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Abstract This paper describes an experimental study of moisture migration in a small dwelling. Experiments were carried out to measure the migration of moisture from the kitchen and bathroom to the rest of the house. Extractor fans and a cooker hood were operated to reduce the migration, and their effectiveness was measured. The tracer gas step-up method was also used to measure the air movement. The transfer index was used to characterise the migration. The results show the relative effectiveness of the fans running at various speeds. They also show how much moisture and tracer gas migrates into each room.

Moisture movement and extractor fans: Experimental study

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1 Introduction

1.1 The problems

In this study the migration of airborne moisture and the effect of extractor fans on this migration were studied in an occupied maisonette, chosen as a typical small dwelling. For a detailed description of the maisonette see below.

More than half of England's householders see damp as a problem, according to the English House Condition Survey[1, 2]. In many of these cases, more than 20% of the total stock, the occupiers complained of damage or mould due to damp. This degree of concern requires solutions. The 1990 Building Regulations[3] have made extractor fans compulsory in all new kitchens and bathrooms. This study investigated the usefulness of extractor fans in reducing indoor humidity.

There are three main sources of damp in housing: penetrating damp (leaks), rising damp, and condensation. The largest, but least severe, problem is condensation due to insufficient heating or ventilation. This affects over half of the households in England[1] and ranges in severity from steamed-up windows to large wall areas covered in mould. It can lead to structural damage.

In recent years the draught proofing of homes has been a very popular way to reduce heating requirements. In many cases this has led to increased condensation problems[4, 5]. The simplest solution to these cases is increased ventilation. Obviously, air must be extracted selectively from the sources of moisture, or the energy saved by draught-proofing will be lost again. This study aims to show the effect of various extract locations and rates on the migration of moisture around an occupied house, from sources in the kitchen and bathroom.

The use of extractor fans does not only reduce condensation problems. Because the indoor humidity is reduced, minor problems from rising damp or penetrating damp may be alleviated as the walls dry out. Additionally, possible health problems caused by high humidities and fungal spores[6] and dust mites[7] may be decreased. These factors are suspected of causing allergic reactions, and irritation to asthmatics, and can be reduced by controlling the indoor humidity.

Extractor fans work in two ways. Firstly they extract large quantities of contaminants from near their source, and secondly they prevent the migration of contaminants by drawing air into the source room. In this study their effectiveness in both respects was investigated.

1.2 The maisonette

This experimental work was carried out in a maisonette in Hackney, East London, built in the 1940s (Figure 1). The flat was chosen because it is typical of low-rent housing in London, and because it suffered from condensation on most windows for much of the winter.

The maisonette is situated on the north-west corner of the top two floors of a five-storey block of flats. The floor area is 60 m^2, of which 40 m^2 are downstairs, with just one attic room upstairs. The external walls consist of 300 mm brick and the windows are timber framed and singly glazed. There is no thermal insulation in the walls or the roof.

Ventilation is provided by sash windows, window vents and vents into a bricked-up chimney in the living room. Because of noticeable draughts, all the window vents had been blocked up by the occupants, except for one vent in the living room. Heating is provided by a time-controlled gas boiler and standard radiators in every room apart from the bathroom. In the bathroom there is an electrical wall-mounted radiant bar heater which is rarely used.

For the purpose of this study, the house was fitted with extractor fans in the kitchen and bathroom and a cooker hood in the kitchen, in order to measure their effectiveness at removing moisture from the kitchen and bathroom, and in preventing moisture migration from these rooms to the remainder of the house.

1.3 Extractor fans

Three extract devices were installed in the maisonette, two in the kitchen and one in the bathroom. The maximum flow rates quoted are those supplied by the manufacturers. In all cases they comply with the 1990 Building Regulations (Part F, Schedule 1)[3].

