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**Paper 15**

## Airborne Moisture Movement in Occupied Dwellings. A Case-Study Approach.

M. Kolokotroni, N. Saiz, J. Littler

Research in Building Group, The University of Westminster, 35 Marylebone Road, London NW1 5LS, United Kingdom

## ABSTRACT

This paper reports the results of humidity and ventilation measurements in occupied residential buildings to study the effect of airborne moisture movement on condensation risks. The dwellings have been fitted with a cooker hood and an extractor fan (both with variable speed control) in the kitchen and an extractor fan in the bathroom. The investigation of each case-study included monitoring the temperature and humidity at four locations in the house for a number of weeks during the heating season in order to examine the water vapour cycles in each room as affected by moisture production in the space and moisture migration from adjacent rooms and outside. Detailed short time measurements have been also taken to study the effect on the humidity in one room of water produced in other rooms, and the efficiency of the variable flow-rate extract devices for the local removal of moisture before it becomes well mixed.

In this way the efficiency of each ventilation device, in isolation and in combination with the others, in removing moisture from the rooms in which it is produced, has been examined as well as its effect in reducing the rate of moisture migration to the rest of the house. It has been possible to find relationships between the moisture loads in the rooms in each case-study, thus describing the effects of interzonal moisture flows in situations typical of those found in dwellings at risk of condensation.

## 1 INTRODUCTION

Water vapour is one of the internal environmental contaminants which is rarely mentioned when discussing air quality. However, although it might not affect people in the same dramatic manner as $CO_2$, $NO_x$, $O_3$ and HCHO, it is present in a large proportion of buildings, mainly residential, it is transported in a similar manner [1] and it is impossible to eliminate its sources. High relative humidity can cause structural deterioration and is connected to human illness such as asthma and allergies due to dust mites [2-5]. Excessive humidity can create condensation, mould problems and discomfort; but low humidity can cause its own problems. Apart from discomfort due to dehydration of the skin and mucous membranes, some bacteria and viruses like lower humidities [6]. Therefore, humidity extremes need to be avoided, with an optimum zone in the middle of the relative humidity scale.

A high percentage of the residential building stock suffers from the effects of excessive moisture. According to the latest English Housing Survey [7] more than half of UK households are affected with problems ranging from condensation on windows to mould on walls and furniture. The problem is also present in other cold countries such as Canada where results of a survey in 1991 indicated that 39% of the people had at least one moisture or mould indication in their homes [8]. The problem appears to be more acute in new housing where low ventilation levels coupled with cold bridges have increased the problem [9].

It is only the last 30 or so years that there is evidence that air movement is very important in moisture migration in the same way as water vapour diffusion through the fabric of the buildings [10]. Only recently the importance of ventilation in removing moisture at source has been emphasised in the Building Regulations [11] and publications on methods of avoiding condensation and evaluating the risks have appeared [12] including international efforts aimed at providing solutions to the problem [13].

Increased ventilation seem to be the solution in most cases. The effectiveness of extractor fans and cooker hoods in reducing the migration of moisture to other spaces of the dwellings is the subject of this paper. Three small homes were investigated before and after the installation of extract devices and it was found that excess vapour pressure (internal vapour pressure above outside vapour pressure) has been reduced in source rooms (kitchens and bathrooms) and also in sink rooms (living rooms and bedrooms).

## 2 DESCRIPTION OF THE CASE-STUDIES

The floor plans of the three case studies are presented in Fig. 1.

The first case study is a maisonette in East London, a region of low cost housing with most of the house stock built after World War 2. Two adults live in the flat which comprises a kitchen, living room and bathroom on one floor and a bedroom on another, with a total floor area of approximately $65m^2$. The maisonette is situated on the two upper floors of a five storey block of flats containing 70 housing units. There is no thermal insulation in the brick walls or the roof and the windows are timber framed and singly glazed. Heating is provided by a time-controlled gas boiler (located in the kitchen) and radiators in every room apart from the bathroom which is heated with an electric wall mounted radiant bar. Ventilation is provided by sash windows, window vents (which were all blocked by the occupants) and vents into a bricked-up chimney in the living room.

The second case study is a 60's maisonette in South London in a council owned block of flats. Two adults occupy the flat which comprises a kitchen and living room downstairs and a bathroom and two bedrooms upstairs with a total floor area of $60m^2$. The maisonette occupies the two upper floors of a four storey building containing 55 housing units. The walls are not thermally insulated and the windows are steel framed, singly glazed. However, plastic double glazed windows have been recently installed in the bedroom windows, following complaints about condensation and draughts. Heating is provided by a open gas fire in the living room and an electric heater situated at the top of the staircase. The only ventilation means is through the openable windows.

