms, they will benefit from convective heat flow.

- Some benefit may be derived from solar gain depending on shading by adjacent buildings.

- Due to replanning, there may be an internal Bathroom, mechanically ventilated.

Back addition

- Back additions often accommodate moisture generating rooms (Kitchens and Bathrooms).

- Bedrooms are often situated above Kitchens. They will receive water vapour from below but no useful convective heat from the Living Rooms in the main terrace.

- Rooms in back additions are not usually provided with a fixed heat emitter.

It was particularly noticeable in the case of Housing Associations, that the standard of renovation varied considerably, depending on the regional cost limits in force. In many cases, only short term repairs were carried out and even the 'improvement' of amenities was kept to an absolute minimum. For example, only loft insulation was considered as "essential" and often, heating was restricted to the Living Room only. There was also no requirement even for simple draught stripping of large windows to be carried out. The result was that many tenants on low incomes were not able to maintain sufficiently high temperatures to avoid condensation and mould growth.

Generally, Housing Association staff were aware of the inadequacy of these measures, but were forced to wait until condensation and mould growth had occurred before they could claim extra funds for additional insulation and heating.

1.2 The condensation problems

Traditionally, these old dwellings were heated by burning cheap fuel on open fires, which ensured sufficient heating and ventilation. Apart from cooking, moisture generating activities such as bathing and internal clothes drying did not take place on the same scale as today. Similarly, households did not have the benefit of non-electric portable heating appliances.

The problem is that tenants are encouraged to spend their money on the amenity provided by labour saving appliances such as tumble dryers, but they are then unable to afford a level of heating throughout the dwelling, which is necessary to avoid condensation, especially with the poor level of thermal insulation provided. In other cases portable heating appliances run on calor gas or paraffin are purchased because fixed economical arrangements are not made for heating their dwellings.

Clearly, the current provision of heating and thermal insulation is not providing an adequate solution. But opinions differ on where the emphasis should be placed.

1.3 Alternative solutions

Traditionally, remedies for condensation problems were based on increasing heat input and providing permanent (uncontrolled) ventilation in the form of air bricks, this being cheaper to install than additional thermal insulation.

This solution inevitably puts a heavy financial burden on the tenant and at the same time provides no increase in comfort. It is understandable therefore, that tenants will block up the ventilation openings in an attempt to keep warm.

Alternatively, the provision of additional thermal insulation, although more costly, enables higher temperatures to be achieved for less heat input and being part of the building fabric cannot be "turned off". It is therefore guaranteed to work in the tenants' best interests in avoiding condensation problems.

2. CONDENSATION PREDICTION CRITERIA

There is general agreement on two criteria by which to predict whether condensation and mould growth is likely to persist as a problem.

The first coarse test of condensation risk is that the relative humidity of a room or dwelling should on average over a given period be no greater than 70%.

Secondly, the relative humidity of the air at the enclosing surfaces of a room should be maintained below 100% to avoid the formation of surface condensation.

In the past, the first criterion has been used as a general indicator that if the room air is kept below 70% RH, mould is unlikely to grow on organic materials, but also that the air at internal surfaces of external wall and roof elements would not be saturated. Whilst this general rule may apply for the main wall area, particularly if it is insulated, it may not be the case in the corners of rooms and behind curtains where air movement is restricted and a greater internal surface resistance results in reduced surface temperatures. Under these circumstances surface condensation can occur when the room RH is less than 70%.

The relationships between heating, ventilation and thermal insulation in achieving the above criteria for the least heat input may be illustrated graphically.

3. WHOLE DWELLING ANALYSIS

The relative influence of the three variables is illustrated in Figures 1 and 2, the first relating to a 5 person, 3 Bedroom house (volume 230m^3) and the second showing the position for a ground floor/basement maisonette (2 storey flat) of similar accommodation but much greater size (volume 326m^3). The floor plans are shown in Figures 3 and 4.

The two stages of the calculation are shown together on the graph. Firstly, relating to the left hand scale are the average dwelling air temperatures which are necessary to maintain the relative humidity at 70% at a range of ventilation rates.

Curves related to the right hand scale show, for the same ventilation rates, the heat input necessary to achieve these dwelling temperatures, depending on their heat loss characteristics (in these cases influenced also by the dwelling location - middle or end of terrace).

In deriving these curves, the following assumptions were made:

1 - The time period is 24 hours.

2 - The moisture emission over 24 hours is 8.76 kg:

	kg
Occupants respiration	3.76
Cooking (3 hours)	3.00
Washing dishes	0.50
Washing clothes *	1.00
Bathing	0.50
	8.76

* It is assumed that clothes are dried outside the dwelling.

3 - The average external temperature is 4^{o}C, typical of the London Area during December, January and February.

The following conclusions may be deduced from the graphs:

(1) As the ventilation rate is increased the average internal temperature requirement decreases.

