#6447

H	Relative humidity
Ckj	Concentration of tracer gas number k in zone number j [ppm]
N.D	Undetermined permeability
δ_{ij}	KRONECKER symbol
Vi	Volume of zone i
Tk	Temperature of tracer number k
Sik	Amount of tracer number k injected in zone number i
Cik	Concentration of tracer number k in zone number i
qij	Air flow rate going out of zone number j into zone number i

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EFFECTS OF AIR MOVEMENT ON THE MOISTURE DISTRIBUTION WITHIN A ZONE

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ABSTRACT

Water vapour concentration variations within an enclosure in steady state and time dependent modes and the effect of the temperature driven air flows on the distribution are investigated using a Computational Fluid Dynamics (CFD) model. It was found that moisture variations during water vapour production and decay are significant not only on vertical but also on horizontal planes. The major influence is the air flow which is determined by the buoyant plume and positions of air supply and extract. The prediction of moisture distribution in single zone spaces like kitchens and bathrooms is important for the location of air extraction points so that the effectiveness of moisture removal for a given ventilation rate can be improved. The validity of using CFD models to study airborne moisture movement is examined by comparing the simulation predictions with measured values in an environmental two zone test chamber.

INTRODUCTION

Concerns about energy conservation in recent years have resulted in the reduction of ventilation levels in residential building. This has increased condensation problems in a large number of dwellings particularly in cold climates like the UK [1] where the reduction of ventilation is coupled with low internal air and surface temperatures in some parts of the dwelling. The importance of ventilation in reducing condensation risks and the importance of the removal of moisture at source have been long recognized and recently implemented in the British Building Regulations [2].

There exist simple prediction models for the evaluation of condensation risks in specific buildings and rules of thumb for the avoidance of condensation [3-8]. There have also been many experimental studies of moisture in test rooms and dwellings, but the measured points were few or covered a small area of the zone because of experimental restrictions [9-12]. However, most available prediction models and most of the experimental results deal with the average relative humidity of a space and do not take into account the moisture distribution within the space, which is an important consideration especially during times of water vapour production. CFD modelling offers the option of examining a large number of points in the enclosure without the constraints and uncontrollable parameters of an experiment. In addition, it is possible to examine parameters which affect moisture movement in insolation, thus determining the influence of a particular parameter. In the present study, it was possible using CFD modelling to study a large number of grid points in the three dimensions in order to examine in detail the distribution of moisture within a zone. Water adsorption by the surfaces and condensation on surfaces are not examined.

The distribution of moisture within a zone was studied in a steady state and transient mode using the Computational Fluid Dynamics model FLOVENT. This model was chosen because it is a CFD code developed specifically for applications in buildings, and can be used in a variety of computer platforms in a form accessible to designers and engineers with a convenient input and output.

In section 2, CFD predictions are compared to simple steady state vapour pressure algorithms. The variations of water vapour distribution in relation to the location of air inlet and extract and the position of the moisture source in a steady state mode are studied. In section 3, the transient model is described, and a comparison of CFD predictions with measurements taken in an environmental test chamber is presented. In section 4, CFD predictions of time dependent water vapour distributions, (ie the distribution during a rise or fall in humidity) are studied. In particular, the moisture distribution within a space at two time steps is examined. In section 5, the results are discussed and conclusions drawn.

STEADY STATE WATER VAPOUR PREDICTION

There exist simple steady state equations to predict the internal vapour pressure in buildings. Two of them have been widely used for the prediction of the internal moisture content by designers; these are the equations included in the British Code of Practice BS5250 [2] and in the International Energy Agency Annex XIV [4].

The available equations are as follows:

The equation in BS5250:

$$p_i = p_e + \frac{C}{0.191NV}$$

where

p_i = internal vapour pressure (kPa)
p_e = external vapour pressure (kPa)
C = mean inside vapour production (kg day^{-1})
N = the mean outside air ventilation rate (AC H^{-1})
V = the air volume of the zone (m^3)

The equation in IEA Annex XIV takes into account the internal temperature as follows:

$$p_i = p_e + \frac{462\,(q_i + 273)\,G_m}{nV}$$

where:

p_i = internal vapour pressure (Pa)
p_e = external vapour pressure (Pa)
q = internal temperature (°C)
G_m = the mean inside vapour production (kg s^{-1})
n = the mean outside air ventilation rate (AC s^{-1})
V = the air volume of the zone (m^3)

The above equations have been compared with CFD simulation predictions in a simple situation assuming the following:

Room Dimensions: 2.00x3.00x2.50m
Volume: 15.00m^3
Moisture production: 1.5kg day^{-1}= 1.73×10^{-5}kg s^{-1}
External and internal temperature : 20°C (the temperature is kept the same inside and outside to eliminate the effects of temperature in the flow fields)
External water vapour pressure : 0.977kPa (0.006kg kg^{-1} dry air or 42% relative humidity). The same water vapour pressure is used as the initial value for CFD calculations.
Ventilation rate : 0.5AC H^{-1}= 1.389×10^{-4}AC s^{-1}

Four variations of the air supply and extract locations and three variations of the moisture source were examined. These parameters were investigated because the simple equations do not account for the positions of the air inlet and extract or the location of the moisture source, and predict a uniform vapour pressure for the whole of the space. CFD modelling on the other hand differentiates between concentrations depending on the air supply/extract and vapour supply positions. The alternative cases examined are shown in Fig 1 and are described below:

Case A: low supply - high extract, on the same wall, moisture source at a corner
Case B: high supply - low extract, on the same wall, moisture source at a corner
Case C high supply - low extract, opposite walls, moisture source at a corner
Case D: low supply - high extract, opposite walls, moisture source at a corner
Case E: low supply - high extract, opposite walls, moisture source near the air extract

Case F: low supply - high extract, opposite walls, moisture source near the air supply.

For the parameters described above, Table 1 summarises the equations' results and CFD modelling predictions. The contours of moisture through a section of the room (see Fig 1) are shown in Fig 2 for the six cases simulated.

Table 1. Simple equations and CFD modelling predictions.