The last case study is a converted end of terrace ground floor flat also in South London. A single parent with a child lives in the flat which consists of a kitchen, bathroom, living room, bedroom and spare room, all on one floor covering a total area of $70m^2$. The brick walls are uninsulated with single glazed timber framed openable windows for natural ventilation. Heating is provided by a time controlled gas boiler (located in the kitchen) with radiators in every room of the flat.

For the purpose of this study, all three dwellings were fitted with extract devices in the kitchen and bathroom in order to evaluate their effectiveness at removing moisture in source rooms and in preventing moisture migration to sink rooms. In the kitchen a window mounted extractor fan was installed with a maximum flow rate of 78.6l/s equipped with variable speed controller. In addition a cooker hood was installed and ducted outside, with a maximum flow rate of 82l/s. In the bathroom the humidistat controlled extractor fan has a maximum flow rate of 28l/s. In all cases, they comply with the 1990 UK Building Regulations [11].

## 3 MONITORING THE HUMIDITY AND TEMPERATURE

The temperature and relative humidity were monitored for a minimum period of one week before the installation of the ventilation equipment and at least one week after, by placing thermohygrographs in the main rooms of each house, ie: kitchen, bathroom, living room and one bedroom. The data is used to characterise the basic climate of the houses; that is, temperatures, mixing zones, basic flow paths and occupant use/interference.

The aim is to examine whether there is a reduction in the excess vapour pressure not only in the moisture source rooms (kitchen and bathrooms) but also in the moisture sink rooms (living room and bedroom). The assumption is that the only different parameter (apart from the external conditions) affecting the internal moisture balance before and after the installation of the fans is the way that they are used.