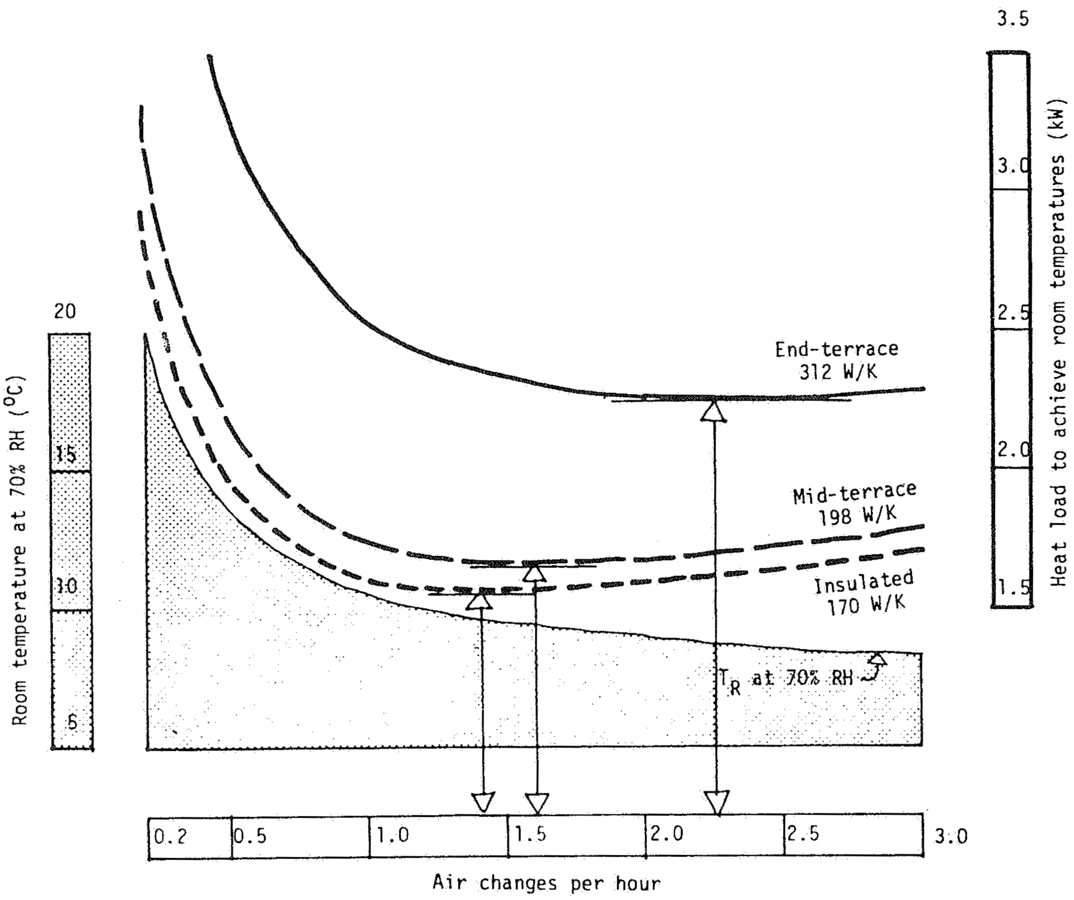


Figure 1 Room temperatures and corresponding heat loads necessary to achieve a relative humidity of 70% in a modernised HOUSE

