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Domestic Kitchen Extract Fans: Effectiveness in Surface Condensation Prevention

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Many authorities propose domestic kitchen extract fans as effective measures against surface condensation. This paper describes field study, and computer modelling, work to improve quantitative information for fan specification. A detailed computer model is described and used to determine air flows, humidity levels and condensation quantities with different fans and humidistat or manual control. Conclusions are that: low rate fans are unable to prevent condensation; condensation is difficult to remove once present even with extended running from humidistat control; moisture migration through open doors cannot be prevented because of thermally induced air movement and full transient analysis is essential in assessing mould risk.

1. INTRODUCTION

SURFACE condensation and mould are extremely common in both local authority and private housing [1, 2]. The results for poorer occupants, who suffer most because of their inability to afford adequate heating, is mould growth, a range of associated psychological and physiological illnesses [3] and a deterioration in the building fabric. This paper describes the practical investigation and computer modelling conducted to analyse the effects of kitchen extract fans in the prevention of surface condensation.

Installation of kitchen extract fans has been extensively proposed as one of the cheapest and most effective of the active measures that can combat condensation [4–6]. Extract fans are assumed to remove moisture laden air from where it is generated to the outside thereby reducing humidity levels. Natural ventilation also causes air exchange between inside and outside, however this is: (a) often not at a sufficient rate; (b) not reliable because of variability of the wind and occupant activity; (c) liable to take moisture into the rest of the dwelling if the kitchen is on the windward side of the dwelling and (d) a major cause of cooling and draughts. Mechanical extract ventilation has the advantages of: (a) ensuring a minimum air change rate which is less dependent on external conditions and (b) reducing moisture movement to other rooms.

Design recommendations for natural and mechanical ventilation are purely nominal, treating all domestic kitchens in the same way. BS5250 [6] recommends a mechanical extract rate of 80 l s^{-1} (288 m^3 h^{-1}). Most fan manufacturers concur with this figure but state their recommendations in terms of air change per hour which accounts for the size of the kitchen; for example: Vent-Axia 15–20 ac h^{-1} [7]. Xpelair 10–15 ac h^{-1} [8]. These imply extract rates of between 200 and 400 m^3 h^{-1} for a 20 m^3 medium sized kitchen.

There is little quantitative information to back up the assumed operation of extract fans as regards: (i) the relationship between the size of fan (extract rate) and: (a) humidity levels and incidence of surface condensation; (b) moisture migration to the rest of the dwelling and (c) the removal of condensation from surfaces. (ii) The effectiveness of automatic (humidistat) vs manual fan control. The present study sought to provide some of the quantitative data required through two complementary approaches: (a) a field study to ascertain how fans are used and operate in reality and (b) computer modelling.

2. FIELD STUDY

The London Borough of Islington commissioned the present authors to assess four types of remedial condensation control equipment: dehumidifiers, night storage heaters, heat exchange extract fans, and humidity controlled kitchen extract fans. Field trials were conducted at Bentham Court which is an estate of five four-storey blocks of flats and maisonettes. Built in 1948, the estate is now being rehabilitated in several phases. The equipment was installed as a temporary measure until full rehabilitation could be effected. The importance of such equipment in alleviating the problems is essential as often the delay between the strategic decision to commence, and the completion of, refurbishment on many local authority estates is considerable. The results of the work were presented in a report to the council [9].

2.1. *Methodology*

The study involved continuous monitoring of temperatures and humidity, and status of the fans in the

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dwellings over a period of six weeks during the winter of 1986/87 (three weeks with the equipment disabled and three operational), weekly observations of conditions in each dwelling over the six weeks, and one-off experiments on aspects of performance of the fans.

Temperature and relative humidity were measured with seven day thermohygrographs (THGs) with the operational status of the fans being recorded on the charts by means of a small modification to the THGs. THGs were chosen for reasons of low cost and because they provided an immediate visual record which could be understood by the tenants.

Temperature and humidity were measured in at least two locations in a dwelling so that both the local and distant effects of the fans could be recorded. In all cases the THGs were placed at about 2 m from the floor usually on specially fitted shelves. One THG was used to monitor the outside conditions and was placed on the balcony of a vacant dwelling.

2.2. *Anecdotal observations on extract fans*

The kitchens at Bentham Court were approximately 30 m^3 in volume. All the extract fans were humidistat controlled and were permanently wired so that the tenants could not disable them. The fans had a free air extract rate of 43 $m^3 h^{-1}$ under humidistat operation (set point 60% RH) and a manually controlled boost rate of 96 $m^3 h^{-1}$. Fan noise was not regarded as a problem and only on boost was there any awareness of operation with a slight drumming caused by the fan noise being amplified by the window in which it was sited. The use of the manual boost control depended on individual tenants and their assessment of conditions in the kitchen. In one flat studied, it was not clear whether the tenants understood that the fan would come on automatically, given that its operation was imperceptible, and they used the boost switch on more occasions. It was observed that the fans under humidistat control operated for long periods in some dwellings.

During heavy cooking some tenants perceived that the fans did not stop steam formation or excessive temperatures in the kitchen. They would then open external doors/windows as they did before installation of the fan. It was thought at the time of the field study that this negated the effect of the fan, particularly in preventing moist air moving to other rooms.

It was not possible to assess the extent to which internal doors were kept closed during cooking, however, it was observed that the doors from the kitchen to the living room were often open (e.g. in order to supervise children or watch television).