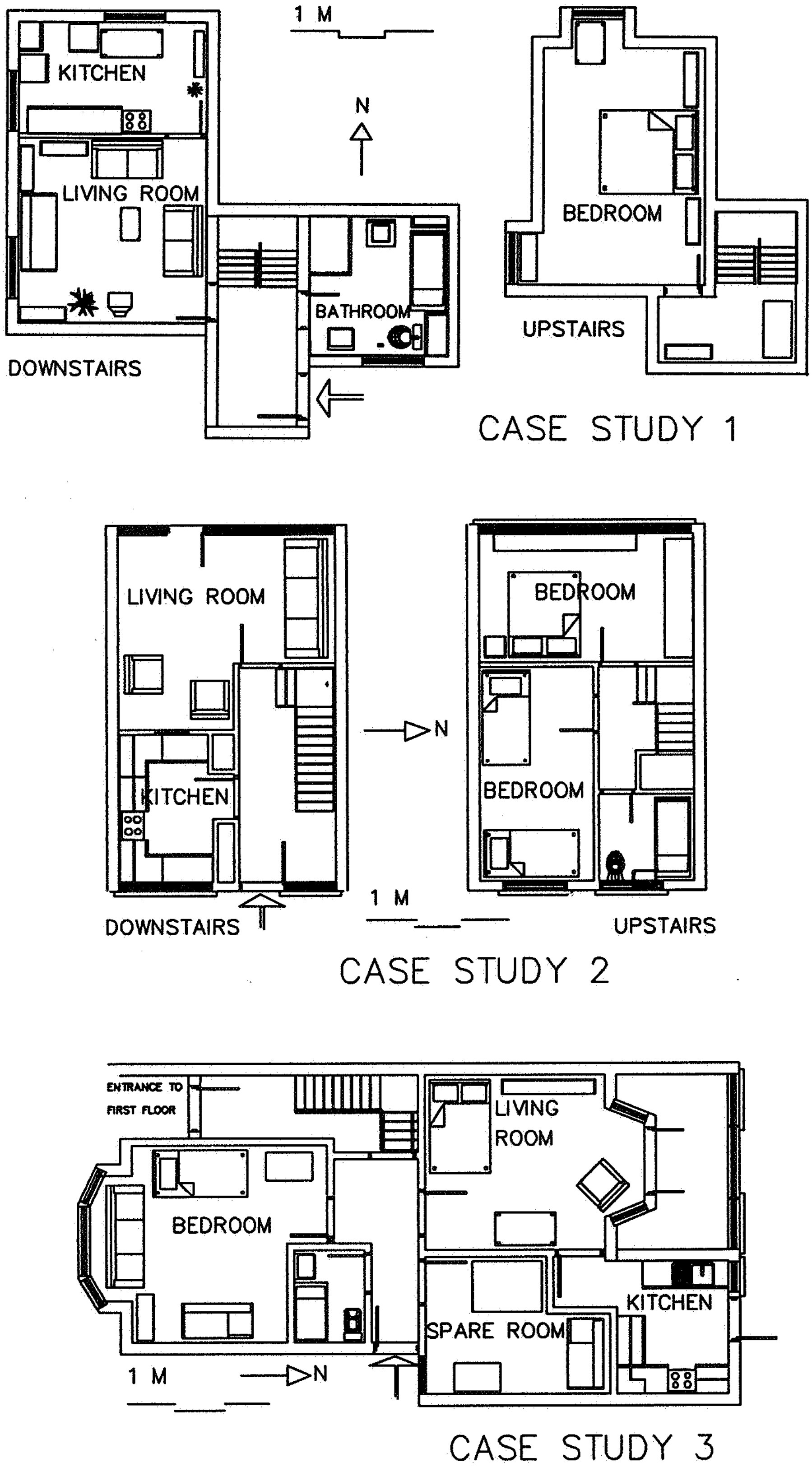


**Figure 1:** Floor plans of the three case-studies.

An example of the vapour pressure outside and four locations in the first case study under normal occupation and fan operation regime is shown in Fig. 2. Vapour pressure is significantly higher indoors than outdoors indicating the effect of interior moisture production and restricted ventilation as is usually the case in the majority of homes in winter. Vapour pressure is the highest in the unheated bathroom (equipped with a humidistat controlled extractor fan), followed by the kitchen, living room and bedroom. Although, the vapour pressure in the living room and bedroom are similar, temperatures in the bedroom are lower than in the downstairs living room, so that the relative humidity is much higher upstairs, thus creating more condensation problems. As expected, there is a loose correlation with external humidities apart from the times that high and sudden moisture production indoors alters the internal patterns.

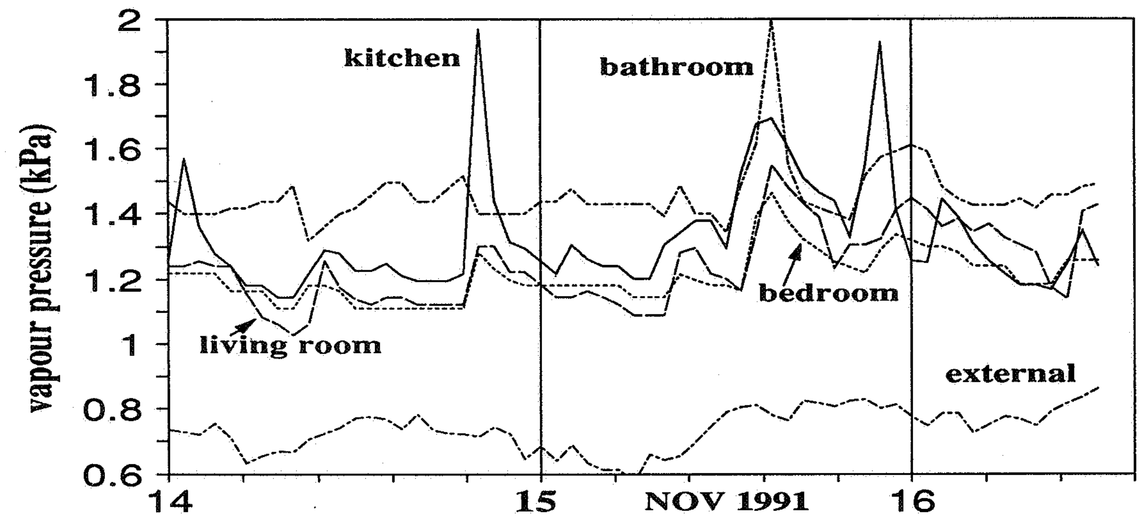


**Figure 2:** Typical plot of vapour pressure indoors and outdoors.

Figure 2 also presents data for two subsequent days during which the home was used in a different manner. During the first day cooking for dinner was the only source of moisture (apart from metabolic activities) while in the second day, cooking for lunch and dinner, bathing and laundry were performed. This has resulted in elevated vapour pressure in all the rooms for longer time during the second day.

It is evident that moisture produced in the kitchen or the bathroom has an effect on the vapour pressure in the living room and bedroom. It seems that the living room is affected more than the bedroom both from moisture migration from the kitchen and the bathroom for this particular house layout. This is a point requiring closer examination because it determines how much the moisture produced in one room affects the moisture in another, and discussed in section 4.