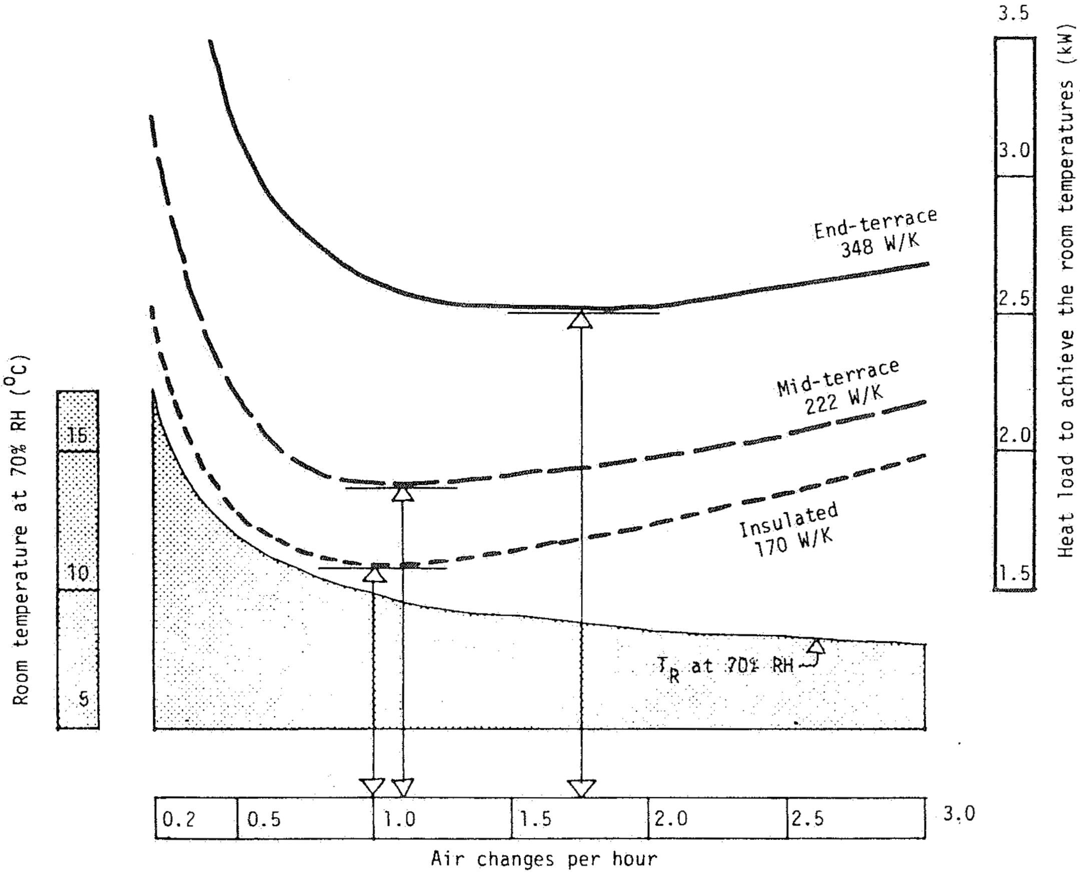
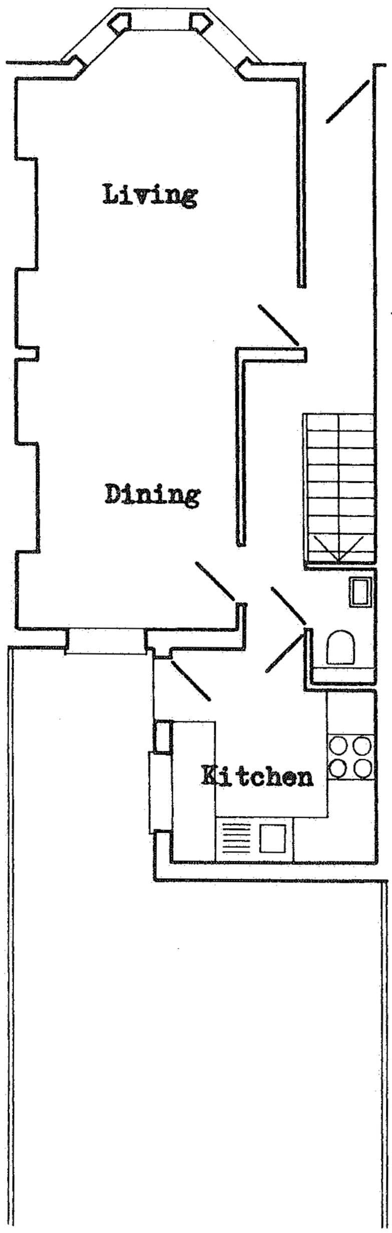
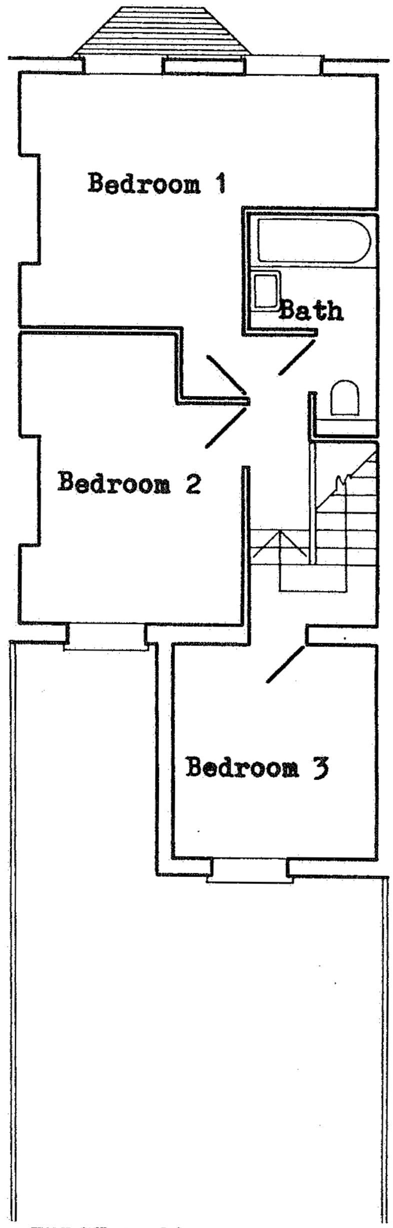


Figure 2 Room temperatures and corresponding heat loads necessary to achieve a relative humidity of 70% in a modernised MAISONETTE