The window-mounted unit in the kitchen (an Airflow CR6 150 mm diameter fan) with a maximum flow rate of 78.6 $l\,s^{-1}$ was installed with an infinitely variable speed controller. The cooker hood (Xpelair Continental) was ducted outside, and has a maximum flow rate of 82 $l\,s^{-1}$. The humidistat-controlled bathroom unit (Xpelair Condensation Control Unit) has a maximum flow rate of 28 $l\,s^{-1}$.

2 Experiments

These experiments were carried out in an occupied house and involved the production of water vapour by boiling

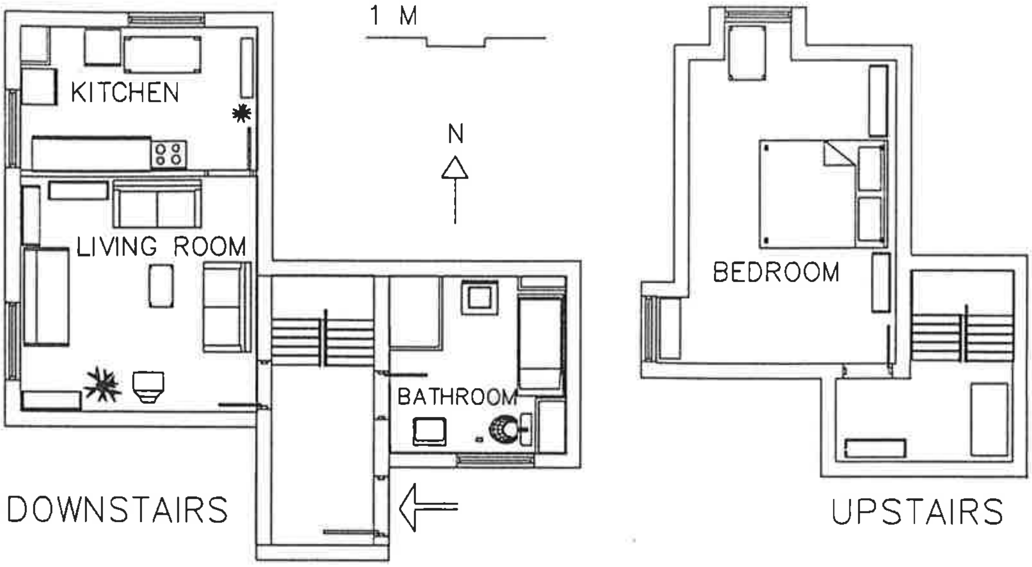

Figure 1 The maisonette in Hackney

water in a kettle. To avoid an excessive build-up of moisture in the walls the order of the experiments was carefully chosen. A typical day consisted of a highly ventilated kitchen experiment followed by a bathroom experiment and then another kitchen experiment leaving a poorly ventilated experiment until the end of the day. In this way, all the experiments could be completed in 5 working days.

Table 1 Experimental conditions and measurements

Simulation	Condition	Flow rate ($l\,s^{-1}$)†
	No fans on	0
	Bathroom extract on low power I	14
	Bathroom extract on low power II	17.5
Bathing	Bathroom extract on low power III	19
	Bathroom extract on low power IIII	22
	Bathroom extract on Boost	28
	No fans on	0
	Cooker hood on, power I	53
	Cooker hood on, power II	66
	Cooker hood on, power III	82
Cooking	Extract fan on 20%	15.7
	Extract fan on 40%	31.4
	Extract fan on 60%	47.2
	Extract fan on 80%	62.9
	Extract fan on 100%	78.6