2.3. *Monitored data*

The THG charts were compared in an attempt to determine whether (a) the fan operation reduced moisture levels in the kitchen, and (b) the fan operation prevented moisture moving to other rooms. It was not possible to determine from the monitored data whether the fans did reduce room humidity or excess vapour pressure due to unpredictable changes in other variables affecting kitchen humidity (e.g. moisture generation, actual ventilation rate). (Excess vapour pressure is the difference between vapour pressure in the room and the outside air.) Even when the fans were operating there were large increases in relative humidity (RH) and excess vapour pressure. Even switching the fans off and on at intervals during cooking did not produce any response in the measured parameters. In addition the excess vapour pressure in the halls followed those in the kitchen.

An example of two days of transcribed data from the kitchen and hall of one flat are shown in Fig. 1 when the fan was operating continuously. If kitchen extract fans are to reduce condensation risk significantly they must necessarily produce a marked and measurable reduction in vapour pressure in the kitchen and reduce the rise in the hall. This was not observed, possibly due to the changes in other variables affecting kitchen humidity, and prompted a deeper investigation.

3. THEORETICAL ANALYSIS

A model of condensation requires the interactions of thermal, moisture and ventilation parameters. Much less work has been carried out on moisture and condensation models than on thermal models. There has been no perceived national disaster driving the work as occurred with

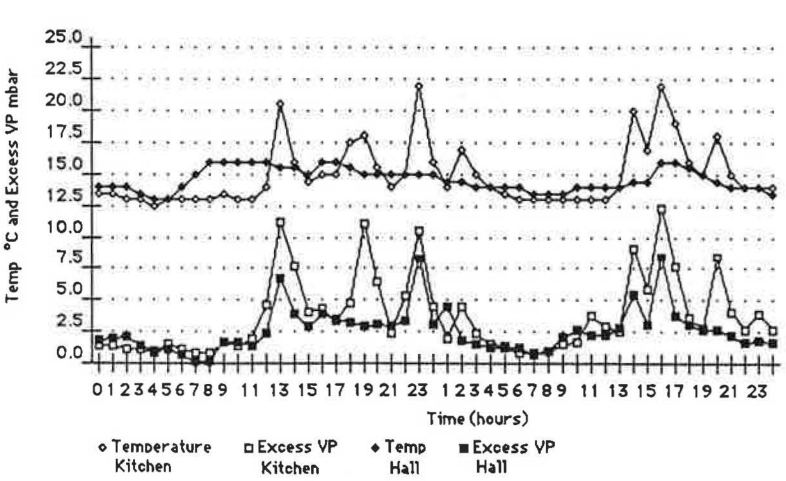


Fig. 1. Temperature and excess vapour pressure data from the kitchen and hall for 27 and 28/11/85: Fan operational.

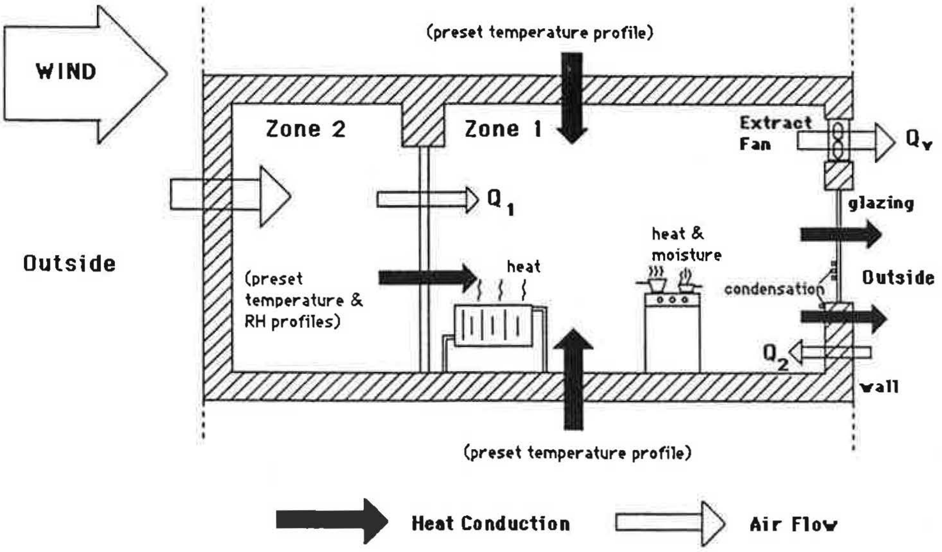


Fig. 2. Schematic diagram of configuration modelled by 'HUMID' computer programme.

the energy crisis and the elimination of condensation and mould growth has not been seen as saving money in the same way.

The work of Loudon [10] used just two equations (one thermal balance and one moisture balance) to see how ventilation rates, house insulation level and heating levels affected condensation under steady state conditions. Other workers [11–13] have considered some aspects of the dynamic effects of moisture but have not integrated the parameters to obtain practically useful results.

3.1. *Condensation model "HUMID"*

The authors have developed a model, "HUMID", to analyse specifically the problems of surface condensation [9, 14].

The current version of HUMID considers two zones: the first is the room to be analysed (in this case the kitchen) and the second is the rest of the dwelling (see Fig. 2). Zone 1 has conductive and convective coupling of heat and moisture with the rest of the dwelling, and the outside. The temperature distribution through the thermally massive external wall is determined using a transient finite difference method. Temperature and humidity in zone 1 are calculated minute by minute using interpolated hourly values for external weather data, and using profile values of internal heat and moisture inputs from occupants and household activities.

The air flows in a kitchen may be viewed as in Fig. 2 similar to those considered by Billington [15]. The magnitude of the air flows Q_1, Q_2 and Q_v shown in Fig. 2 depend on a number of parameters including: (a) wind pressure; (b) fan extract rate; (c) thermal driving force (temperature differences causing buoyancy driven effects) and (d) flow resistance through openings and cracks.

This situation was modelled using the simple network shown in Fig. 3 which incorporates details of the flow coefficients of the various openings between the room, the rest of the dwelling and the outside. The model can account for variations in wind velocity and wind direction. Wind pressure coefficients on the opposite faces of the building are determined using the angle of incidence of the wind from published look-up tables [16].