GROUND FLOOR



FIRST FLOOR

Figure 3 Floor plans of a typical modernised HOUSE

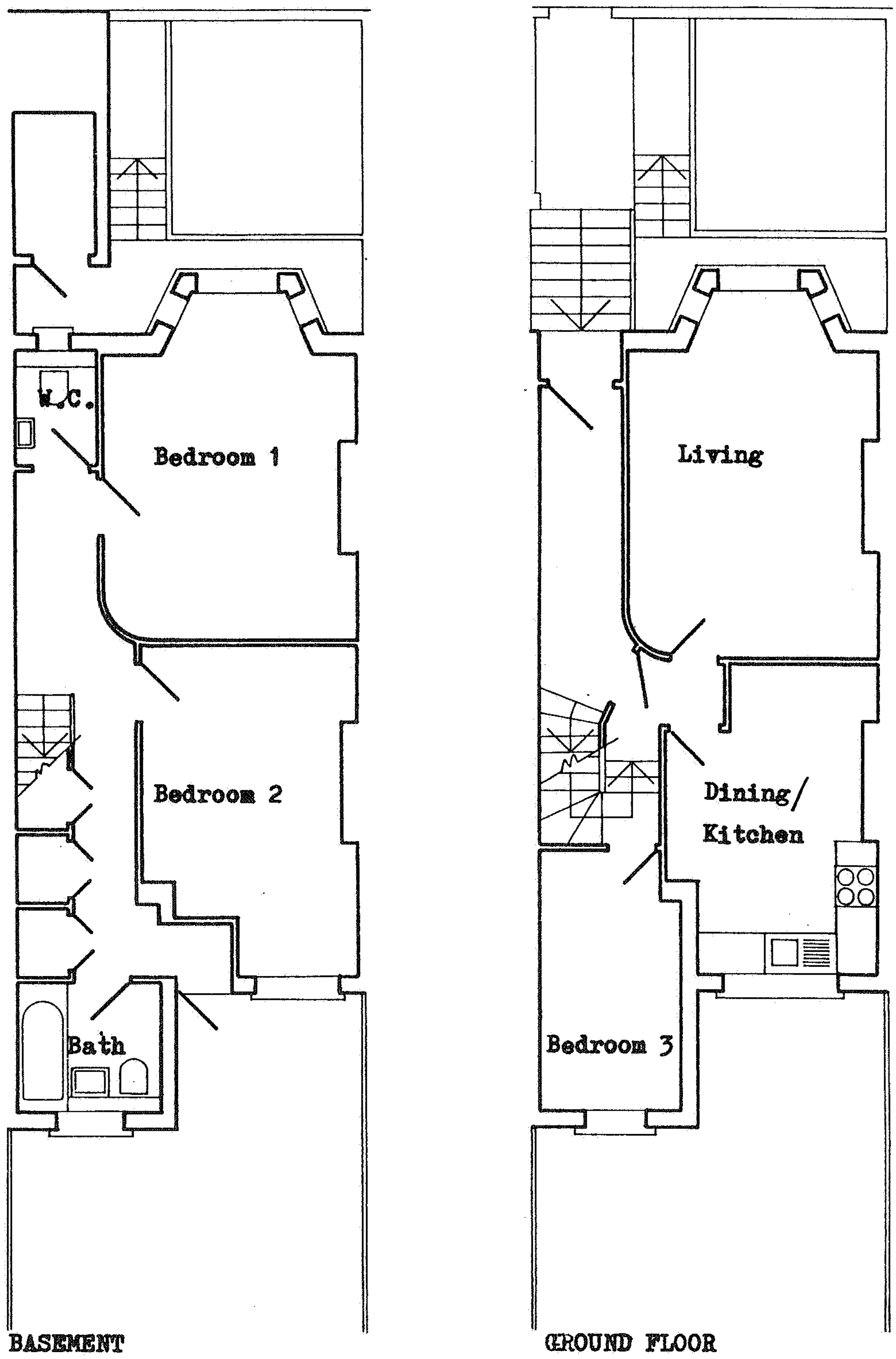


Figure 4 Floor plans of a typical modernised MAISONETTE

(2) In all cases, there is an optimum air change rate at which the heat input necessary to achieve the required internal temperature is at a minimum.

(3) The optimum ventilation rate becomes less as the heat loss characteristics of the dwelling are improved (ie. as the characteristic heat loss rate is reduced by additional insulation). This suggests that measures to reduce air infiltration and control ventilation may be taken without increasing potential condensation problems, provided the dwelling is insulated at the same time.

(4) The traditional approach of increasing ventilation rates is self defeating; the required heat input is increased and is accompanied by a reduction in internal temperature, below that acceptable for thermal comfort.

(5) If the air change rate is reduced below the optimum, it must be accompanied by an increase in heat input and/or a reduction in moisture emission to avoid condensation risk.

(6) Acceptable anti-condensation conditions can be maintained at lower temperatures in large dwellings than in small units, because the water vapour produced is diluted in a greater volume of air.

(7) Given the moisture emission of 8.76 kg/day, an external temperature of 4°C and an equivalent characteristic fabric heat loss rate of 170 W/K for both types of dwelling (achieved by insulating external walls in the house example and in addition insulating the Basement floor and double glazing the Living and Dining Room in the flat), we derive the following optimum air change rates and heat inputs as well as the associated average house temperatures achieved under these conditions:

	Ach/hr	Heat input	Average house Temperature
House	1.5	1.56 KW	9.50°C
Flat	1.0	1.60 KW	9.75°C

Figure 5 shows the heat input curves for the house and the flat when insulated to achieve a characteristic fabric heat loss rate of 170 W/K. It should be noted that the average internal temperature is less than 10°C for the whole house and may be considered unacceptably low for comfort.

4. ANALYSIS OF BEDROOMS

This technique may be extended to an analysis of the single and double Bedrooms in our typical rehabilitated house example, but in this case it is assumed that the outside temperature is 0°C and the time period 8 hours.

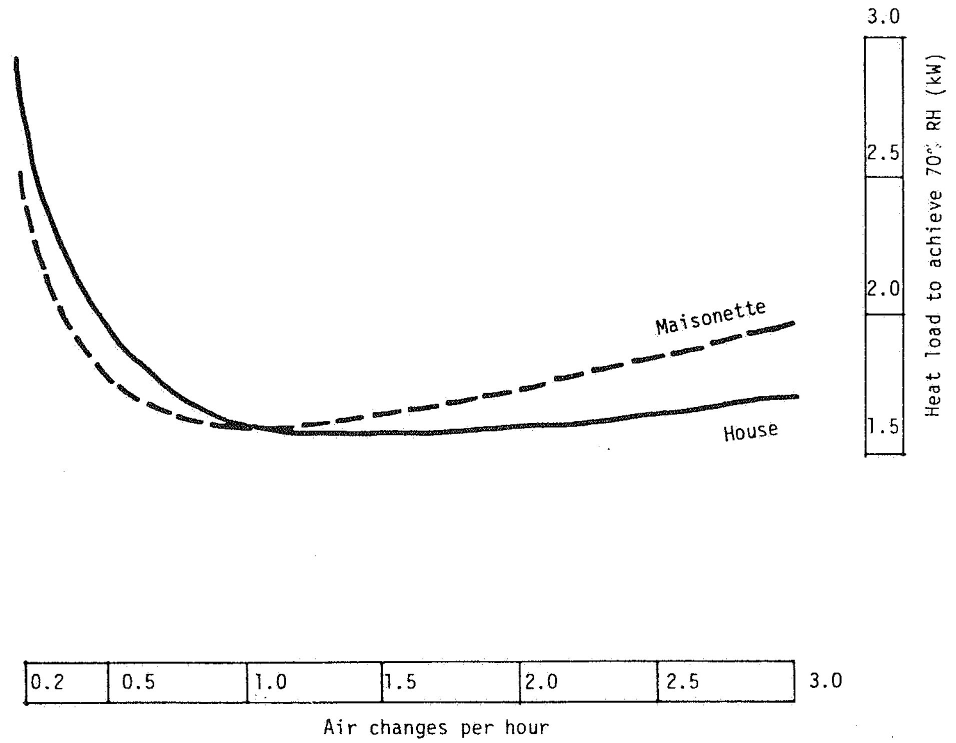


Figure 5 Comparison between the required heat inputs for the house and maisonette insulated to provide the same fabric heat loss characteristic (170 W/K).