Equations	Vapour pressure (kPa)		Concentration (Kg kg^{-1})		Relative Humidity (%)	
	Mean	STD	Mean	STD	Mean	STD
BS5250	2.02	-	12.71	-	86.45	-
IEA Annex XIV	2.10	-	13.22	-	89.86	-
CFD modelling						
Case A	1.77	0.312	11.12	2.0	75.80	13.5
Case B	>2.337 (saturated)		17.17	1.4	100.00	
Case C	1.94	0.250	12.19	1.6	83.00	10.7
Case D	1.76	0.360	11.05	2.3	75.40	15.5
Case E	1.77	0.420	11.15	2.7	76.3	18.1
Case F	1.92	0.250	12.08	1.6	82.2	10.7

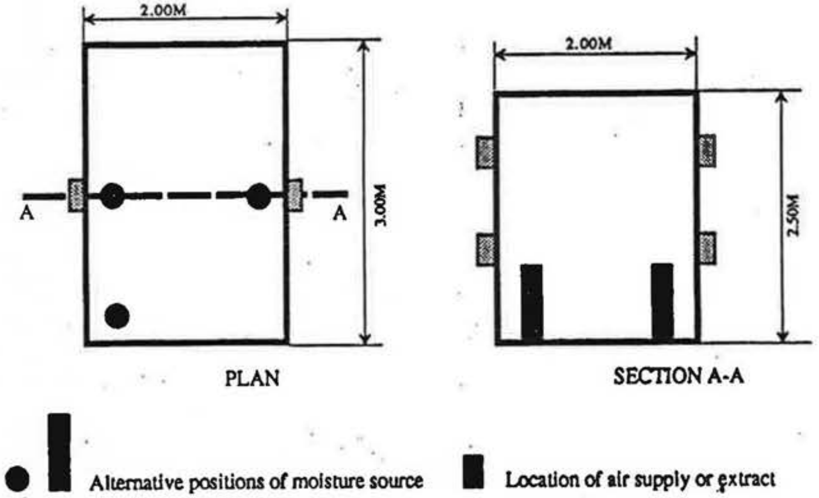
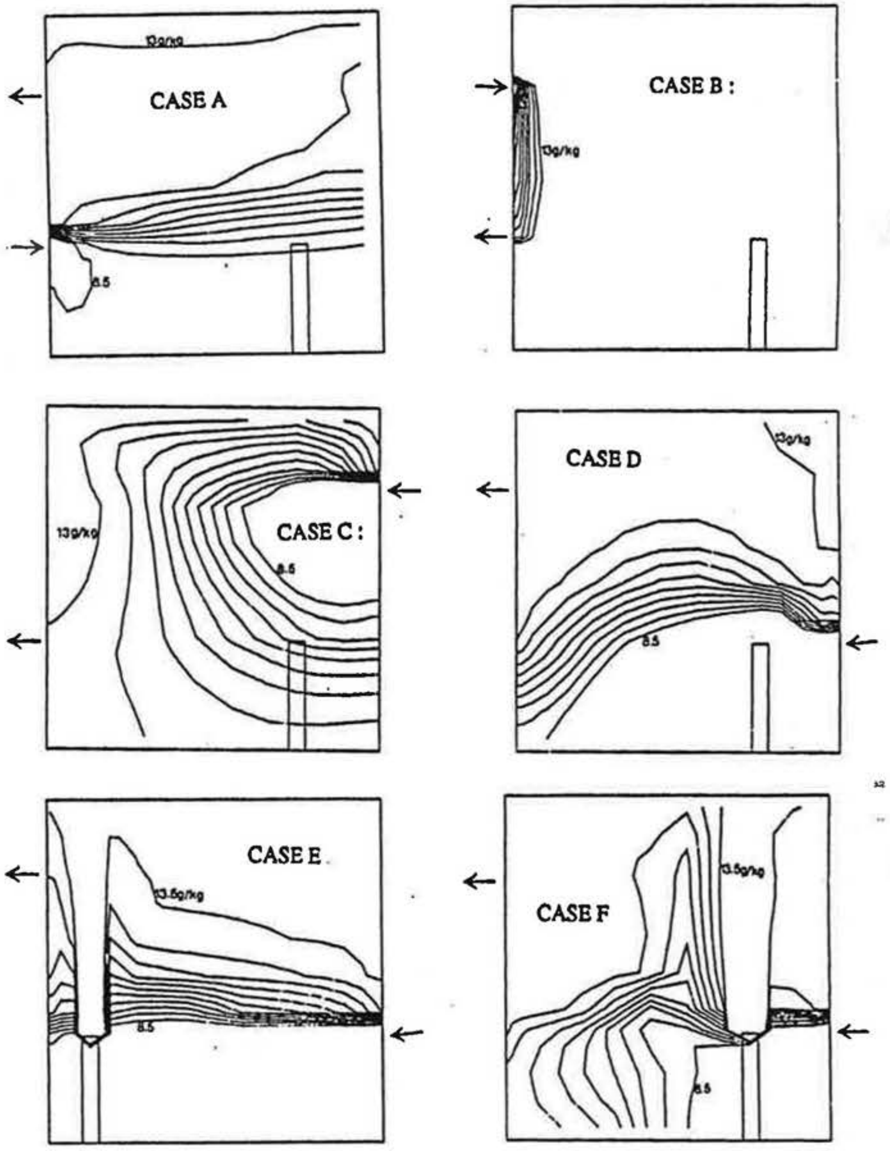


Figure 1. The geometrical details of the steady state simulations.



Contour interval : 0.5g/kg dry air

Figure 2. Moisture concentration contours for the six steady state cases (see Figure 1 for the location of the section).

In all but one case, simple equations overestimated the internal vapour pressure. This is because they assume perfectly mixed air and do not account for variations in humidity. It is interesting to note that in the simulated cases the lower the volume weighted average humidity in the space, the larger the variation of the humidity in the room. This indicates that when the water vapour is allowed to mix within a room before extraction starts, the extraction efficiency is reduced because the outlet air has become less humid by mixing with the drier air of the room. Therefore, extraction at the time that water vapour is starting to be produced, from where the moisture is more concentrated is essential for increasing the efficiency of extraction devices.