† Manufacturer's data

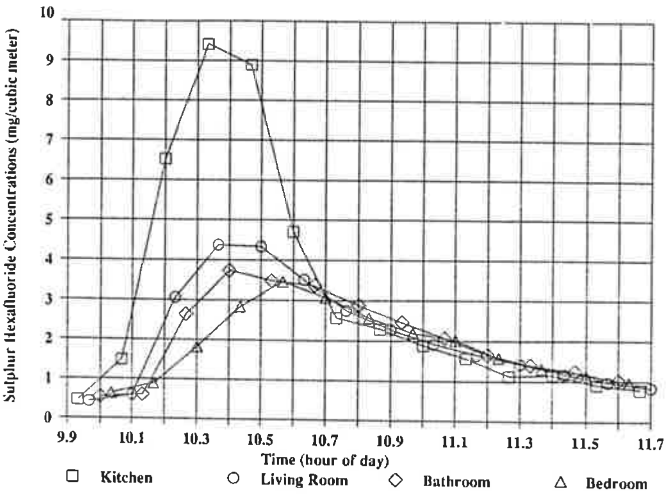

Figure 2 Sulphur hexafluoride concentrations versus time, measured in the kitchen, living room, bathroom, and bedroom, following SF_6 release in the kitchen, with the kitchen extractor on full power

2.1 Contaminant spread

In these experiments periods of cooking and of bathing were simulated. The spread of two contaminants from a hot source to various rooms was measured. An electric kettle was boiled to produce water vapour as one contaminant, and tracer gas was released simultaneously into the boiling water as the second contaminant. The tracer gas used was 10% by volume sulphur hexafluoride ($\rho = 6.08\,mg\,cm^{-3}$) in nitrogen ($\rho = 1.17\,mg\,cm^{-3}$), overall density $1.66\,mg\,cm^{-3}$.

To simulate cooking the contaminants were released from the cooker's hot plate for 25 min. During this experiment 1.46 l of water was boiled, and $2500\,cm^3$ of tracer gas was released (1521 mg of SF_6).

To simulate bathing the contaminants were released for 11.5 min from the middle of the bath. In this case 0.62 l of water and $1150\,cm^3$ of tracer gas (700 mg SF_6) were released. During these experiments the concentrations of the two contaminants were measured at four locations in the house: in the middle of the kitchen, living room, bathroom, and bedroom, at a height of 1.7 m. The four locations were measured for up to 2 h to observe the rise and fall of the contaminants' concentrations.

The concentrations were measured with a Bruel & Kjaer photo-acoustic effect gas analyser which pumped samples of air from each room in turn via an automated manifold, measuring one room in two minutes. This measures both gas concentrations to three significant figures. During the experiments all of the doors in the flat were kept open, and all windows were kept shut. This is a simplification of the real situation, but it enables direct comparisons between the experiments. It can be seen as a worst case for contaminant spread. This experiment was repeated for the cases detailed in Table 1.

3 Results

In order to compare the water vapour movement with that of the tracer gas the results from the gas analyser were processed in a spreadsheet program where the transfer index[8] in each room was calculated for the moisture and sulphur hexafluoride.

The transfer index is simply the area under the concentration peak divided by the total contaminant released[8]. The transfer index was calculated from the first ten readings in each room, i.e. up to 64 min after the start of contaminant release. The area was calculated using the trapezium rule, and was taken as the area above a horizontal line drawn from the first measured concentration in each room. By converting the contaminant concentrations into transfer indices the two contaminants are normalised so that they can be compared directly.

Typical graphs showing the rise and fall in water vapour and SF_6 concentrations are presented in Figures 2 and 3.

Figure 2 shows the development of sulphur hexafluoride concentration with time in the four monitored rooms. The gas was released for 25 min in the plume of steam from the moisture source in the kitchen. The first point measured in each room shows the background concentration before the start of the contaminant's release. The steep rise in concentrations occurs during contaminant production, followed by the slower decay. The transfer index was calculated from each room's peak in order to compare how much tracer gas migrated into each room.

Figure 3 shows the development of water vapour concentration with time during the same experiment as shown in Figure 2. Again, the contaminant was released for 25 min. The shape is very similar to that of the previous graph of sulphur hexafluoride concentrations and the areas under the peaks have been measured in the same way. The transfer index is considerably lower for moisture than for SF_6 because of hygroscopic adsorption onto walls, ceilings, and furniture. By comparing the transfer index for moisture with that for SF_6 the extent to which moisture has been adsorbed onto surfaces can be deduced.