Condensation rates and quantities are calculated for the external wall and for the glazed areas using the "Lewis" relationship [17]. The rate of condensation (or evaporation) is determined from the driving vapour pressure difference between the bulk air in the room and that at the surface. Accumulation of water is allowed to take place at the surfaces.

A greatly simplified flow chart of the model is shown in Fig. 4. Although ventilation is treated separately, all parameters interact through the thermal and moisture network shown in Fig. 5.

There are three forms of output: a graph of parameters changing with time; hourly temperature and humidity levels presented on a psychrometric chart; and cumulative frequencies of temperatures and humidities in the room.

The results of the model run in a steady-state mode have been successfully checked against those of Loudon [10].

3.2. *Use of model*

In order to analyse the operation of extract fans in kitchens HUMID was used to model a specific three

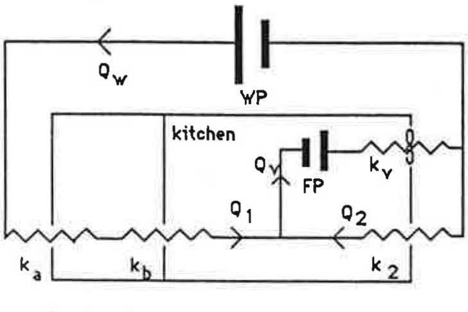


Fig. 3. Electrical network simulating airflow.

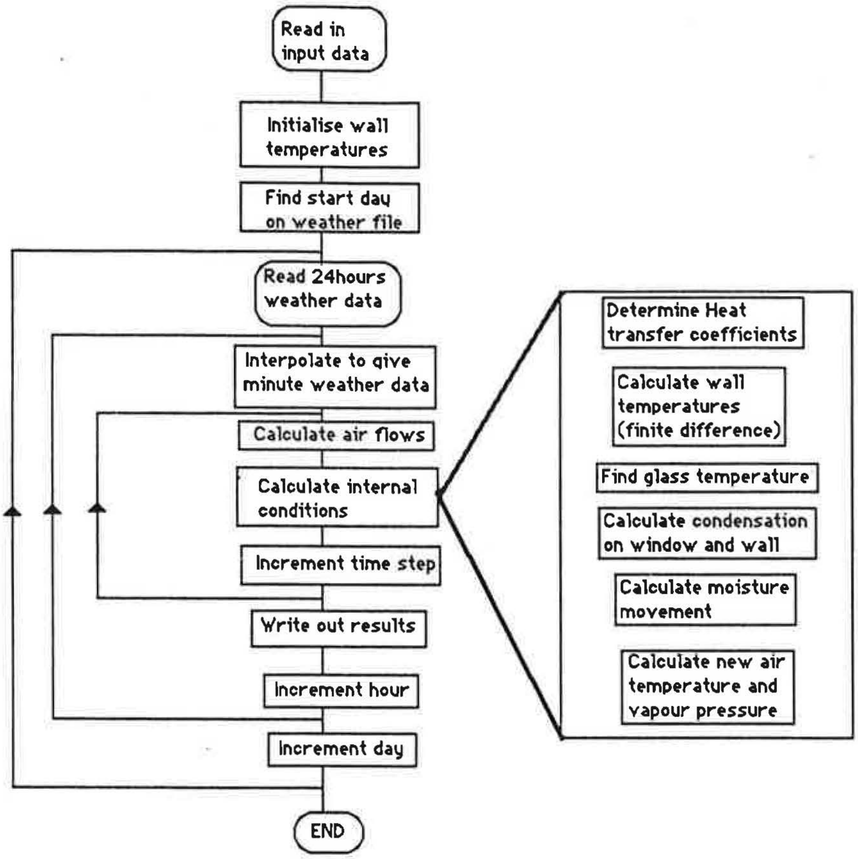
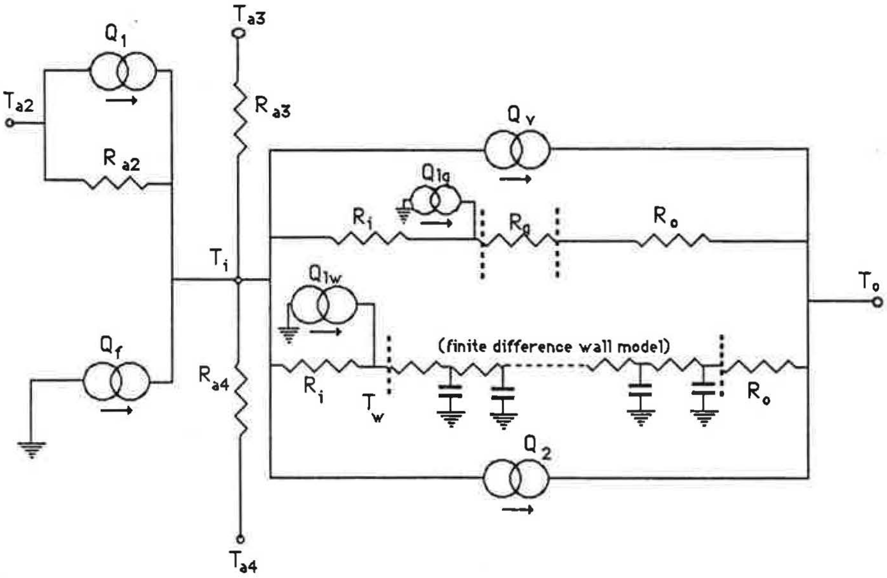


Fig. 4. Simplified flow chart of program 'HUMID'.