It is evident from Table 1 that the location of the air inlet and extract affects the average vapour pressure within a zone. This is because water vapour distribution varies through space and so in some of the cases more humid air is extracted. For example, the location of the extract point at an upper level of the room where the warm moist air rises helps in the extraction of higher amount of moisture, thus the room is maintained at lower humidity levels on average (Fig 2a, 2d). Low extraction coupled with high inlet at opposite walls produces higher average humidities because high and low vapour concentrations are mixed near the extract point (Fig 2c). The location of low extract and high inlet produces an air flow short cut with the cool air sinking and immediately extracted from the low extract without much mixing with the rest of the room, thus being unable to reduce the moisture content of the room at the same rate as the other cases (Fig 2b).

The location of the moisture source is also important. An extraction point situated near the moisture source enables the extraction of water vapour at high concentration near the point of production, thus reducing the average vapour pressure in the room (Fig 2e). Locating the moisture source near the air inlet disperses the water vapour in the whole room (including the lower half) thus reducing the efficiency of air extract (Fig 2f).

Therefore, the location of the openings and the moisture source must be considered in any algorithm estimating the average moisture content of a space. This will help in the decision for the location of extractor fans in spaces with high but relatively short in time moisture production such as kitchens and bathrooms so that to avoid the migration of water vapour in other internal spaces of the dwelling. Time should also be a consideration in the algorithm, as a steady state equation will only give general indications and does not consider the built up and decay of water vapour which is the real situation in kitchens and bathrooms of residential buildings.

A time dependent model was examined in an attempt to understand the mechanisms of airborne moisture transfer and its distribution within a zone. The simulation results of this model were compared with experimental results in order to built up confidence in the use of CFD models in examining airborne moisture movement.

THE CFD TIME DEPENDENT MODEL AND COMPARISONS WITH EXPERIMENTAL VALUES

In this section a time dependent vapour distribution was measured experimentally as well as being modelled computationally. A graph of the comparison between experimental and CFD results is shown in Fig 4. In the CFD model FLOVENT, water vapour was simulated as a contaminant having the same properties as air. For most properties this is a fair approximation, but for some like density and specific heat capacity there are significant differences which cannot be ignored. The conductivity and viscosity of the air/water mixture is very close to that of air, while the diffusivity has been shown [13] to have a negligible effect on moisture migration under typically turbulent conditions. The model does not take account of adsorption or condensation of the contaminant, and so the experiment was carried out in an aluminium foil lined cell and high humidities were avoided.

The experiments were carried out in an environmental test chamber as shown in Fig 3. Only the inner cell was lined with aluminium foil as this is the area of concern. Water was boiled by a calibrated electrical immersion heater near one corner of the cell, the total power of the heater were measured and simulated. The cell had one low level extract/inlet opening of 0.5 m^2, as shown in Fig 3. The experiment consisted of measuring the vapour concentration at seven heights at the centre of the inner cell, plus one point in the middle of the outer cell. The experiment lasted two hours, water was boiled for the first 30 minutes and then stopped, the concentration decayed for the rest of the time. The temperature difference across the opening was around 1.0°C during the moisture production period and 0.3-0.4°C during the decay.

Measurements were made with an infra-red photo-acoustic gas analyser (Bruel & Kjaer Type 1302). This sampled air drawn through tubing via a 16 way automated valve from the 8 locations, drawing one sample per minute. Thus each location was sampled every 8 minutes. Samples were drawn through 3 meters of nylon tubing, this tubing turned out to have been absorbing a proportion of the water vapour during the peaks. To account for this the experiment was repeated, but alternate samples were drawn from one location through either 3m of tubing or none at all. This showed the amount of vapour absorbed in the tubes, which was added as a correction to the results. The tubes were reducing the height of a peak by about 15%.

The assumption in the model that the contaminant has the properties of air, causes errors due mostly to the wrong values for density and specific heat capacity (at 100°C: air C_p=1005 $Jkg^{-1}k^{-1}$, ρ=0.94 kgm^{-3}; water C_p=4216 $Jkg^{-1}k^{-1}$, ρ=0.63). These affect the speed, temperature, and ventilation rates; but only in value, the flow patterns are much the same. The problem is that if the contaminant is introduced at the source at 100°C with very little velocity, then the buoyancy will be underestimated because water vapour should be less dense than air. The thermal energy in the plume will be underestimated too

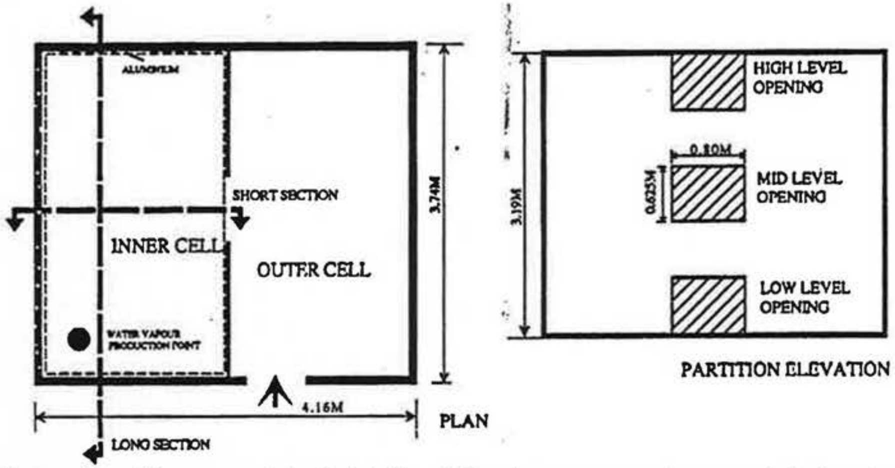


Figure 3. The geometrical details of the two zone environmental chamber.

because water has a much higher specific heat capacity than air. The net effect is that the simulated plume rises too slowly and does not carry enough energy into the cell. It is a better estimate to introduce the contaminant at 400°C to bring both density and heat input closer to their real values.

The comparison between experiment and CFD is shown in Fig 4, the experimental values have been corrected for losses in the sampling tubes. The agreement is certainly good enough to use FLOVENT for studying this type of airflow, care must be taken however in trying to calculate precise values, since these are so sensitive to uncertain input parameters such as temperature, turbulence and draughts, which can only be guessed at for most of the domain.

