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THE EFFICIENCY OF VENTILATION IN A DETATCHED HOUSE

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1. Synopsis

The SEGAS "Autovent" constant concentration apparatus was used to measure the fresh air entering and the local ventilation rate in each cell of a multi-celled dwelling with both natural and mechanical extract ventilation.

Two measurements were made. The fresh air entry into each cell was measured using constant concentration techniques and then the uniform tracer gas concentration was exploited to perform a decay test. The decay tests were conducted without artificial mixing and were interpreted by computing the area under the decay curve to yield a measure of the local ventilation rate. Comparison of the two measurements gives the ventilation efficiency of each cell and an idea of air quality in each room of the house.

Further insight into the pathways of air movement around the house was gained by injecting an amount of tracer gas into one room and following the transfer to all other rooms of the house. Results of these experiments are reported.

2. Introduction

The quality of air inside dwellings is a topic of growing interest. The building industry and the general public are both becoming aware of the need to ensure that excessive ventilation rates (and consequent ventilation heat loss in winter) do not occur. As a result more houses have draught excluding measures applied to them and new houses are built with greater attention to the details of jointing between building components. These changes are leading to lower overall ventilation rates in houses and possible higher exposures to the normal domestic contaminants. The need to understand in detail the pattern of air movement within a house and the consequences of this movement in diluting or removing a contaminant is becoming more important.

It is not sufficient just to know what the overall ventilation rate is, it is now necessary to address the question of local ventilation rates at different points within a house.

This paper concerns itself principally with the methodology for measuring the efficiency of ventilation in a dwelling. In this case a detached, 2 storey, brick built house.

The experiments described here were made possible by the flexibility of the Autovent apparatus, designed initially for continuous monitoring of room ventilation rates, but easily adapted to different operating configurations.

3. Experimental Measurements

3.1. Autovent System and Its Different Configurations

The apparatus[1,2] consists of twelve sampling and twelve injection solenoid valves. Each valve is operated independently by command from a Zilog MCZ/125 microcomputer which controls the operation of the rig. From each valve a 6mm O.D. nylon gas sampling or injection line runs to each room of the house. The injection valves are two-way solenoid valves connected to a gas manifold in which Nitrous Oxide tracer gas is held at 10 p.s.i.g. pressure. Between each solenoid valve and the injection line to the room is a fine metering valve which is used to adjust the flow in each individual line. Flow rates are measured in-situ with a bubble flow meter.

The sampling valves are 3-way with the normally open port connected to a purge pump. The normally closed ports are connected through a 12-way junction to a Leybold Herraeus Binos 1 analyser. Only one sampling valve is open at any time.

The computer controller allows a very flexible pattern of usage. The basic operating schedule is to produce a constant concentration of gas in all rooms of the house, but, since the apparatus is really only an assembly of controllable solenoid valves it can be used for other experiments. Three modes of operation are described and used in this paper, constant concentration, constant concentration followed by decay, and injection at a point followed by decay. We have also written programmes to perform constant emission experiments and step-wise injection experiments.

In the constant concentration mode the operating sequence is as follows. Each room is sampled in sequence for 8 seconds. At the end of the sampling period the computer reads the analyser and calculates the necessary injection period for that room. The injection valve is opened and the next sampling valve is selected and so on in a continuous loop. at the end of each 30 minute period the computer produces a summary of the fresh air entering every room and adds these to provide a whole house ventilation rate.

Averaged values of wind speed and direction and ambient temperature are also printed.

Constant concentration with decay is identical to constant concentration until, at the pressing of a key, the decay mode is entered. In this mode the computer samples each room 3 in sequence for 8 seconds and records and accumulates the values of gas concentrations in each room. All injection valves are closed. The decay process is allowed to continue until, at the pressing of another key, the computer produces a summary of the accumulated area under the decay curve for each room.

The averaged wind speed and direction and ambient temperature are recorded every 30 minutes.