T_i	room air temperature
T_o	outside air temperature
T_{a2}, T_{a3}, T_{a4}	temperatures in adjoining spaces
Q_f	heat input from heating and cooking
Q_v	heat loss through extract fan
Q_{lg}, Q_{lw}	latent heat input to glass and wall respectively
Q_1, Q_2	ventilation heat flows
R_i, R_o	internal and external surface resistances
R_{a2}, R_{a3}, R_{a4}	thermal resistances to adjacent spaces

Fig. 5. Thermal network model of kitchen.

Table 1. Details of Bentham Court kitchen

External wall (310 mm solid brick)	
Area (net)	7.7 m^2
'*U*' value	1.8 W m^{-2} K^{-1}
Glazing:	single
Area	1.9 m^2
Volume	30 m^3
Partition wall	
Areas: to living room	9.6 m^2
to rest of dwelling	14.4 m^2
'*U*' value	3.3 W m^{-3} K^{-1}
Floor/ceiling (to other dwelling)	
Area	25 m^2
'*U*' value	2.0 W m^{-2} K^{-1}
Flow coefficients	
k_1 closed kitchen door	8.41×10^{-3} m^3 s^{-1} $Pa^{-0.5}$
open kitchen door	4.24×10^{-2} m^3 s^{-1} $Pa^{-0.5}$
k_2 external window, door and vent	7.09×10^{-3} m^3 s^{-1} $Pa^{-0.5}$

bedroomed mid-floor flat at Bentham Court, with characteristics presented in Table 1.

Three ventilation regimes were considered in the analysis: natural, mechanical with manual control and mechanical with humidistat control. The effectiveness of all three depends on the location and size of the openings and cracks, and the former are largely determined by how occupants open doors and windows. Occupants also influence mechanical ventilation regimes when under manual on-off control. It has been reported that manually controlled fans are only used for a few hours per week [18] and their use as condensation control devices in local authority houses has been questioned. However in this analysis it was assumed that manual fans were operated during the cooking periods.

Humidistat control removes the responsibility for fan operation from the occupants by automatically initiating operation when the relative humidity exceeds a set threshold. However, humidistat control has one major disadvantage in that the fan may come on at unexpected times and stay on for long periods. Thus, it is important that fan noise is barely perceptible and that power consumption is low which requires a small fan. Humidistat fans are smaller (96 m^3 h^{-1}) than normally recommended for kitchens (200 m^3 h^{-1}). It has been proposed, however, that a low extract rate fan operated over a long period will allow the removal of moisture even if some has condensed.

HUMID was used to analyse: (a) the magnitudes and directions of the airflows between the kitchen, the rest of the dwelling and the outside when the kitchen was on the leaward or windward side, and when the kitchen door to the rest of the dwelling was open or closed. (b) The surface condensation in the kitchen under natural and mechanical ventilation during 48 h of steady-state external weather conditions with the moisture release and heating due to cooking determined from a time profile. (c) Cumulative frequency data for surface condensation and humidity in the kitchen under natural and mechanical ventilation over a period of one month (February) using meteorological data.

3.3. *The initial conditions*

Moisture generation was profiled to simulate three cooking periods; 1.7×10^{-4} kg s^{-1} for 1 h at breakfast and lunch and 3.1×10^{-4} kg s^{-1} for 2 h at the evening meal. The kitchen was considered unheated and during cooking periods heat input to the room (rather than into the food) was taken as 1.6 kW [19].

Conditions surrounding zone 1 were set using monitored data during average outside conditions of 4.5°C and 85% RH: bedroom 12°C and 58% RH: kitchens 14.5°C and 56% RH; living rooms 15.5°C and 50% RH. These concurred with the data obtained from a detailed study of condensation problems on the Darnley housing estate in Glasgow [20].

The manually operated fan was taken to have a free-flow extract rate of 288 m^3 h^{-1} and a stall pressure of 52 Pa and the humidistat controlled fan an extract rate of 68 m^3 h^{-1} and stall pressure of 123 Pa. The data on both fan units were based on commercially available models. The manually controlled fan was assumed to operate only during periods of cooking while the humidistat controlled fan operated whenever the kitchen relative humidity exceeded 60%.

3.4. *Results: air flow rates*

This analysis considered an external wind speed that gave a kitchen ventilation rate of 1.0 h^{-1} when the door to the rest of the dwelling was closed. The diagrams in Fig. 6 illustrate how air flows vary; for different wind directions, for natural ventilation and for the two sizes of fans, and for the door to the rest of the dwelling open or closed. The results when the kitchen door is open are only valid if the same temperature occurs in the kitchen and the adjoining space (see Section 3.5).

The humidistat fan approximately doubles the kitchen air change rate from that achieved by natural ventilation. The manual fan produces a 2 to 3 times higher air change rate than the smaller humidistat fan. For both fans, the air change rates are significantly lower when the kitchen is on the windward side of the building. The manual fan under these wind speeds produces a movement of air from the rest of the dwelling, however the humidistat fan does not achieve this when the kitchen is on the windward side. Opening the kitchen door increases the air change rate by 60% under isothermal conditions.

3.5. *Steady external conditions*

The model was run over a period of 48 h with fixed external conditions and the door to the rest of the dwelling closed in order to avoid highly variable conditions which would obscure the preliminary analysis. The graphs presented here generally show the second period of 24 h analysed when the effects of the initial conditions assumed at time zero are insignificant. The calculated values of kitchen air temperature, vapour pressure, and relative humidity are shown in Figs 7–9. These show similar trends to the monitored results shown in Fig. 1.

The use of a fan reduces the peak temperatures in the kitchen (Fig. 7), the humidistat fan gives a reduction of about 1°C whereas the higher extract rate manual fan gives a 2.5°C reduction from the naturally ventilated case.