TIME DEPENDENT VAPOUR CONCENTRATION

The time dependent vapour distribution was examined at two time steps; a) at 30 minutes during which moisture was produced at a rate of 0.083g s^{-1} (150g over 30 mins) and b) at 120 minutes ie 90 minutes after moisture production was stopped. This set up can be compared to the build up and decay of heat and moisture in a kitchen during cooking. Initial conditions are vapour content of 0.006 kg kg^{-1} dry air and temperature of 20°C.

Three different heights of the opening and two heat input regimes have been simulated so as to examine their effect in the distribution of moisture within the enclosure.

The three openings examined have the same area of $0.5m^2$ and are positioned on the partition wall (Fig 3). The first is located at the same level as the moisture source starting at floor level, the second at mid height between ceiling and floor and the third at high level near to the ceiling. The

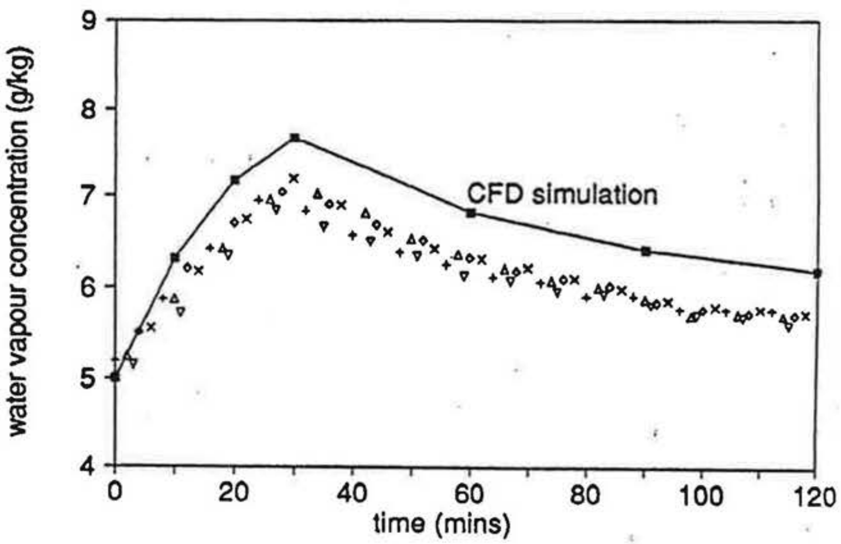


Figure 4. Comparison of CFD modelling results with measurements in the environmental chamber. The solid line is the CFD simulation results and the unconnected symbols the measured values.

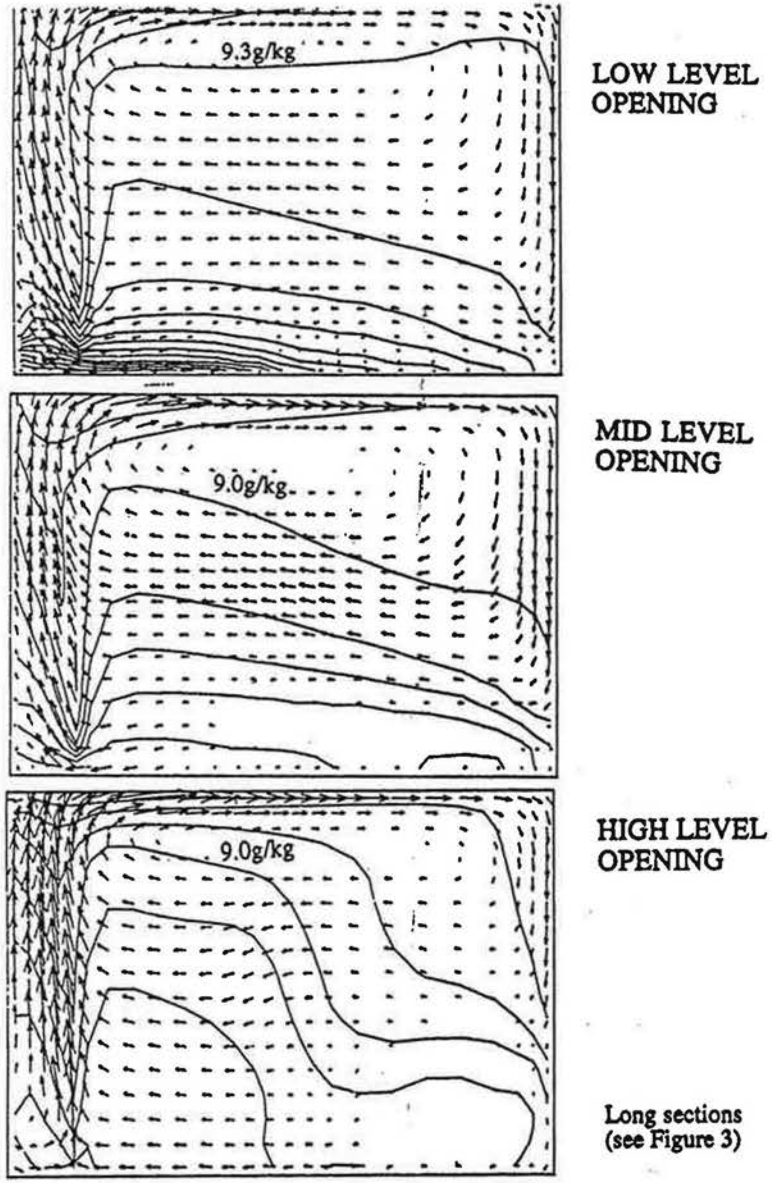
hypothesis is that the opening near the ceiling would be more effective in removing moisture as air would be extracted at the higher concentration levels of the rising humid air due to buoyancy forces.

Two heat input cases have been simulated to examine the effect of temperature driven air movement within the enclosure. The assumption is that the low heat input case by creating less air movement in the room will produce higher concentration levels in the room and less mixing, thus creating bigger differences in the moisture distribution within the space.