The processed results have been presented in two ways. Firstly, the *effectiveness* of each fan speed is compared; the whole-house average transfer index is calculated for each contaminant; higher fan speeds reduce the house average. Secondly, each room's peaks are compared to see how well the air in each room is *linked* to the source.

A higher transfer index in a room means a higher contaminant load in that room, and better *linkage* to the source. Generally the source room will have the highest load and best *linkage* to the source, and the most distant rooms will have the lowest load and poorest *linkage* to the source. The *linkage* indicated by the sulphur hexafluoride is based purely on air movement, whereas that of the moisture is also affected by hygroscopic adsorption onto the room surfaces.

3.1 Effectiveness

Figure 4 can be used for assessing the flow rate required to reduce the contaminant load in the whole house.

The average transfer index of all rooms in any experiment represents the total contaminant load in the house. Obviously, this should be lower for higher extraction rates. The averages of tracer gas loads and of moisture loads are shown in Figure 4. There are considerable differences between the extractions of the two gases, due mostly to hygroscopic adsorption onto surfaces.

This comparison has the drawback that different experiments carried out on different days under different conditions are not perfectly comparable. For example, if low fan speeds are used on a windy day then they may appear more effective at removing contaminants than higher fan speeds on a calm day. Even so, there are good correlations between these experiments, the only serious exception being the experiment with the kitchen fan on full power; this is probably due to wind blowing directly into the fan.

From Figure 4 it can be seen that the moisture and tracer gas behave similarly in the kitchen, but not in the bathroom. This is because the bathroom air became saturated during some experiments, and much of the water condensed. This was also the case in the unventilated kitchen experiments. Figure 4 illustrates the advantage of using a ducted cooker hood rather than a window-mounted fan. Even at a low flow rate most of the contaminants have been extracted.

3.2 Linkage to source

In Figures 5 and 6 are shown the mean transfer indices for all the experiments, giving a general impression of

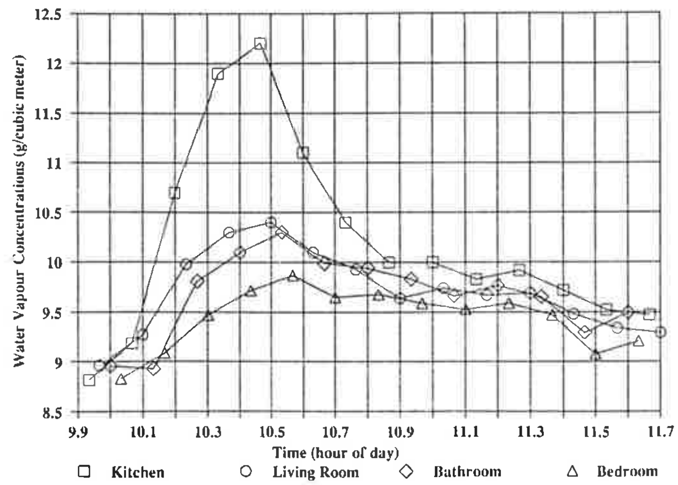

Figure 3 Water vapour concentrations versus time, measured in each room following water vapour release in the kitchen, with the kitchen extractor on full power

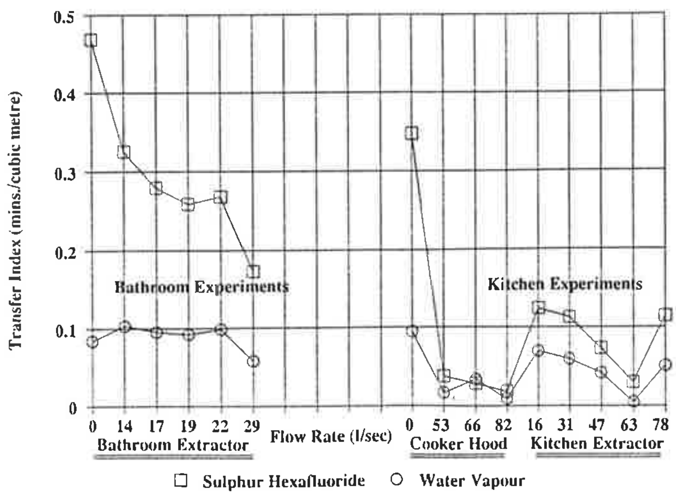

Figure 4 The *effectiveness* of the various fans and flow rates at removing the contaminants. The mean transfer index into all four rooms is shown for each experiment.