The effect of the increased air change rate due to fan operation in reducing internal relative humidity can be

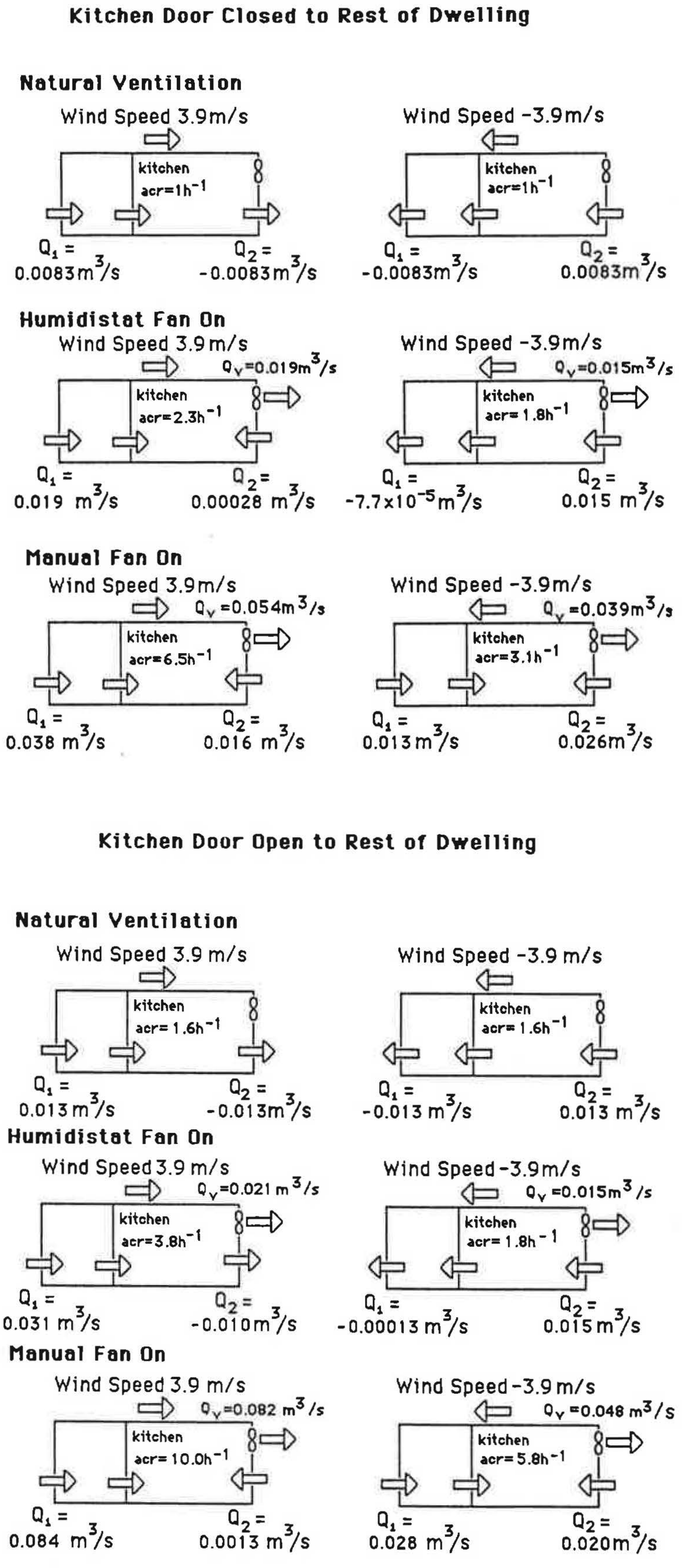


Fig. 6. Air flows for wind direction and fan size for isothermal conditions.

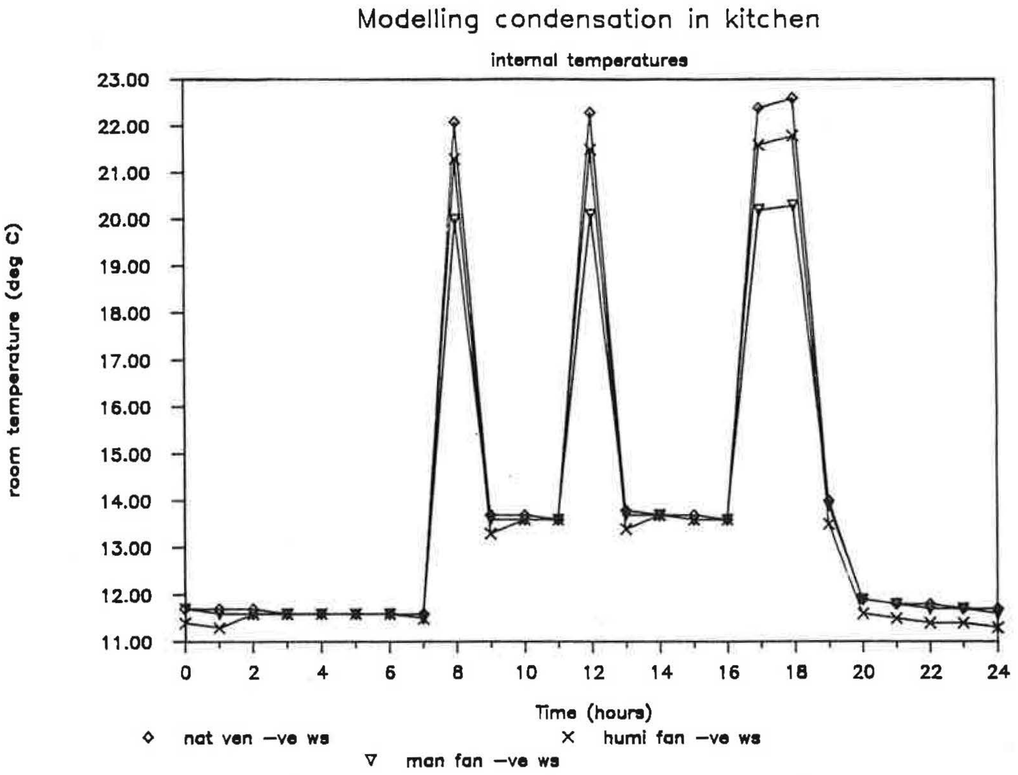


Fig. 7. Calculated kitchen air temperatures under steady external conditions.