Water vapour production period

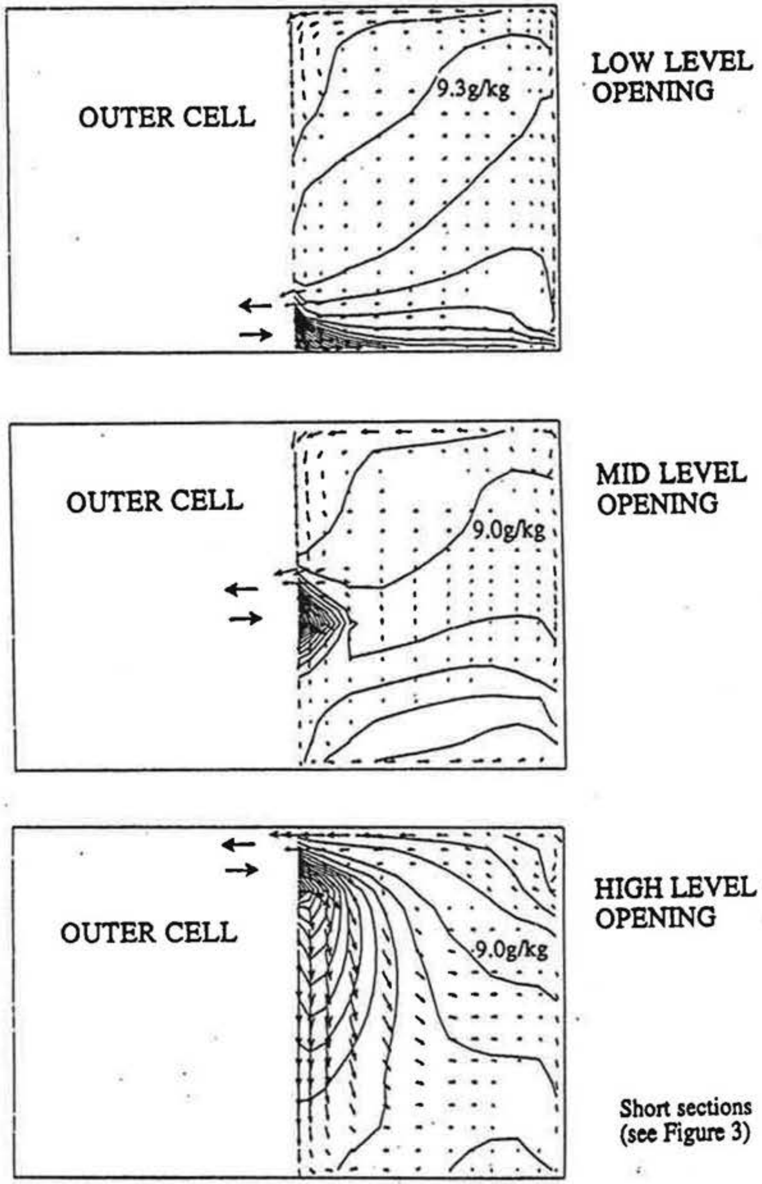
The simulation results at the end of the water vapour production period for two sections of the inner room are presented in Fig 5, where the air flow vectors and water vapour concentrations contours are marked. The long sections are through the water vapour source and the short through the opening.

Examining the long sections (Fig 5a), it can be seen that water vapour from the moisture source moves upwards due to buoyancy forces which create relatively high air flows. When the air hits the ceiling, it changes direction and moves across the ceiling surface towards the wall away from the moisture source. Upon reaching the far wall, it moves primarily downwards and secondarily to the centre of the room from where it is drawn towards the



Long sections
(see Figure 3)

Figure 5A. Moisture concentration contours and air flow vectors at the end of water vapour production period for the typical heat input case. The airflow patterns are shown in the form of arrows and the concentration contours as solid lines with a contour interval of 0.15g kg^{-1} dry air.



Short sections
(see Figure 3)

Figure 5B. Moisture concentration contours and air flow vectors at the end of water production period for the typical heat input case. The airflow patterns are shown in the form of arrows and the concentration contours as solid lines with a contour interval of 0.15g kg^{-1} dry air.

moisture source due to the temperature difference. It is also observed that in all cases there is a larger difference in moisture concentration between floor and ceiling in the middle of the room than near the walls. This is mainly due to the mixing of water vapour near the surfaces because of the higher air movement.

Examining the sections through the opening (Fig. 5b), it is obvious that the position of the opening affects to some extent the air flow and moisture distribution in the room. In all cases, there is less air movement in the lower half of the room. In the case of the low level opening a laminar flow towards the open area is created and there are larger differences of moisture concentration because of the intake of dry fresh air at this level. The concentration contours are more evenly distributed in the case of the mid level opening. In the case of the upper level opening, the concentration differences increase next to the partition wall due to the downwards direction of fresh air. Some of the fresh air is diverted to the middle of the room with the effect of larger variations in moisture at high and low level with a mixed layer in the middle of the room.

Water vapour decay period

At the end of the second time step, 90 minutes after the end of water vapour production, the concentration levels have been reduced and moisture variations throughout the zone are less marked. The moisture concentration contours for the section terminating at the opening are presented in Fig 6.

In the case of the low level opening, the moisture concentration variations appear mainly at the lower half of the room where air extraction and fresh air intake is occurring. In the mid level opening case, there is little evenly distributed concentration differences while in the high level opening case there appears a distribution difference only near the opening.

Therefore, it can be said that moisture distribution within a zone is less critical during the decay period because of the mixing of moisture due to the air movement. In particular, mid to high level extraction points (which is usually the typical arrangement in dwellings) result in very little variation apart from the area surrounding the opening.

The water vapour distribution within the zone

In order to quantify the variations of water vapour concentration within the simulated zone, the moisture distribution in the middle of the room at different heights and the distribution on three horizontal planes has been examined.

First, the simulated concentrations at 18 heights in the middle of the room have been plotted for the two time steps for each of the six examined cases (Fig. 7). As expected, the concentration levels are lower in the typical heat input case and also the difference between floor and ceiling concentrations are smaller than the low heat input case. Although the highest opening has reduced the concentrations most at the moisture production time, the mid level opening appears to be more effective during the decay time. This is most likely because the more humid air of the upper half of the room is able to escape more easily (without further mixing) from the upper part of the opening, while the fresh air is directed downwards without mixing with the humid upper layer.