Considering the humidity status of the dwellings for the weeks before and after the installation of the extract devices, it was obvious that the mean humidity level has been reduced as a consequence of the combined use of the two extractor fans and cooker hood. An example of this, is shown in Fig. 3, where the external and internal relative humidity for the four rooms of case-study 1 have been plotted. Similar temperatures were maintained during the "before" and "after" periods due to the thermostat located in the hallway (there is a difference in the living room and in the bedroom of $1^0$C but the kitchen and bathroom are almost identical). The relative humidity however has fallen quite considerably in the three rooms (kitchen, living room and bedroom) but not in the bathroom. In this case the low flow rate, humidistat controlled extractor fan, set to 80% RH cut off point, has maintained the RH below 80%. However, it is now apparent that the humidistat was incorrectly set and this has influenced the internal humidity. As a result of less ventilation as the windows are opened

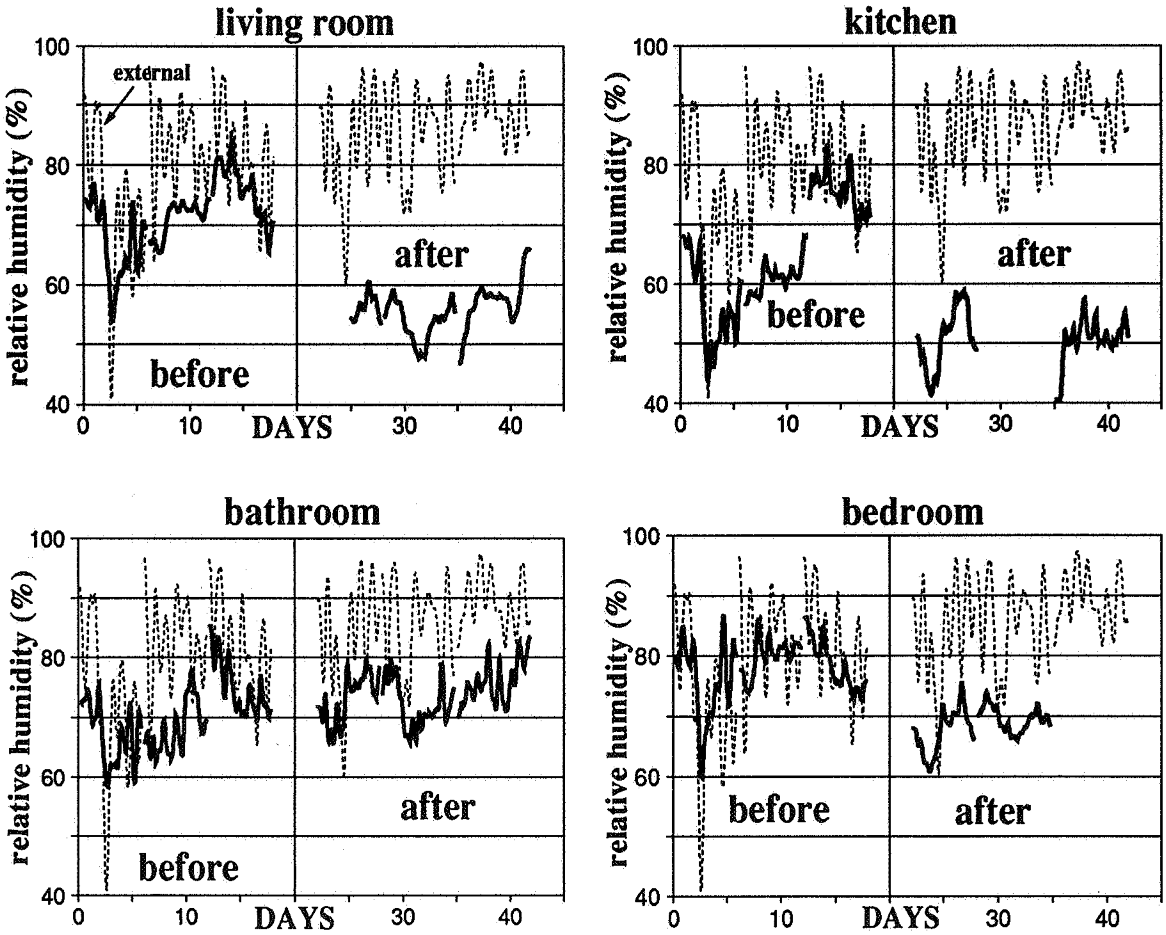


**Figure 3:** External and internal relative humidity values for the monitored four rooms of case-study 1. The average external temperature is 9.9$^0$C before the installation and 7.4$^0$C after. The internal temperatures are 18.3, 21.3, 18.6 and 16.7$^0$C in the living room, kitchen, bathroom and bedroom correspondingly before the installation and 19.2, 21.0, 18.3 and 15.4$^0$C after.