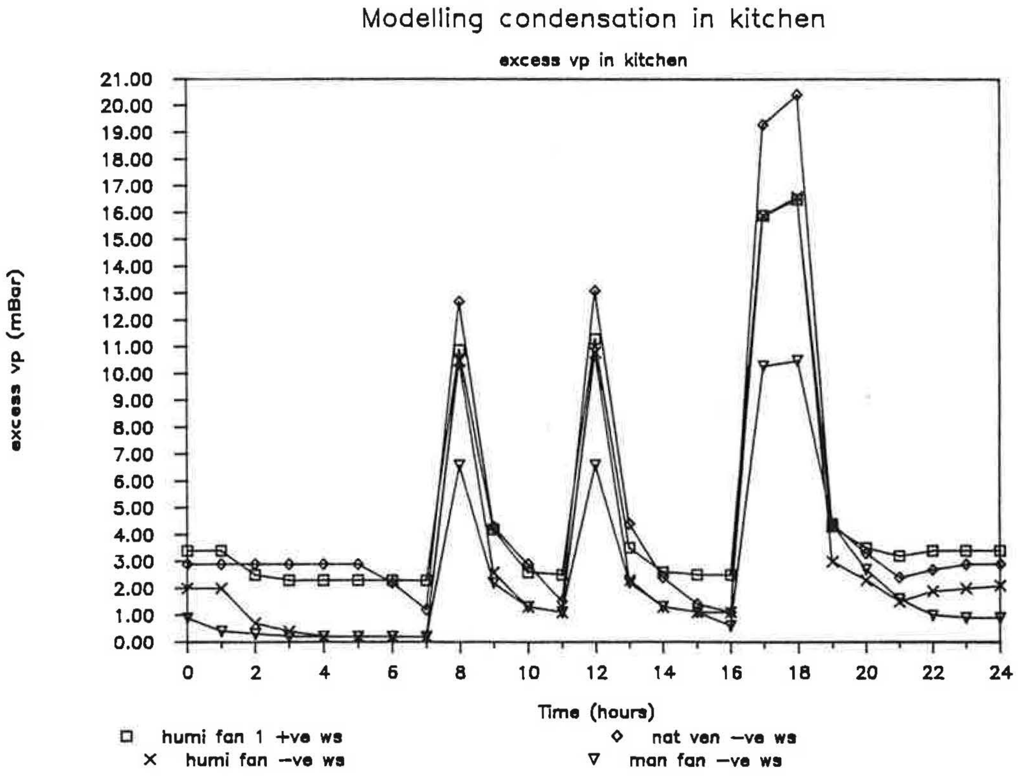


Fig. 8. Calculated kitchen vapour pressures under steady external conditions.

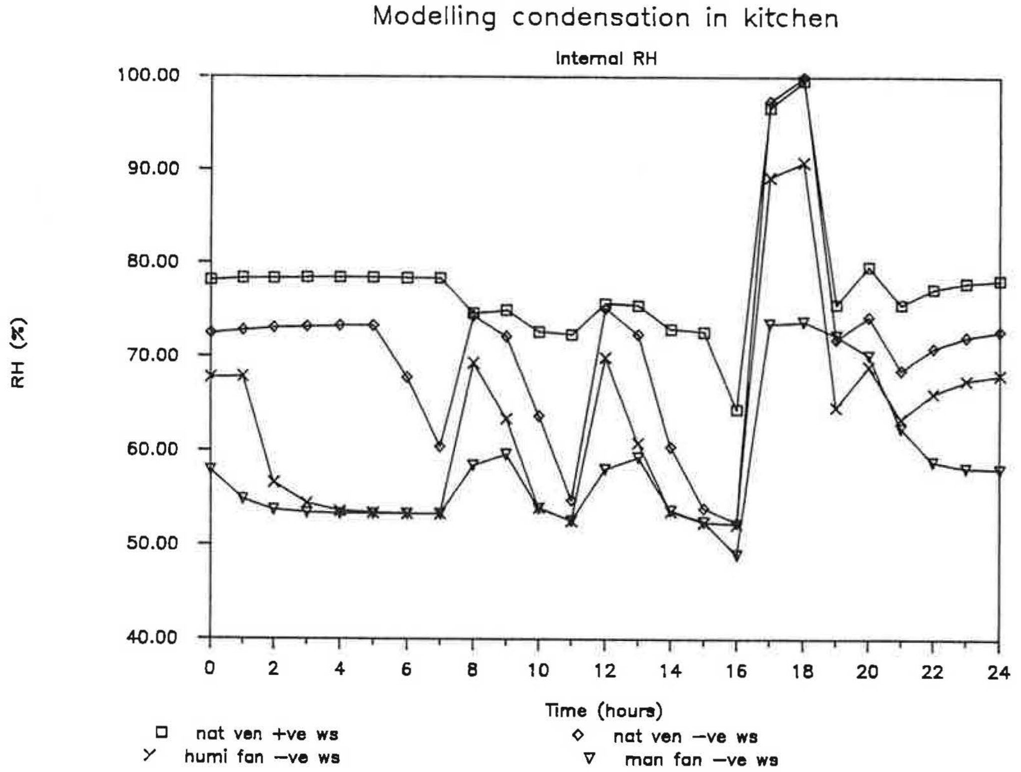


Fig. 9. Calculated kitchen relative humidities under steady external conditions.

clearly seen in Fig. 9. In this case a humidistat fan can reduce the peak RH by 10 percentiles and a manual fan by 25 percentiles. The data in Fig. 9 also confirm that RH is consistently greater with the kitchen on the leeward side of the dwelling (wind speed +ve) because of the air that is drawn in from the living area of the dwelling having a higher moisture content than that from outside.