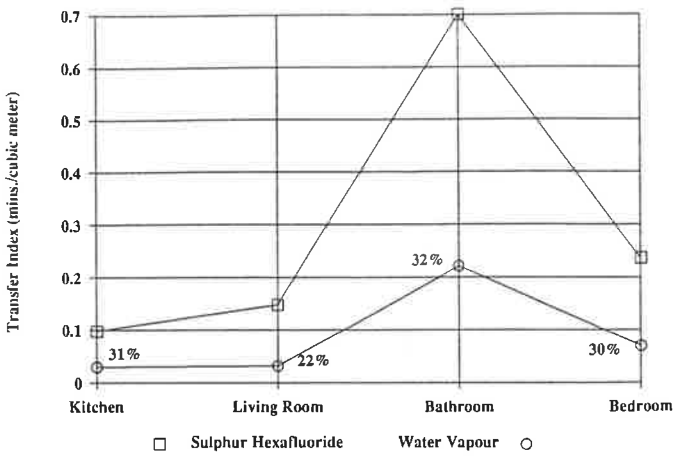

Figure 5 The mean transfer indices into each room, from the bathroom, for sulphur hexafluoride and water vapour. The water vapour transfer index as a percentage of the SF_6 transfer index is shown for each room.

how much the air in each room is *linked* to the contaminant source. However, each experiment has different proportions of contaminants in each room, and graphs can be plotted of each experiment in turn. Note that the water vapour transfer index in the bathroom is kept low because the air is saturated. Note also that the kitchen is too damp because of residual moisture from the cooking simulations. Note that the bathroom and kitchen are slightly too damp because of the number of experiments carried out.

The room transfer index is an indication of how much air flows from one room around the house. It can be used for spotting potential problems and indicating the source of the contaminants reaching each room, for example, what proportions of a bedroom's moisture comes from the kitchen and the bathroom. The transfer index can also be used to see how much water vapour condenses and adsorbs in each room.

By comparing the transfer index in each room, we can see the *linkage* of each room to the source, either in the kitchen or bathroom. This type of comparison is naturally less erratic than that of the *effectiveness* because we are comparing four values in one experiment, rather than comparing one room's values in many experiments from different days. This comparison gives two values for each room's transfer index, one from the sulphur hexafluoride peaks and one from the moisture peaks.

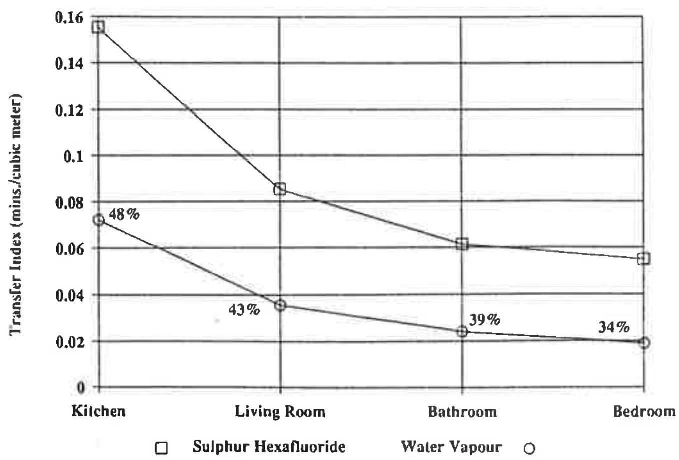

Figure 6 The mean transfer indices into each room, from the kitchen, for sulphur hexafluoride and water vapour. The water vapour transfer index as a percentage of the SF_6 transfer index is shown for each room.