Figures 6 and 7 show the 70% RH and dewpoint temperatures for these typical rooms.

In practice, moisture is introduced into the Bedrooms from the occupants or from the remainder of the house and ventilation air from the house or from the outside air. The change in room moisture content will not take place immediately but there will be a gradual change until an equilibrium moisture content is reached. The time taken will vary with room volume and air change rate. For these moisture contents there will be a corresponding temperature at which the relative humidity is 70%.

In the single Bedroom, for example, at a ventilation rate of one air change per hour, this equilibrium condition is reached after 3 hours of occupation. The required temperature at the start of the occupancy period may be higher or lower than the 8.8°C equilibrium temperature depending whether the moisture in the room air is assumed to be taken from the rest of the house or from the external air. The equilibrium (70% RH) temperature for the double Bedroom is much greater than the single room because of its greater occupancy to volume ratio.

The lower the air change rate, the longer it will take for the steady state to be reached. This could be all night for a double Bedroom at a ventilation rate of a half an air change per hour.

When, therefore, the wind direction is such that ventilation air is being drawn into the room from the rest of the house, the moisture content of the Bedroom air will be generally greater than when the Bedroom is on the windward side. In the latter case, the moisture content of the room air during the unoccupied period will tend towards that of the external air, thus reducing the room temperature necessary to avoid the RH rising above 70%.

The moisture content will also be reduced if the majority of the water vapour from the Kitchen and Bathroom is extracted at source. For example, the use of selective mechanical ventilation in these rooms could depress the Bedroom temperature requirement by 2°C.

The more the temperature required to maintain 70% RH can be reduced, the less heat is needed to offset the conditions likely to cause condensation.

This preliminary consideration of the dynamic condition shows that, although the temperature and therefore the heat requirements increase at low ventilation rates, the risk in practice may be reduced because of the greater time taken to reach the equilibrium condition. The time taken will of course depend on the source of the ventilation air. This approach needs further study.

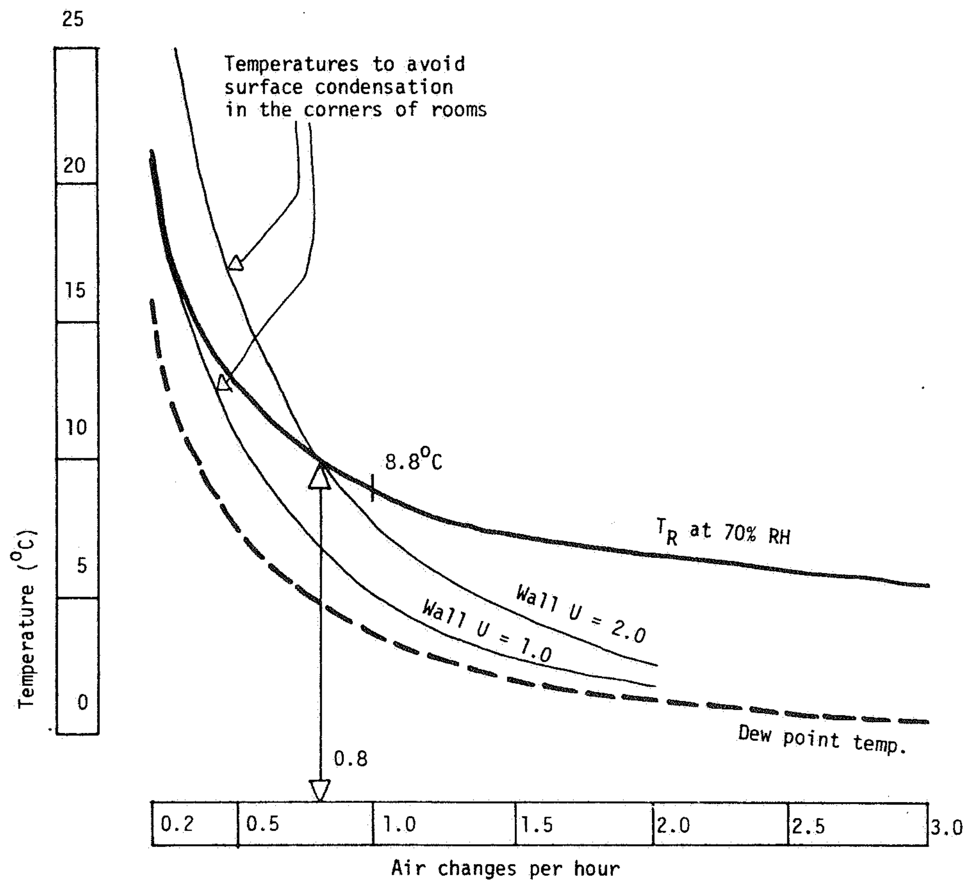


Figure 6 The relationship between airchange rate and internal temperature in a typical SINGLE BEDROOM