The total mass of condensate on the external wall at the end of each hour is given in Fig. 10. This figure shows that the greater extract rate of the manual fan reduces the rates of condensation on the external wall to leave the maximum amount of condensate on the wall less by a factor of seven compared to the naturally ventilated case. The wall has water on it for 6 h day^{-1} with use of the manual fan against 11 h day^{-1} for the humidistat controlled fan.

The humidstat controlled fan only reduces the initial amount of condensate formed by 20%, and although the fan continues to operate after cooking is completed condensate is not removed quickly. This is because: (i) the energy input from cooking is no longer available and the wall surface cools. This reduces the wall's potential (i.e. its saturation vapour pressure) to evaporate condensate. (ii) The rate of evaporation (and/or deposition) of condensate is also determined by the vapour pressure in the immediate vicinity of the wall surface. The rate of reduction in room vapour pressure once cooking stops is very rapid at first (see Fig. 8) due to the removal of the water vapour in the air at the air change rate. After this initial reduction in vapour pressure, the presence of condensate on the walls and windows provides a source of water vapour which helps to keep the vapour pressure higher (and so the evaporation rate lower) than if there was no condensate. Further, the proportion of the air entering from the rest of the dwelling (see Fig. 6), and its humidity, are crucial in maintaining the vapour pressure, thus reducing the evaporation rate further.

The external wall considered here was of heavyweight construction. Thus, wall surface temperatures rise relatively slowly during periods of cooking and air temperature rises rapidly. A lightweight construction *of the same U-value* would undoubtedly lead to a less stringent requirement for moisture removal by fans during cooking. This emphasises the benefits of both internal insulation and continuous background heating for the prevention of condensation.

3.6. *Unsteady external conditions*

Current practice for assessment of surface condensation risk in dwellings is to use steady-state calculation methods [21], [6] and [10]. The computer model described in Section 3.1 above goes a stage further towards modelling a realistic situation by considering unsteady conditions within the dwelling. A further useful assessment is provided by presenting data on how internal conditions vary over an extended period. The number of hours that external wall inside surfaces are wet or have local humidity in excess of a given threshold are good indicators of the risk of mould growth and damage.

The present model has been run using external weather data (Cardington, UK, February 1980): (a) to give a realistic input on external temperature and humidity and (b) to provide the means of calculating variations in ventilation due to changing wind speed and direction.

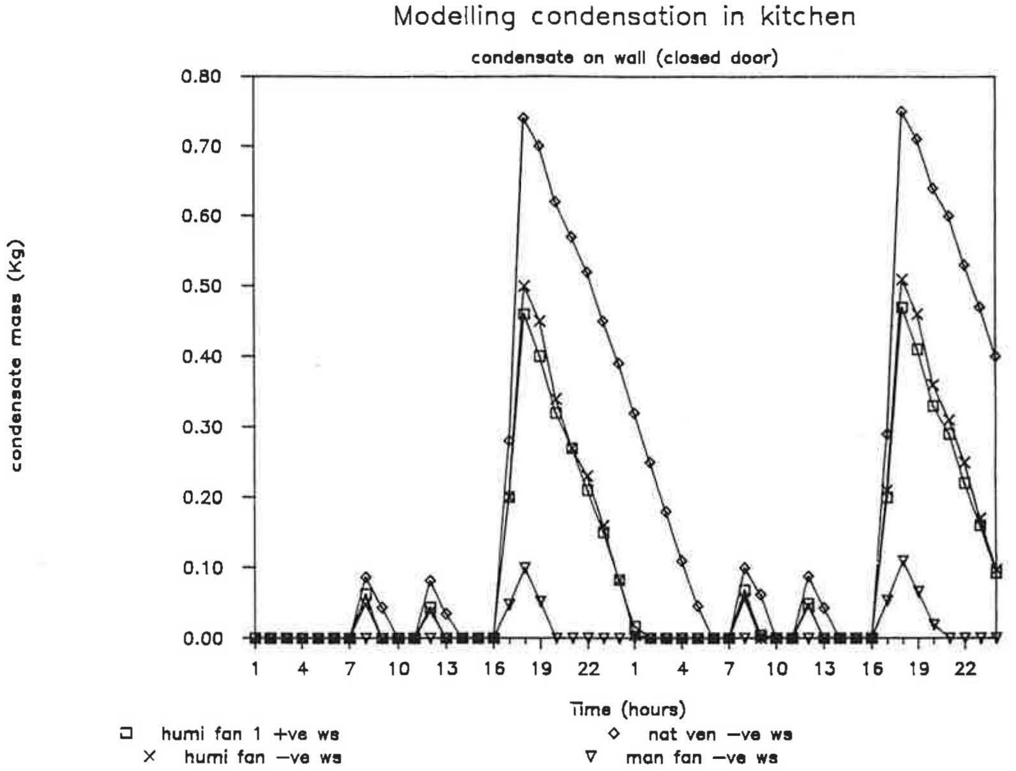


Fig. 10. Calculated kitchen wall condensation quantities under steady external conditions.

Cumulative frequency data on various parameters have then been used to compare the effectiveness of various anti-condensation remedial measures. This is a potentially powerful method of presentation of internal conditions from which condensation and mould growth risk can be assessed.