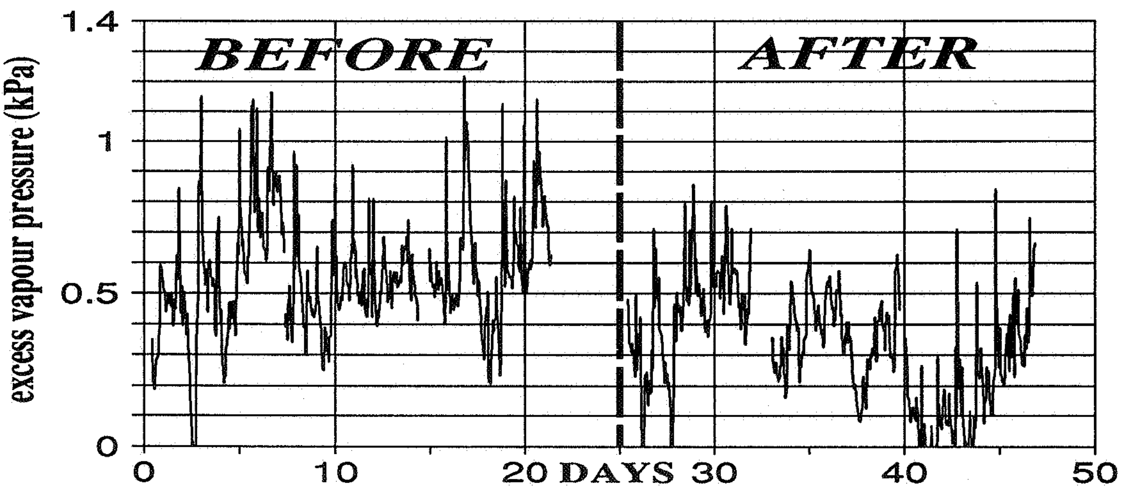


**Figure 4:** The installation of extract devices in case study 1 in normal use, reduced the mean excess vapour pressure in the three of the four rooms.

less frequently, the excess vapour pressure has increased. The average excess vapour pressure of the three rooms (excluding the bathroom) are presented in Fig. 4. The average reduction of mean excess vapour pressure is over 40%, which for an average temperature of 19°C results in an average RH reduction of more than 10%. The RH in the bathroom has increased by 4% (from an average value of 70% before the installation of the fans to 74% after).

BS5250 [14] classifies households as "dry", "moist" and "wet" occupancy. Dry occupancy (usually a building unoccupied during the day) results in an internal vapour pressure up to 0.3kPa in excess of the external vapour pressure. In moist occupancy water vapour excess is between 0.3kPa and 0.6kPa while in wet occupancy water vapour excess is greater than 0.6kPa. As shown in Table 1, the three households studied although unoccupied during the day fall into the moist category.

In case study 1, excess vapour pressure was reduced by 50% in the kitchen, almost 40% in the living room and 25% in the bedroom, bringing the values near the "dry" occupancy category. The reverse has happened in the bathroom, because of the high setting of the humidistat.

**Table 1**: Mean values of excess vapour pressure in the three case studies before and after the installation of extract devices.

| | | Kitchen | Living Room | Bedroom | Bathroom |
|---|---|---|---|---|---|
| CASE 1 | before | 0.68 | 0.51 | 0.51 | 0.52 |
| | after | 0.33 | 0.31 | 0.38 | 0.64 |
| | % change | -51 | -39 | -25 | +23 |
| CASE 2 | before | 0.54 | 0.22 | 0.43 | 0.66 |
| | after | 0.51 | 0.36 | 0.41 | 0.45 |
| | % change | -5 | +63 | -5 | -32 |
| CASE 3 | before | 0.54 | 0.45 | 0.53 | 0.45 |
| | after | 0.46 | 0.34 | 0.26 | 0.30 |
| | % change | -15 | -24 | -51 | -33 |

In case study 2, the results are less dramatic with only 5% reduction in the kitchen and in the bedroom but more than 30% reduction in the bathroom. In this case the volume of the bathroom is smaller than case study 1 and the humidistat was set more reasonably to 70%RH. The operation of the fans has increased the humidity in the living room. This is probably due to the fans in the kitchen and bathroom through which the air is mainly extracted so that infiltration occurs mainly through the living room in the downstairs half of the dwelling. This change of air flow patterns coupled with the higher external vapour pressure during the "fans operating" monitoring period and the low ventilation rate in the living room, has increased the vapour pressure in it.

In case study 3, there is also a reduction in the excess internal vapour pressure after the installation of the fans. In this case, the greatest reduction is observed in the bedroom (more than 50% reduction) which is affected by moisture in the kitchen and the bathroom because of the flat's layout.

As nothing has change in the operation of the households after the installation of the ventilation devices, we can assume that the operation of the fans (higher ventilation rates where and when required) has produced the reduction of the excess internal vapour pressure. Also, because moisture is extracted at source rooms at the time it is produced, the effect should be greater than uniformly increasing the ventilation rate at all times. Intermittent ventilation as and when required also eliminates energy waste.