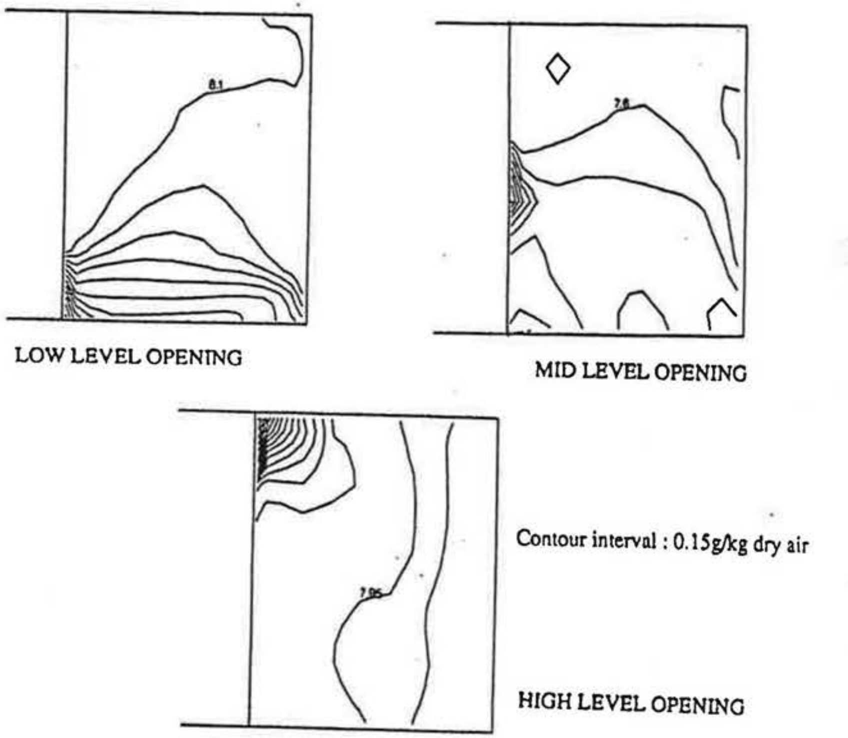


Figure 6. Moisture concentration contours during the water vapour decay period for the typical heat input case. (See Figure 3 for the location of the sections).

The concentration differences between floor and ceiling, taking as reference the concentration at mid height, are presented in Table 2. It can be seen that as expected, differences are higher during the water vapour production period and higher at the low heat input case because of less mixing due to the lower air movement. The higher the opening is located, the more the concentration differences are reduced during the decay period.

Apart from the vertical distribution, there is a significant horizontal distribution also affected by the height of the opening and heat input (ie created air movement). In order to quantify these differences, the ratio of water vapour concentrations at a large number of grid points at three

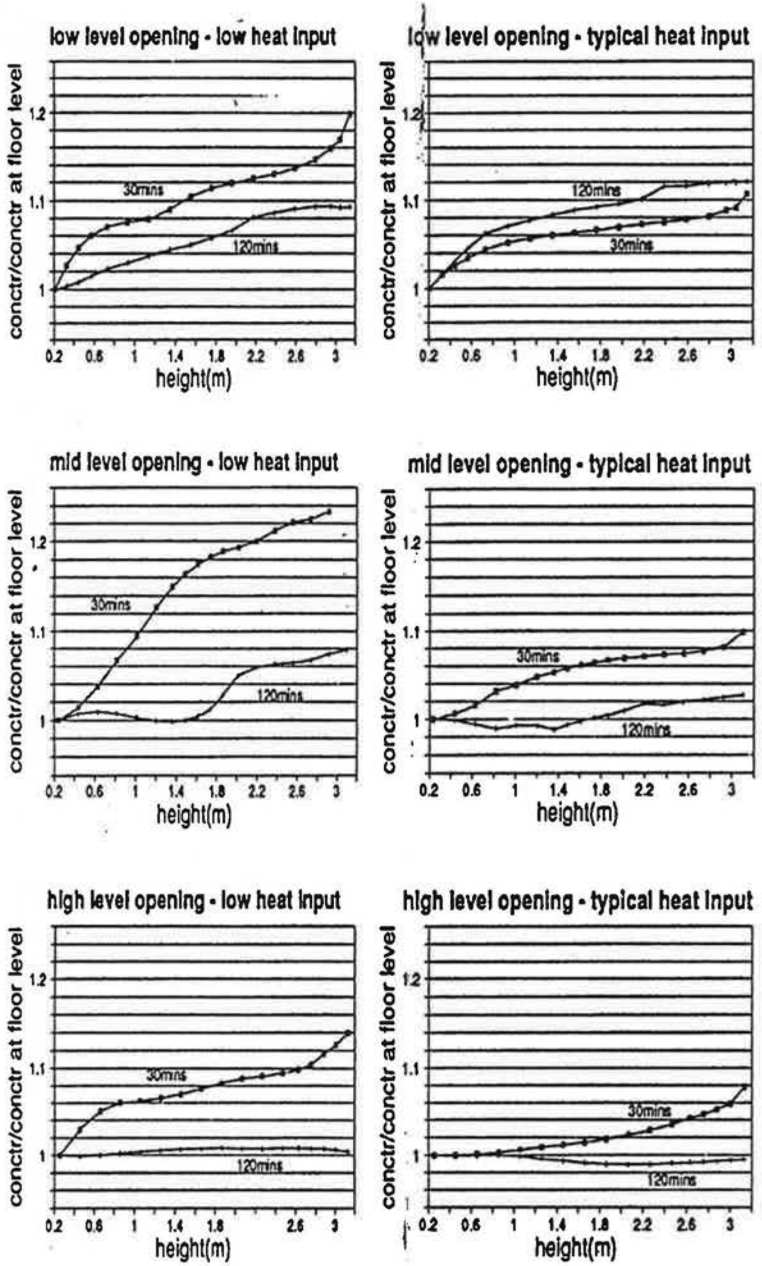


Figure 7. Water vapour concentration at 18 heights in the middle of the zone for two heat input regimes.

horizontal planes to the concentration at the central point of the plane, were plotted against the distance of each grid point from the central point. Some examples of the graphs are shown in Figure 8 and the computation is summarised in Table 3. It can be seen that there are differences up to 20% from the central point especially at the level of the openings during the water production period. These variations are higher than the vertical variations between floor and ceiling. It should be noted that the immediate area around the moisture source has been excluded from the graphs.