One commonly used measure of unacceptable condensation risk is that when RH inside a room is greater than 70%. The percentage of time when RH exceeds 70% is shown in Table 2 for the three ventilation modes modelled in the Bentham Court kitchen.

Clearly the manually operated fan reduces condensation risk considerably. However, it should be noted that the relative efficacy of the two fan types is influenced by factors such as moisture generation rates during cooking. With a high moisture input (2.7×10^{-4} kg s^{-1} for breakfast/lunch and 5.4×10^{-4} for evening meal) even the manual fan fails to prevent significant condensation and its usefulness is actually slightly less effective than the humidistat controlled fan because of the latter's extended operating time.

Under natural ventilation, the model predicts the outside kitchen wall will be wet during virtually the whole of February. Use of the humidistat fan reduces this to 55% of the time and the manual fan to 22% of the time.

Mould is known to grow on surfaces under conditions of RH > 85% at the surface [22]. The percentage of time the model predicts surface RH greater than 85% are shown in Table 2. The model accounts for the fact that water may be present on the wall due to earlier condensation *which is not the case in other simpler calculation methods.* In order to analyse the consequences of using these simpler methods, the relative humidity at the surface was also calculated from the instantaneous room vapour pressure and the wall surface temperature. The bottom row of Table 2 gives cumulative frequency data for

Table 2. Percentage cumulative frequency data of room and wall humidities for February 1980

	Natural ventilation	Humidistat fan	Manual fan
% of time room RH > 70%			
standard moisture generation	93	51	30
high moisture generation	94	70	72
% of time wall wet	98	58	22
% of time surface RH > 85%			
accounting for previous condensation	98	59	29
ignoring previous condensation	32	19	20

Location: Cardington, U.K.

surface RH > 85% ignoring water present from previous condensation. Once on a wall, condensate takes a long time to evaporate, thus the simple steady-state calculations may grossly underestimate the amount of time that conditions suitable for mould growth prevail, i.e. ignoring previous wetting of a wall gives a highly misleading picture of condensation and mould risk.

3.7. *Two way air movement*

As indicated earlier, air will move in both directions through an open door due to a temperature difference between the air in the two adjacent spaces. There is evidence of this phenomenon in the field study data shown in Fig. 1 where the vapour pressure in the hall follows the temperature in the kitchen. This is a well documented phenomenon under natural convection situations, i.e. when there is only temperature induced air movement [23–26]. Shaw and Whyte [27] have investigated the situation under combined natural and forced convection (i.e. when there is also mechanically induced air movement) in order to determine the air flows necessary to prevent contamination into an operating theatre. Although the situation they examined was slightly different from that pertaining to a kitchen, it is instructive to utilise their analysis for the case of the Bentham Court kitchen.

To prevent temperature induced air flow from a kitchen to the rest of the dwelling, the mechanically induced air flow through a 0.9×2.1 m door with a temperature difference of 2°C needs to be $0.6\ \mathrm{m^3\ s^{-1}}$ which is equivalent to more than 60 ac $\mathrm{h^{-1}}$. Temperature differences of up to 10°C between the kitchen and hall during cooking were found at Bentham Court. This suggests that no reasonably sized fan can achieve the desired effect of totally preventing moisture flow from the kitchen to the rest of the dwelling if a significant temperature difference exists.

Under natural ventilation conditions wind induced air movement may be with or against the temperature induced movement; again the magnitudes of this air flow are unlikely to deviate much from the temperature induced flow. If a temperature difference of 2°C exists across a kitchen door then the temperature induced air flow is $0.19\ \mathrm{m^3\ s^{-1}}$ and this rises to $0.42\ \mathrm{m^3\ s^{-1}}$ when 10°C exists [24]. As shown in Fig. 6, the maximum fan induced air flow through a door is $0.084\ \mathrm{m^3\ s^{-1}}$ with wind assistance.

The importance of this temperature induced air movement should amplify the need to keep kitchen (and bathroom) doors closed and the temperature differences across the doors down in order to prevent the spread of water vapour. Indeed the cooling effect of an extract fan (see Fig. 7) is more significant than its depressurisation effect in preventing moisture migration. Further the need for the provision of cooker hoods to keep the moisture out of the bulk air in the kitchen is enhanced.

4. CONCLUSIONS

This paper has suggested four important issues regarding surface condensation and the operation of extract fans.

(i) Surface condensation should not be allowed to form in a kitchen because once present it is difficult to remove as there are lower evaporation rates, from colder surfaces, and into air with higher vapour pressures.

(ii) Low extract rate fans, even with humidistat control, are unable to stop condensation in poorly insulated kitchens. Their extended run times do not significantly help to remove condensation once formed. There is a great dilemma, however, between: (a) installing a fan with a much larger air extract rate and humidistat control (as the fan is noisier and the extended running times activated by the humidistat may be a nuisance); (b) installing a fan with a larger extract rate and manual operation (as there is some reluctance by tenants to use such fans) [18].

(iii) Thermally induced air flow through an open kitchen door to the rest of the dwelling overwhelms the positive air flow induced by all practical sized fans and so fans are unable to prevent moisture movement from the kitchen to the rest of the dwelling when the kitchen door is open. As a consequence it is important that the kitchen door is kept closed and that the kitchen and rest of the dwelling should be kept as near the same temperature as possible. The cooling effect of the extract fan in this respect is most significant.

(iv) The use of steady state techniques (or even transient techniques where previous condensation is ignored) may predict erroneously low condensation and mould growth risk due to the accumulation of moisture at a surface. This also has implication in field study monitoring when surface RH should be measured and not just calculated from room RH and surface temperature.

The process of this study has shown that field work alone cannot give answers on the efficacy of the use of extract fans because of the complexity of the real situation. There are insufficient data available on the effects of kitchen extract fans and work is needed on a laboratory and theoretical level before more definitive results can be offered.

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