The facility to switch from constant concentration mode to decay mode in less than 15 seconds is a great advantage and ensures that a uniform concentration of gas is present at the initiation of the decay. Uniform concentration is very hard to achieve by other means.

Injection at a point followed by decay is very similar to the previously described mode of operation. One room is selectively injected with gas until a target is reached. at this point the decay of gas in the source room and the build up and subsequent decay of gas in all other rooms is monitored by successive 8 second samplings from each room. The areas under each gas concentration curve are calculated at the termination of the experiment.

3.2. The Test House

All experiments were undertaken in a 2-storey, brick-built detached test house. The house details are shown in Figure 1 (p 4.). There are 3 rooms and an entrance hall on the ground floor and 4 bedrooms, a bathroom, a toilet and a landing on the upper floor. The total volume of the house is $240m^3$. It is equipped with a mechanical extract ventilation system with registers in the kitchen, the bathroom and the toilet and a wet central heating system with radiators in all rooms.

The house had been extensively modified to reduce its leakage area. The suspended wooden floor had been taped over at ground and first floor levels, cracks around fittings and around skirting boards had been sealed as had those in the ceiling and walls. Service pipes penetrating the outer leaf were sealed around and all external doors and windows were weatherstripped with compressible foam strips. The leakage flow rate of the house was found to be 0.46 m^3/s at 50 Pa. This corresponds to about 7 air changes per hour.