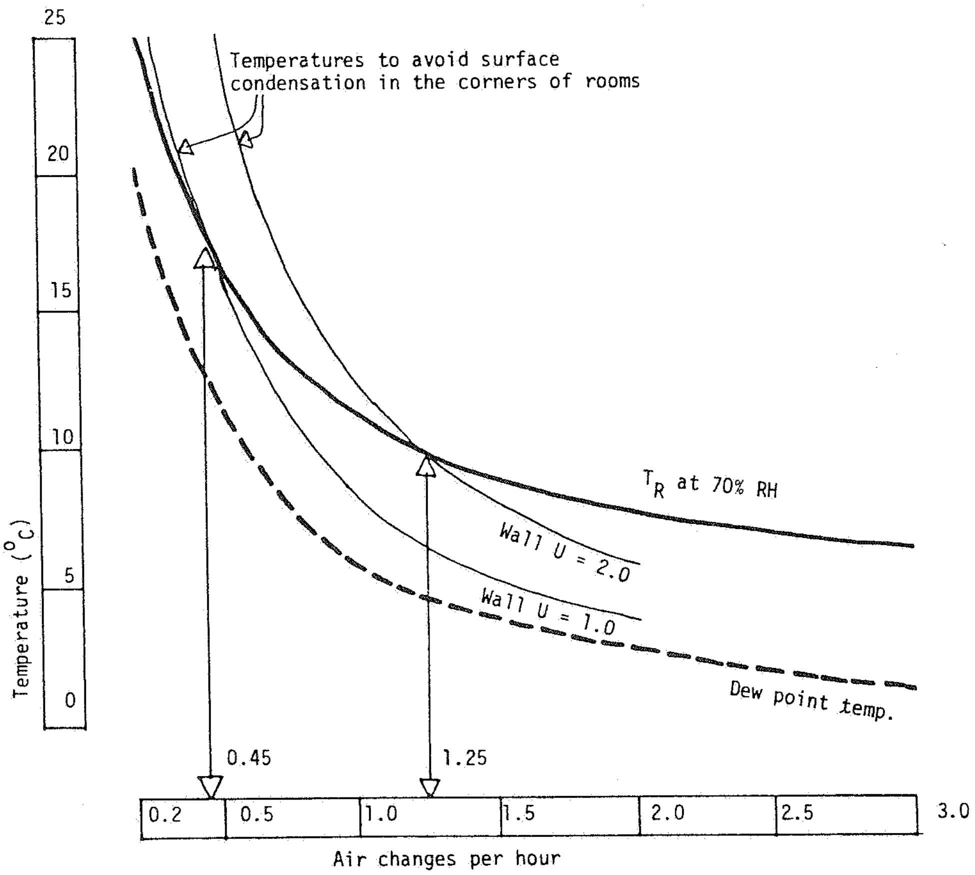


Figure 7 The relationship between air change rate and internal temperature in a typical DOUBLE BEDROOM

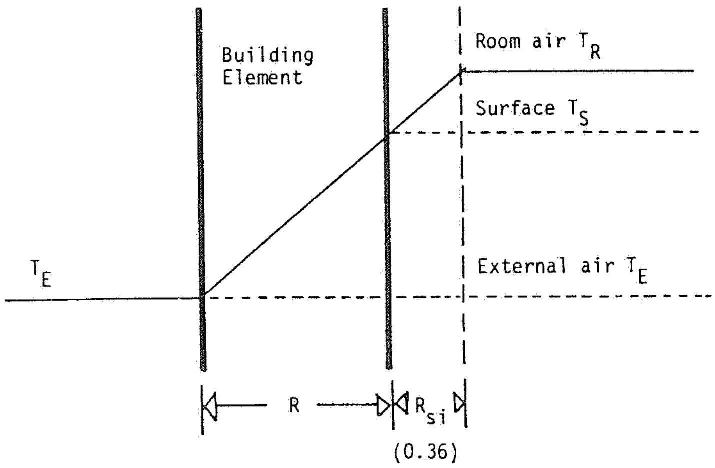


Figure 8 The temperature profile across a building element at an exposed corner of a room.

5. SURFACE CONDENSATION AT LOW AIR CHANGE RATES

The analysis so far has been based on the use of the initial coarse criterion for avoiding the risk of condensation ie. that the average temperature of the room air should be such that the relative humidity does not rise above 70%. This has identified optimum air change rates when the heat input to achieve this RH is the least.

However, the internal temperatures at these air change rates are perhaps too low for comfort. It is important, therefore, to explore the situation when air change rates are reduced to 1 or even ½ an air change per hour.

Under these circumstances, when the enclosing surfaces of the room are not well insulated, it is possible for the air at the surface to reach saturation before the air in the room generally reaches 70% relative humidity. This is particularly true in the corners of rooms or behind curtains - indeed any location where, due to lack of air movement, the internal surface resistance to heat transfer is increased above the normal condition and where the external surface resistance tends to zero due to the high exposure at the external corners of a building.

It is German practice to quantify the situation at the internal corners of exposed rooms, by assuming that the internal surface resistance to heat transfer is three times the normal value (ie. 0.36 rather than 0.12 m^2 K/W) and that the external surface resistance is zero.

We can therefore derive a relationship between the U values of the enclosing elements at the corners of rooms and temperatures on their surface and in the room generally. (See Figure 8)

Given, for example, a construction element with a particular 'standardised' U value, we can determine its own specific thermal resistance (R) by subtracting the sum of the 'standard' external and internal surface resistances and then, knowing the dew point temperature of the room air, calculate the room air temperature necessary to maintain surface temperatures in the corners above the dew point.

$$R = \frac{1}{U} - 0.18 \qquad \text{.............. (1)}$$

$$T_R + \frac{(T_S - T_E) \times 0.36}{R} + T_S \qquad \text{.............. (2)}$$

Figure 6 shows for the single Bedroom example how, with alternative U values of walls, the room temperatures necessary for surface condensation to occur in the corners of rooms are either within those determined by the 70% RH criterion (as is the case when the wall U value is 1.0 W/m^2K) or over-ride it at a certain air change rate, (in the region of 0.8 air changes per hour when the wall is uninsulated having a U value of 2.0 W/m^2K).