Similarly, larger horizontal than vertical variations appeared during the decay period.

Therefore, horizontal distribution can be significant, and under certain circumstances greater than the vertical distribution. The amplitude of the distribution depends on the ventilation rate; the lower the ventilation rate the larger the concentration variations within the enclosure.

Table 2. Water vapour concentration differences between floor and ceiling in the middle of the space (%).

	Opening at low level		Opening at mid level		Opening at high level	
Heat input	low	typical	low	typical	low	typical
30 mins	18	10	23	9	13	8
120 mins	9	11	8	3	-	-

Table 3. Maximum water vapour concentration variations at horizontal planes (%).

	Opening at low level		Opening at mid level		Opening at high level	
Heat input	low	typical	low	typical	low	typical
at 30 mins						
at 0.20m	45	30	20	15	14	9
1.60m	15	4	20	9	17	14
3.10m	11	6	11	6	20	7
Heat input	low	typical	low	typical	low	typical
at 120 mins						
at 0.20m	30	26	15	14	8	6
1.60m	11	7	25	14	9	8
3.10m	6	4	3	3	25	10

CONCLUSIONS

In this paper the vapour distribution within a zone in steady state and transient modes has been investigated using CFD modelling. The CFD simulation results have been compared with experimental measurements in

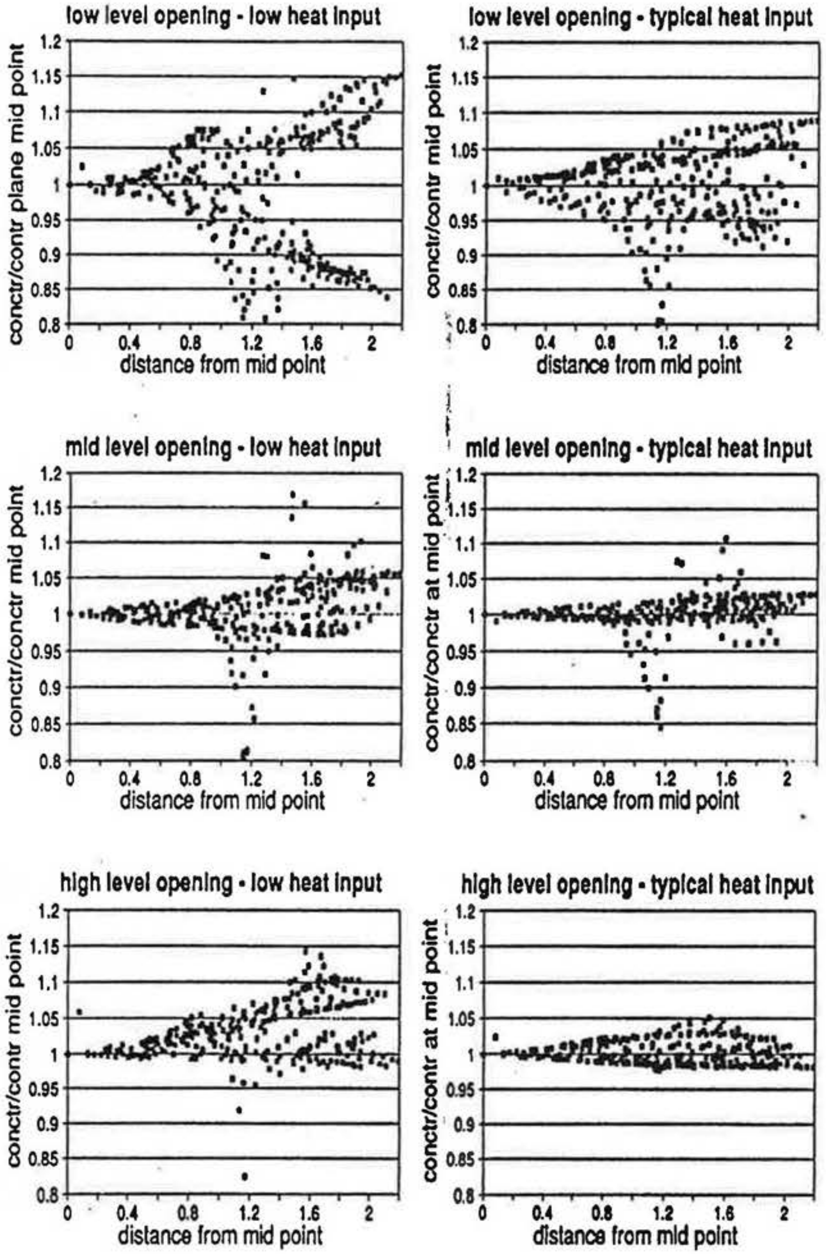


Figure 8. Examples of water vapour variation at horizontal planes.

a two zone environmental chamber and reasonable agreement was found. Measurements in the middle of the enclosure at various time steps during water vapour production and decay have been compared with CFD predictions. Both the experimental and simulations runs were defined as similarly as possible but slight ventilation rate differences and a small adsorption by the surfaces in the environmental chamber account for the small differences in the absolute humidity values. However, the time dependent curve follows the same pattern in experiment and simulation.

This comparison enhances the validity of using CFD modelling in exploring the behaviour of airborne moisture movement so that detailed predictions can be made of its effects on condensation risks due to the airborne moisture migration from one part of a zone to another and through connections (doorways, corridors and stairwells) to other parts of a dwelling. Similar studies using CFD modelling to examine the movement of contaminants in single rooms have come to similar conclusions [14,15].

The comparison of CFD modelling results in a steady state mode, with the single value prediction of theoretical simplified steady state equations, have shown that the latter although they give an estimation of condensation risk in the zone do not account for the humidity variations within the space. Therefore, they give no indication of the humidity ranges expected under given circumstances. An algorithm incorporating these water vapour distribution variations by accounting for the position of the moisture source and location of inlet and extract points will improve the applicability of steady state predictions. In addition, time should be a consideration especially in rooms with brief and relatively high moisture production such as kitchens and bathrooms in domestic buildings.