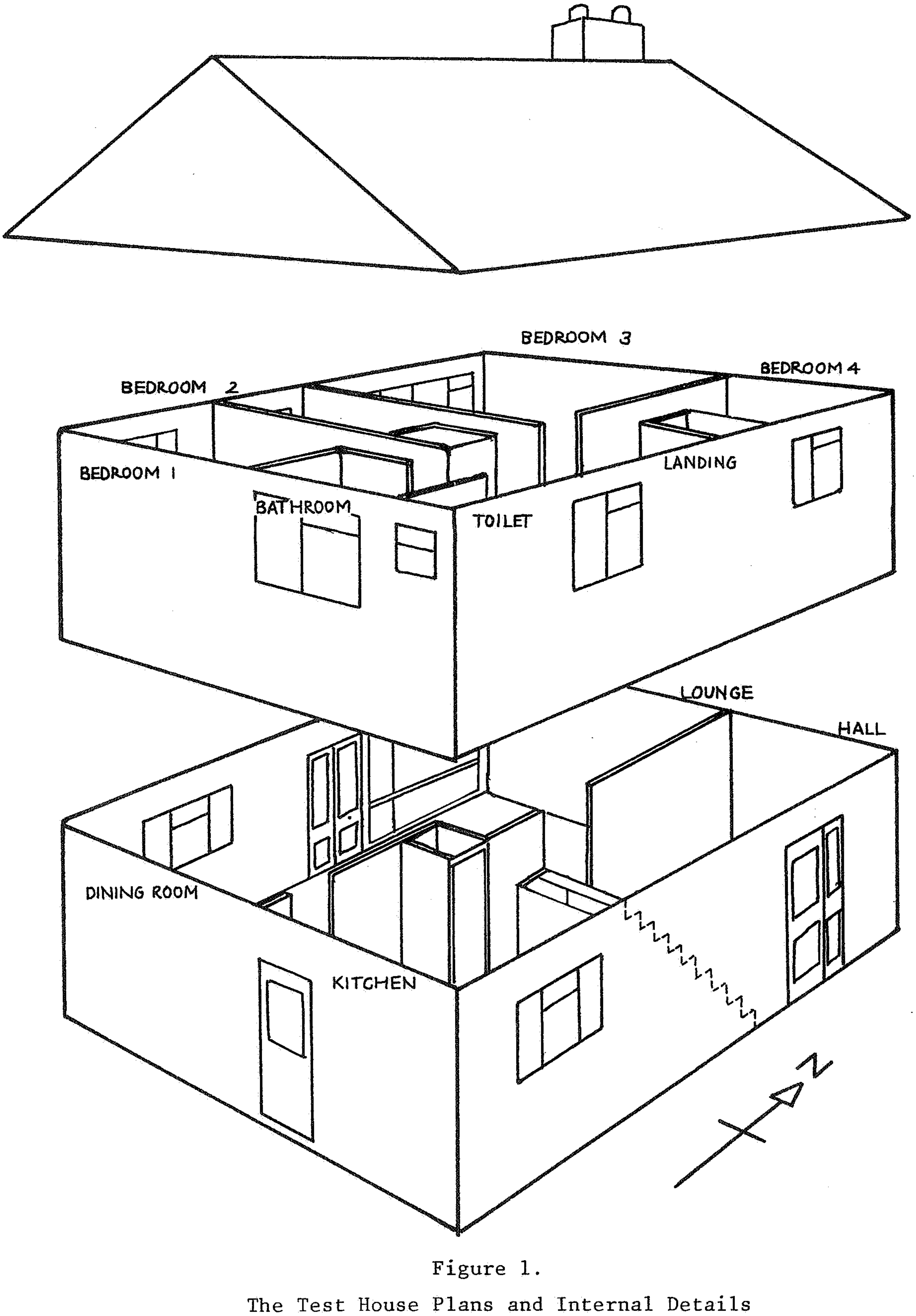

Figure 1.
The Test House Plans and Internal Details

3.3. Experimental Details

Experiments were carried out with and without heating as detailed below. All constant concentration measurements were carried out with mixing fans, all decay experiments were performed without mixing. All samples were drawn from the cenres of the rooms.

In all experiments the internal doors were left open to encourage mixing between rooms. The only exceptions to this were the injection at a point followed by decay. For these tests the door of the source room was kept closed during the initial dosing and opened subsequently. All other internal doors were open.

The experiments undertaken are tabulated below:-

Operating Mode	Ventilation System	Heating System
1. Constant Concentration	Natural	Off
2. Constant Concentration + Decay	Natural	Off
3. Constant Concentration + Decay	Natural	On
4. Constant Concentration + Decay	Mechanical extract	Off
5. Injection in Kitchen	Natural	On
6. Injection in Kitchen	Natural	Off
7. Injection in Bedroom 3	Natural	On
8. Injection in Bedroom 3	Natural	Off

4. Theoretical Background

There are several points to note in interpreting these experimental results. Firstly, it is assumed that conditions remain constant throughout a decay run and are equivalent to those occurring during the preceding constant concentration run. This is of course extremely unlikely. Ambient weather conditions can change very rapidly and quite markedly during a slow decay process.

Secondly, it must be stressed that the decay results cannot be, interpreted to yield room ventilation rates. They provide an insight into the relative ventilation efficiency of each room and an indication of the exposure to an airborne contaminant. The constant concentration followed by decay results relate to an homogeneous pollution source and the injection at a point followed by decay relates to a point pollution source and the movement of the pollutant around the house.

Sandberg [3] has given a full account of the theory of ventilation efficiency. He has shown that, at an arbitrary point, there is a direct relationship between the integrated exposure to a short burst of released contaminant and the steady state concentration attained, at the same arbitrary point, by continuous release of contaminant.

This relationship between transient and steady state phenomena is expressed as;

$$\frac{M}{A} = \frac{\dot{M}}{C^s} \qquad \text{or} \qquad C^s = \frac{\dot{M}A}{M}$$

where, A = Integrated Exposure, the area under the concentration versus time curve following a short contaminant emission.

C^s = Stationary concentration attained by continuous contaminant emission.

$\dot{M}$ = The rate of contaminant emission

M = The amount of contaminant emitted in the short burst.

If we know the integrated exposure we also know the stationary concentration and vice versa.

This relationship offers us a method of obtaining data about steady state conditions from measurements of the response to a short term event. It also gives us the basis of a method of measurement which is described later.

The integrated exposure A obtained when the whole house is filled to a uniform intial concentration, C(o) and then allowed to decay has an important physical interpretation.