Let us use case study 1 as an example to demonstrate this point. The ventilation rate of the dwelling was measured using the tracer gas decay method. It was found the average ventilation is 0.53AC/H without any extract devices on, while the ventilation rate becomes 0.85AC/H when the cooker hood is on in the kitchen. The higher ventilation rate happens only for about one hour per day and this has an effect of almost 40% reduction in the average excess vapour pressure of the house. In addition, it may replace opening windows during cooking which would waste more energy without offering the efficiency of a cooker hood.

The discussion of section 3 was concerned with the steady state performance of the three houses and has shown that reduction of the excess vapour pressure is possible by using extractor fans. This finding agrees with findings of a nationwide survey in UK [15] which concluded that *ventilation devices*, air movement, heating and insulation are more important than occupants' behaviour and energy consciousness. However, what it has not shown so far is by how much the moisture production in the kitchen and in the bathroom affects the humidity of other rooms and what is the effectiveness of each fan in isolation. For this reason, experiments on cooking and bathing simulations with simultaneous tracer gas release were performed in two of the case-studies (1 and 3) to examine the effect of air flow on the migration of moisture and the effect of adsorption by surfaces.

## 4 MEASUREMENTS OF MOISTURE AND AIR FLOW

It has been found [16] that if adsorption and condensation are ignored water vapour behaves very similarly to tracer gases. Therefore, if a way of accounting for absorption and condensation were found, tracer gases, could be used to predict airborne moisture movement in buildings. For this reason, as well as to understand the relation between the layout of a dwelling and the effect of adsorption in the migration of moisture from source to sink rooms, the following experimental procedure was set up.

Periods of cooking and bathing were simulated and the spread of two contaminants (water vapour and sulphur hexafluoride) from a hot source to various rooms was measured. To simulate cooking the contaminants were released for 25mins from the cooker's hot plate. In this experiment 1.46 litres of water was boiled and 2500 ml of tracer gas was released. To simulate bathing the contaminants were released for 11.5 mins, from the middle of the bath (total amounts released 0.62 l of water and 1150 ml tracer gas). The concentrations were measured with a Bruel & Kjaer photo-acoustic effect gas analyser which pumped samples of air from each room via an automated manifold, measuring one room in two minutes. Nineteen experiments were performed in each dwelling to include different settings of the fans.

The Transfer Index (TI) [17] in each room was calculated for the moisture and sulphur hexafluoride. The average Transfer Index of all the rooms in any experiment represents the total contaminant load of the house thus indicating the effectiveness of a specific fan for a specific flow rate for a particular plan configuration. Figures 5 and 6 demonstrate the removal effectiveness of the fans examined in the two flats.

It can be seen from the figures that during the bathroom experiments the air becomes saturated and the fan proved to be underpowered in removing the moisture even at its boost position (29l/s) in both flats. Therefore, no comparison can be easily made with the tracer gas behaviour. However, it can be seen that the flow rate recommended by the Building Regulations for intermittent powered extraction in bathroom (15l/s) is an underestimate.

In the kitchen experiments almost straightforward comparisons between moisture and tracer gas removal are possible. In case study 1 the cooker hood at all settings proved to be more effective than the extractor fan. In case study 3, however, the cooker hood and the fan seem to be almost equally effective. This introduces another dimension into the problem. In case study 3 the fan is situated nearer to the cooking hob than in case study 1. Therefore, the proximity of the source and removal at source appear to be important.