For the double Bedroom, the ventilation rates at which the corner condition becomes the critical factor is 1.2 ach/hr for a wall with a U value of 2.0 and 0.45 ach/hr for one with a U of 1.0 W/m^2K). (See Figure 7)

In both cases, the required temperatures increase dramatically below these critical air change rates. Clearly, there will be a correspondingly high heat input required to achieve these temperatures in rooms which have exposed corners, such as at the ends of terraces and "back additions".

The corresponding heat loads for our Bedroom examples have been calculated for different locations and levels of insulation and are shown in Figures 9 and 10.

Figure 9 shows that for pitched roof single Bedrooms in back additions at the end of a terrace, (BA-2U-ET), the heat load required to avoid surface condensation in the corners of rooms when the walls are not insulated increases dramatically when the ventilation rate drops below 0.8 ach/hr. The same characteristic applies to single Bedrooms at the gable end of the main terrace (T-2U-ET). This suggests that uninsulated single Bedrooms in these locations should not be ventilated below say one air change per hour, unless the daytime heat input is sufficient to evaporate the condensation formed during the night.

The addition of wall insulation to achieve U value improvement from U = 2 to U = 1 W/m^2K, (BA-1U-ET) avoids this situation and makes it possible to reduce the ventilation rate, achieving more comfortable internal conditions for the same heat load. However, when the walls are insulated, a heat load of some 275 W is still necessary, even if the ventilation rate is increased. This must be provided in back additions by a heating appliance, there being insufficient heat leakage from the rest of the house.

In contrast, a typical single Bedroom within the main terrace with walls uninsulated (T-2U) needs approximately one half the heat input required by a similar uninsulated bedroom in a back addition at a gable end. In this case, the heat load remains more or less constant at 220 W at all ventilation rates above 1.5 ach/hr. To increase the ventilation rate of a mid-terrace single room only serves to lower internal temperatures unnecessarily.

In double Bedrooms, not only are higher temperatures required overnight but the heat loads to achieve these temperatures are also greater, particularly as the air change rate is reduced (see Figure 10). The heat load for an uninsulated end of terrace Bedroom (DB-2U-ET) is 400 W even at 3 ach/hr rising to 550 W at 1 ach/hr. However, if the room is insulated (DB-IU-ET) the requirement drops to just above 300 W almost irrespective of air change rate. Clearly, as the room is better insulated, increased ventilation becomes a less attractive solution. Furthermore, whilst under steady state conditions poorly insulated rooms can be shown to require less heat input to avoid