In the present work, the time dependent vertical and horizontal distribution of water vapour concentration associated with low ventilation rates has been examined for three heights of an opening. It was found that the vertical and horizontal distribution within a zone are of the same magnitude and in some cases horizontal differences can be greater. Absolute differences depend on the ventilation rate of the room. Higher ventilation rates reduce the variations because of the moisture mixing they create.

However, in many domestic applications the ventilation rates can be very low, especially during the heating season when condensation and mould growth usually occur. The prediction of the variations in the water vapour pressure distribution within a zone will enable us to identify parts of the dwelling most at risk from condensation.

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SPATIAL FACTORS AS VARIABLES IN INDOOR ENVIRONMENT INVESTIGATIONS

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ABSTRACT

While traditional building lore has often emphasized optimal spatial relationships for built environments, such information is scarce for modern building types. The assumption that spatial factors are no longer of much importance may not be valid. Rather, spatial influences may have been overlooked due to a research emphasis on technological and human factors, an emphasis often needed for dealing with specific or immediate problems. This paper proposes ways of improving the use of spatial information in investigations. Suggestions have been made for making more precise spatial descriptions and for using spatial factors as variables. Examples of a variety of present uses of spatial information have been outlined. The range of potential uses have been summarized according to five different purposes, all of them related to estimating or improving quality of the built environment.

INTRODUCTION

In many parts of the world, traditional building lore has been based on optimizing spatial qualities of buildings and their sites. Planning guidelines have often included preferred sizes and shapes for buildings, and also the relationship of enclosures to each other, to streets, topography or to compass directions. Yet in the presently evolving guidelines for modern healthy buildings, much attention has been given to the more tangible elements such as materials, services and equipment, and comparatively little to spatial qualities. It would seem that the research emphasis of recent decades has been on designing and refining the apparatus, not the container.

From the architect's point of view, soundly based information on shapes and forms for healthy built environments is scarce compared with that available for choice of systems and materials. Advice handbooks may be based on the one hand, on accumulated experience from problem building investigations, or on the other, on intuitive, inspirational approaches to healthy building practice [1]. Because the former approach emphasises equipment and occupants rather than design, it may seem that decisions related to building form are a matter of preferences and beliefs rather than

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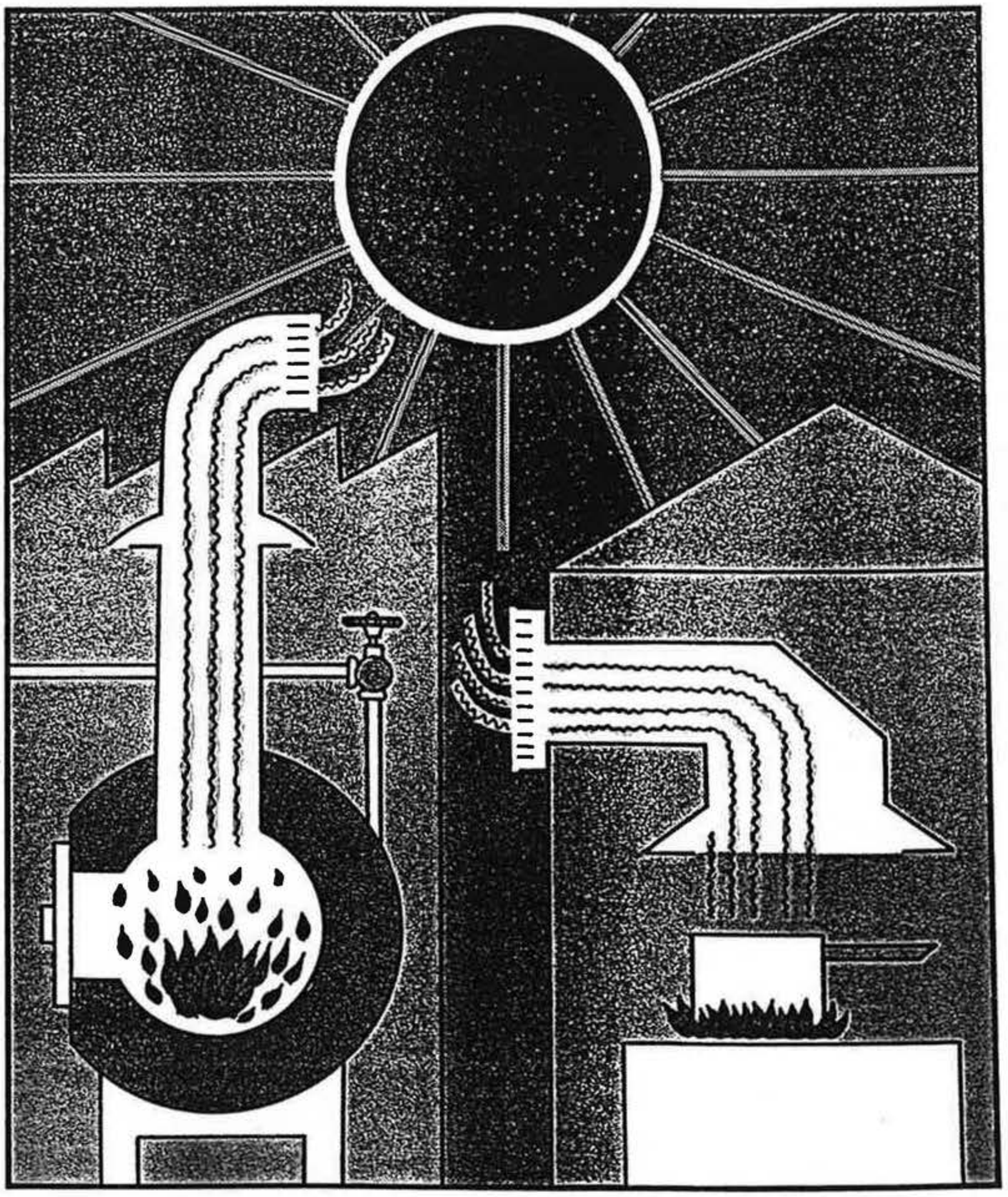

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