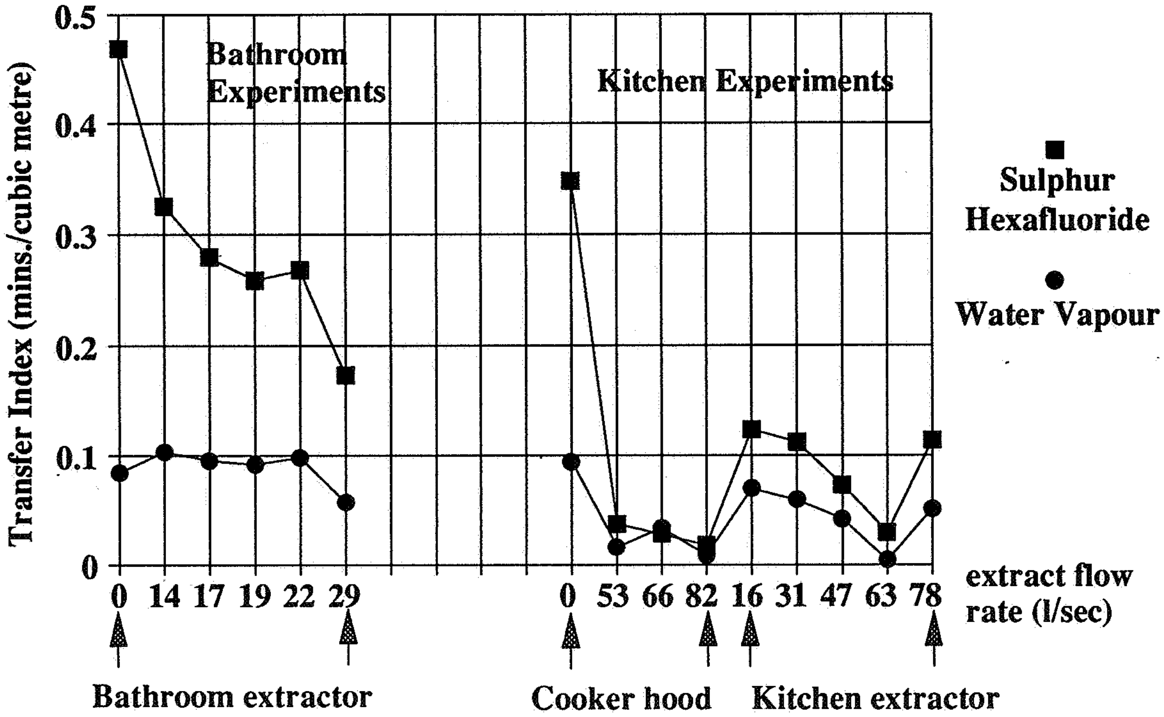


**Figure 5:** Effectiveness of the extract systems judged by the effect in the whole dwelling of case study 1.

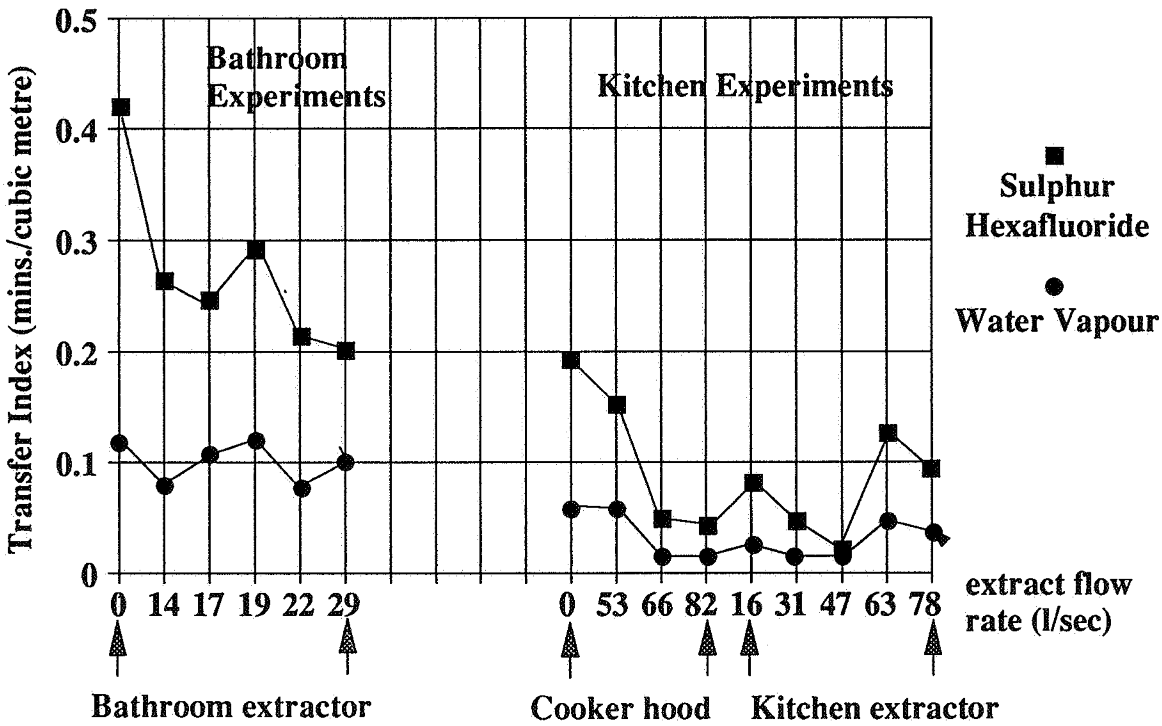


**Figure 6:** Effectiveness of the extract systems judged by the effect in the whole dwelling of case study 3.

So far the average TI of the dwellings as a whole was considered. By examining the TI of each room separately we can begin to understand the impedance of pathways for the pollutant migration between zones. The degree of linkage reflects the adjacency of the rooms and configuration of the building plan. The linkages for the two case studies are presented in Table 2. It can be seen from Table 2 that moisture absorption by surfaces is considerable, resulting in much lower TI values for moisture than for the tracer gas. However a strong correlation between the TI of tracer gas and moisture exists; r=0.993 for case study 1 and r=0.994 for case study 3. This indicates the suitability of tracer gas to describe airborne moisture movement between spaces.