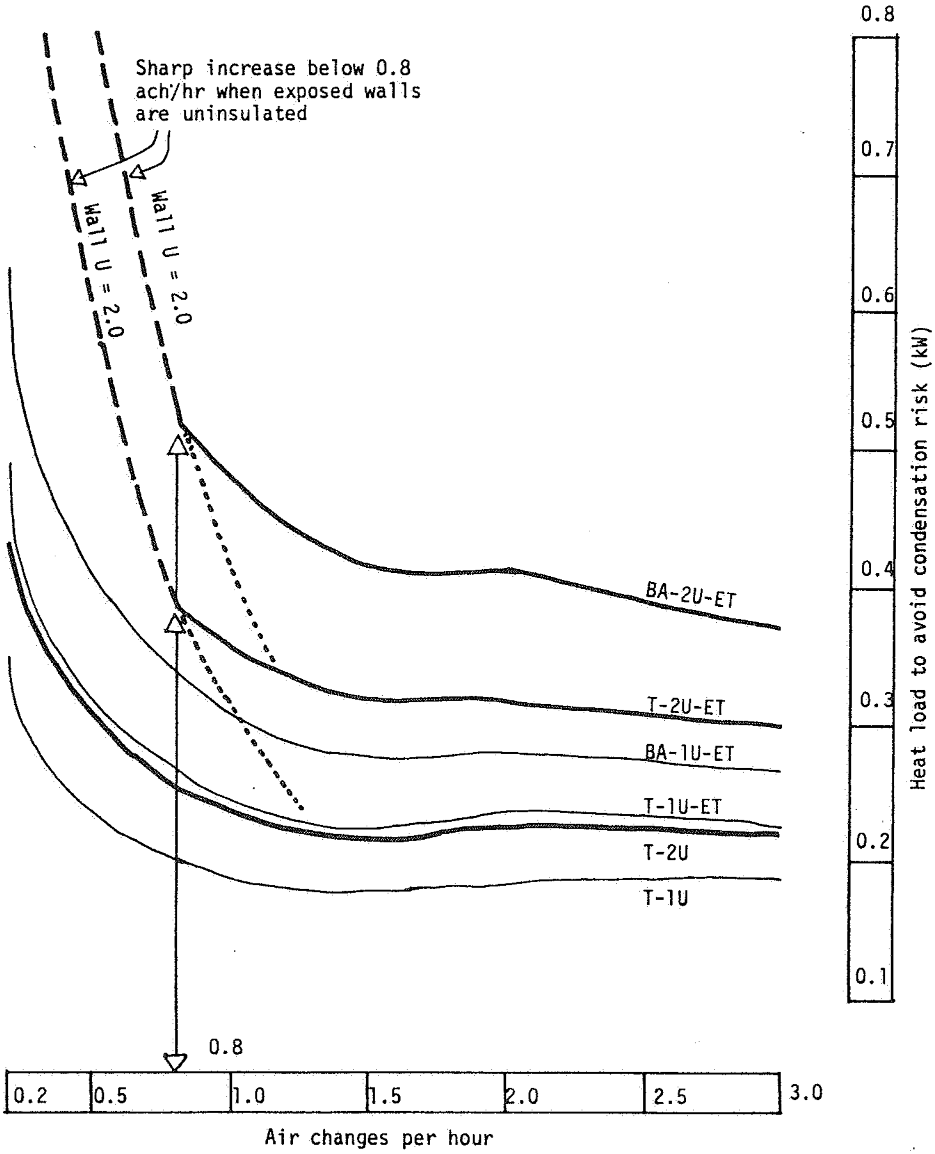


Figure 9 Heat loads necessary to avoid the risk of condensation on wall surfaces, including at corners - SINGLE BEDROOM

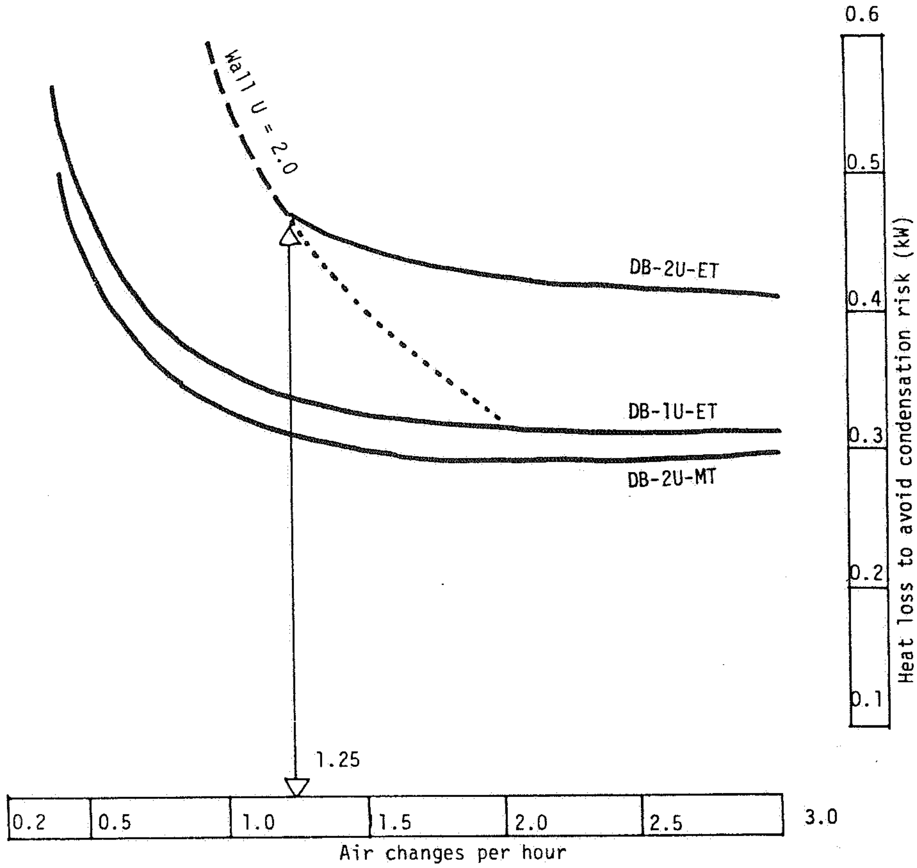


Figure 10 Heat loads necessary to avoid the risk of condensation on wall surfaces, including at corners - DOUBLE BEDROOM

condensation conditions, there is a greater danger of condensation occurring when warmer moist air is introduced to the room following a cold spell.

In the example shown the heating requirement is roughly the same for the uninsulated Bedroom in the mid-terrace position (DB-2U-MT) as for the insulated Bedroom at the end of the terrace (DB-IU-ET). These heat loads will differ depending on the configuration and window area of the room. Double Bedrooms can extend across the whole width of the frontage or be of a narrower configuration. The area of the room will vary considerably between that in a small house and that in a flat conversion. To determine appropriate heat loads, calculations would need to be carried out for a range of typical plan types.

6. CONCLUSIONS

Using accepted condensation prediction criteria, it can be shown that for a particular dwelling type, there is an optimum air change rate at which the heat input necessary to avoid condensation risk is at a minimum.

Large volume dwellings are able to be ventilated at a lower air change rate than smaller units with equivalent occupation and thermal characteristics. Similarly, the better a dwelling is insulated, the lower the optimum air change rate.

Preliminary studies of the build up of moisture in Bedrooms over night indicate that, as the ventilation rate is reduced, the time taken for the moisture content of the room air to reach equilibrium is increased. This could reduce the risk of condensation, provided the incoming ventilation air is introduced from the outside rather than from the remainder of the dwelling.

The optimum air change rates for Bedrooms are higher than those for the dwelling as a whole. But at these ventilation rates, the temperature achieved may be too low to be considered acceptable. It is necessary, therefore, to explore the situation at lower air change rates.

Under these circumstances, condensation may occur on the surface of uninsulated walls in the corners of rooms when the relative humidity of the room air is less than 70%. Calculations indicate that a wall U value of 1.0 W/m^2K is adequate to ensure that the 70% RH criterion can be applied.

Measures to reduce ventilation rates in existing dwellings must be accompanied by the addition of thermal insulation and heating (particularly in Bedrooms) if condensation is to be avoided.