Assuming that the two contaminants are both primarily carried by air movement, then the difference between the two transfer indices is an indication of how much moisture has been adsorbed into the building structure and furnishings. The tracer gas does not adsorb onto surfaces and so its movement closely mirrors the air movement. The transfer indices given by these peaks therefore indicate the *linkage* for air or non-absorbing gases (e.g. some smells and gases such as CO_2). The moisture, on the other hand, is adsorbed strongly onto surfaces over which it passes, e.g. ceilings, walls, and furnishings. Because of this, a distant room will be less well linked to the source room for moisture than for tracer gas; for example, the bedroom receives only about 30% as much water vapour as it would if there were no adsorption, indicated by the SF_6 transfer index. Many pollutants are absorbed as they pass around a building, for example all volatile liquid vapours and all particulates such as smoke and microorganisms.

The percentages shown in Figures 5 and 6 indicate the amount of condensation and adsorption. The tracer gas SF_6 gradually dilutes as it migrates further from its source. If the water vapour did not condense or adsorb onto surfaces then it would dilute in just the same way, and its transfer index would be 100% of the SF_6 transfer index in every room. Since it does condense and adsorb, the transfer index for water vapour into a room is reduced to a fraction of the SF_6 index. The difference in this percentage can be used to calculate how much water has been lost in each room. For example, in Figure 6 the water vapour content of the kitchen air is only 48% of the expected value. The other 52% has been condensed and adsorbed. If there were no more losses in the house then the rest of the rooms would also have 48% of the expected water content. As it is, more water is adsorbed in the living room, giving a further 5% drop in the fraction. Between the living room and the bathroom and bedroom there are further drops in the fraction due to more hygroscopic adsorption. However, these percentages are not very accurate because of the large daily moisture loads in the kitchen and bathroom. Both of these rooms have too high a moisture content because of this. To obtain accurate information on the adsorption in the house long periods of 'drying out' must be left between experiments. This was impractical in this project as adsorption was a secondary part of the work.

4 Conclusions

Figure 4 shows the mean of the four measured transfer indices in each experiment. This represents the total contaminant load in the house. It can be seen that the most effective means of extraction is the cooker hood, and that the three speed settings do not make much difference. The kitchen window fan is also effective at high flow rates, shown by the experiments at flow rates of 47 and $63\,l\,s^{-1}$. It was also noted at the time that it prevented most condensation even at low flow rates, and this can be seen in that the mean transfer index at $16\,l\,s^{-1}$ is well below that for the experiment with no extraction where the air became saturated.

The bathroom experiments all resulted in considerable condensation because the extraction rate was insufficient for the rate of evaporation. The implication is that the bathroom fan, having a low extraction rate, needs a long running time to reduce the humidity, and so the humidistat setting will be of crucial importance.

Using this graph one can choose the extract rate required to reduce the contaminant load in a house to a desired level. For example, a flat has an average winter relative humidity of 80% with an internal temperature of 15°C, that is a moisture content of $8.5\,g\,kg^{-3}$.

The mean air change rate is 0.5 per hour and the volume is $100\,m^3$, giving a daily air change rate of $1200\,m^3\,day^{-1}$. This implies, in a simple model, a daily moisture load of $8.5\,kg\,day^{-1}$. That is the moisture content multiplied by the daily air change rate. Cooking is estimated to produce 5 kg moisture per day. It is desired to reduce the internal humidity to 60%, or $6.4\,g\,kg^{-3}$. This implies a reduction in the daily moisture load of 2.1 kg, to $6.4\,kg\,day^{-1}$. By using a plot such as Figure 4 one can see how large an extract fan is required to reduce the cooking load by 50%. In Figure 4 the mean transfer index from the unventilated cooking experiment is 0.095. The extract fan running at $31\,l\,s^{-1}$ reduces this to 0.059 (62%), and the fan running at $47\,l\,s^{-1}$ reduces it to 0.042 (44%). So a fan rated at $47\,l\,s^{-1}$ will reduce the cooking load to 44% of 5 kg, or $2.2\,kg\,day^{-1}$, which is sufficient to reduce the mean internal relative humidity to 60%. This is in fact a pessimistic view, since the unventilated experiment resulted in a lot of condensation and therefore the extract fan reduced the internal load more than is shown from these purely airborne contents.