In addition, a correlation between the monitored data and short term simulation type experiments of cooking and of bathing was found, indicating that the long term performance of extract devices for each room of a house can be predicted by short term experiments. A correlation of r=0.949 was found in case study 1 and r=0.82 for case study 3. The correlation with tracer gas measurements is also strong (r=0.95 in case study 1 and r=0.734 in case study 3). These results indicate that it might be possible to predict the effect of ventilation devices on moisture by performing short term experiments using either water or tracer gas.

The above correlations were calculated as follows; the steady state change of vapour pressure in each room can be expressed by the ratio of the average excess vapour pressure in each room after the installation of the fans to the average excess vapour pressure before the installation. This value can be compared with the ratio of a room's TI calculated from experiments in which some fans were used to the TI for which no fans were used. It was found that the best relationship exists if the steady state values are correlated with the average of the TI calculated from (a cooking experiment without fans) + (a cooking experiment with the cooker hood on) + (a bathing experiment with the bathroom fan on) divided by the average of a cooking and a bathing experiment with no fans.

**Table 2:** Average linkages between rooms for tracer gas and moisture during cooking and bathing experiments.

| | | Kitchen | Living Room | Bedroom | Bathroom |
|---|---|---|---|---|---|
| **CASE 1** | | | | | |
| Cooking- | $SF_6$ | 0.155 | 0.085 | 0.055 | 0.061 |
| Experiment | $H_2O$ | 0.072 | 0.037 | 0.019 | 0.024 |
| Bathing- | $SF_6$ | 0.080 | 0.131 | 0.205 | 0.668 |
| Experiment | $H_2O$ | 0.030 | 0.035 | 0.073 | 0.226 |
| **CASE 3** | | | | | |
| Cooking- | $SF_6$ | 0.183 | 0.067 | 0.026 | 0.048 |
| Experiment | $H_2O$ | 0.059 | 0.030 | 0.013 | 0.019 |
| Bathing- | $SF_6$ | 0.062 | 0.109 | 0.159 | 0.664 |
| Experiment | $H_2O$ | 0.038 | 0.035 | 0.071 | 0.233 |

## 5 CONCLUSIONS

The effectiveness of extract devices and the merits of user control versus humidistat control, have been discussed before [18,19] and reviewed [20]. Also the capture efficiency of cooker hoods has been investigated [21,22]. In this paper the aim was to examine the effect that the installation of "off the shelf" extractor devices has on the humidity in occupied small dwellings.

The use of tracer gas techniques to augment humidity measurements has been investigated before [23,24], and short term measurements have been made of humidity in kitchens and adjacent rooms [25] and in bathrooms [26]. The uniqueness of the present study is in offering monitored data of moisture before the installation and during normal use of extract devices in occupied dwellings coupled with "laboratory" like experimental measurements of tracer gas and water vapour taken in the same dwellings.

From the monitored data it was found that a reduction of the excess vapour pressure was observed in most rooms of the case-studies after the installation of ventilation equipment. The biggest changes were found in the source rooms (kitchen and bathroom) but considerable changes occurred in the sink rooms (living room and bedroom).

From the experiments the average Transfer Index of the house as well as zone Transfer Indices (for individual rooms) were calculated which give useful information for the linkage of sink rooms to source rooms and information on the effectiveness of individual extract devices for the particular house configuration. The linkage values depend on the length and shape of the pathway and determine how easily contaminants can migrate. Finally, by comparing tracer gas and water vapour measurements we can get an impression of the amount of moisture adsorbed by the surfaces and the effect of surface condensation.

It was found that Transfer Indices derived from water vapour measurements describe the steady state performance of the moisture balance in the examined case studies. There is also a strong correlation between the transfer indices calculated from tracer gas and water vapour measurements. The actual values differ considerably. It was found [27] that this is due to adsorption by surfaces and condensation, and not to any other mechanisms of airborne contaminant migration. Therefore, if adsorption and condensation can be accounted for by using some coefficients [28], tracer gas short term experiments in existing houses or even CFD analysis for proposed design can be used to predict the long term steady state moisture balance of a dwelling.

## 6 ACKNOWLEDGMENTS

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