Using a plot similar to Figure 4, but showing the transfer index to one room, instead of the house average, one can choose the extract rate required to reduce the contaminant load in a single room or selection of rooms.

The good correspondence between the results for the two contaminants suggests that this work could be carried out using just tracer gases. Indeed, tracer gases have no problems with saturation and condensation, and are generally less erratic due to there being no unwanted sources, as there are with water. The bathroom experiments in Figure 4 clearly show the problems of condensation in these experiments, and the advantages, therefore, of using tracer gases. Of course there would be no information on hygroscopic adsorption, but this could be estimated from the airborne load.

Figure 5 shows the contaminant load in each room, per unit of contaminant released in the bathroom, under the average conditions of all the experiments. Similar graphs can be drawn for individual experiments to compare the migration around the house when using particular flow rates. The shape of the plot characterises the flow paths of the house. By looking at the tracer gas lines we see the airflow from the source into each room for these mean conditions. The relative values in each room will be different for different building layouts, primarily according to the airflow path lengths, but will also be affected by fans, temperature gradients and stairwells. For example warm contaminants such as steam will tend to rise up stairwells more than cool contaminants.

Figure 5 also shows where the bathroom moisture migrates, and so it can be used to identify potentially problematic rooms. For example, if most of the bathroom air migrates into the bedroom, then this may cause a serious risk of condensation. The water vapour lines show the transfer index for moisture in each room. Here there is the additional loss due to condensation and hygroscopic adsorption. This accounts for the major difference from the tracer gas lines. Most of this loss occurs in the source room, but there are additional losses along the flow paths, indicated by the percentages. The percentages on these graphs indicate the amount of water vapour which has **not** been condensed or adsorbed. These values should decrease from room to room, as water vapour is adsorbed onto surfaces. This is the general case but there are some exceptions. The amount of moisture produced by the experiments has raised the humidity in the bathroom and kitchen, and in the bathroom during some experiments the air became saturated, thus keeping the water vapour concentration down. For a detailed study of hygroscopic adsorption the house must be allowed to dry out between experiments.

Figure 6 shows the mean contaminant load from all of the cooking simulations. The values in the source room are much lower than those in Figure 5 because of the higher extraction rates in the kitchen.

5 Summary

Each room of a house is linked to the kitchen and the bathroom by an air pathway. The length and shape of this pathway determines how easily contaminants can migrate. Extractor fans work in two ways. Firstly they remove contaminants from the house, and secondly they prevent the migration of contaminants around the house by depressurising the source room. If a house has a condensation problem, then by finding the source of the moisture and the required reduction in load to the problem room, a suitably sized fan can be fitted. The above experiments provide the characterisation of one dwelling. By characterising the flow-paths in many different types of dwelling it should be possible to determine the minimum extract flow rate required to cure a problem with a minimum of experiment. To make this possible the houses need more characterisation; for example, this paper does not address temperature gradients or the effects of closing doors. By characterising enough types of dwelling any particular case can be compared to a similar type in a database in order to optimise the remedial action necessary to combat moisture problems. This type of simplified dwelling characterisation should be of particular use to local authorities and other landlords who own many similar or even identical dwellings. In these cases it could be economical to carry out experimental characterisations of each type of dwelling so that remedial action can be carried out most effectively.

6 Further work

These experiments have been repeated in three other houses. Data on temperatures and the effect of the location of extraction have also been collected. In addition, work has been done on the distribution of moisture within a single zone[9]. Further results will be published in the coming year. In addition, a further study will investigate the importance of air inlet locations in tightly sealed dwellings.

Acknowledgements

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