A local ventilation rate, r, is determined by

$$r = \frac{C(o)}{A} \qquad [1/h]$$

In the special case of instantaneous and complete mixing then the local ventilation rate is equal to the overall ventilation rate. This is defined as the total volume of outdoor air entering the space divided by its total volume. The larger the local ventilation rate the better the ventilation efficiency.

5. Calculation of Results

The experimental measurements were processed in slightly different ways depending on the particular experiment.

Constant concentration results are presented on the computer screen in the form of volumes of air entering each space per hour and so require no further processing.

Constant concentration followed by decay results were calculated in part by the computer which presented values of the area under the decay curve. There remained then an additional truncation error which arose from the fact that the N_2O concentration was never allowed to decay to zero. This extra term was small and was calculated by simple triangulation. The total area under the decay curve, was then divided by the initial room concentration to yield a local ventilation rate. The final slope of the decay curves (the overall ventilation rate) was compared to the whole house ventilation rate calculated from constant concentration techniques with generally very close agreement. Results appear in table I (p 8.).

The analysis of the experiments involving injection at a point again involved the computation of the area under the decay curve for each room and the estimation of an additional truncation error. These two terms gave the integrated exposure to the pollutant in each room. The crude figures were then normalised by dividing by the product of the initial gas concentration and the volume of the source room. In other words the integrated exposure was divided by the amount of pollutant released, so that the results of each experimental run could be compared directly.

In the subsequent sections we discuss each of the results, extend the interpretation and draw conclusions about the movement of air around this 2-storey house. An earlier paper in this section presented results from laboratory experiments on a 2-roomed test structure and many of the conclusions apply to this real house.

6. Discussion of Results

6.1. Constant Concentration Technique - Natural Ventilation

The results for an overnight run are depicted in Figure 2 (p 10). The constant concentration technique tells us where fresh air enters a house as a result of the wind and stack effects. Figure 2 (p 10) shows a low overall fresh air entry and quite a strong dependence on ambient conditions. Roughly speaking, the individual room ventilation rates follow the same pattern as the whole house rates, although their precise dependance or the ambient conditions is not immediately explicable.

6.2. Constant Concentration Technique - Mechanical Extract Ventilation

Figure 3 (p 11) shows an overnight run with the mechanical extract operating at approximately 0.5 ach. The first thing to notice is that the overall ventilation rate is reasonably constant but there are some wide variations in individual rooms. The extraction points are the kitchen, the bathroom and the toilet. The bathroom and kitchen seem to have widely varying fresh air entries whereas the other rooms remain constant. This may have been due to the relatively large leakage areas associated with these two rooms and their positions in the house.

6.3. Constant Concentration Followed by Undisturbed Decay

This technique was used to examine the pattern of air movement around the house under natural ventilation with and without heating and with mechanical extract ventilation.

The results are presented in Table 1 (p 8.)and discussed below. In these circumstances the final slope of the decay curve is equivalent to the overall ventilation rate.

TABLE 1. CONSTANT CONCENTRATION FOLLOWED BY DECAY
LOCAL VENTILATION RATES (h^{-1})

VENTILATION SYSTEM	NATURAL	NATURAL	MECHANICAL EXTRACT
HEATING	OFF	ON	ON
Kitchen	0.052	0.22	0.45 *
Dining Room	0.051	0.21	0.39
Lounge	0.052	0.21	0.39
Hall	0.053	0.21	0.43
Landing	0.048	0.20	0.45
Bedroom 1	0.047	0.20	0.49
Bedroom 2	0.047	0.20	0.44
Bedroom 3	0.047	0.19	0.42
Bedroom 4	0.048	0.18	0.41
Toilet	0.048	0.17	0.46 *
Bath	0.048	0.14	0.46 *
Final slope, h^{-1}	0.043	0.2	0.43
Constant concentration whole house rate, h^{-1}	0.041	0.3	0.41

* Extraction points

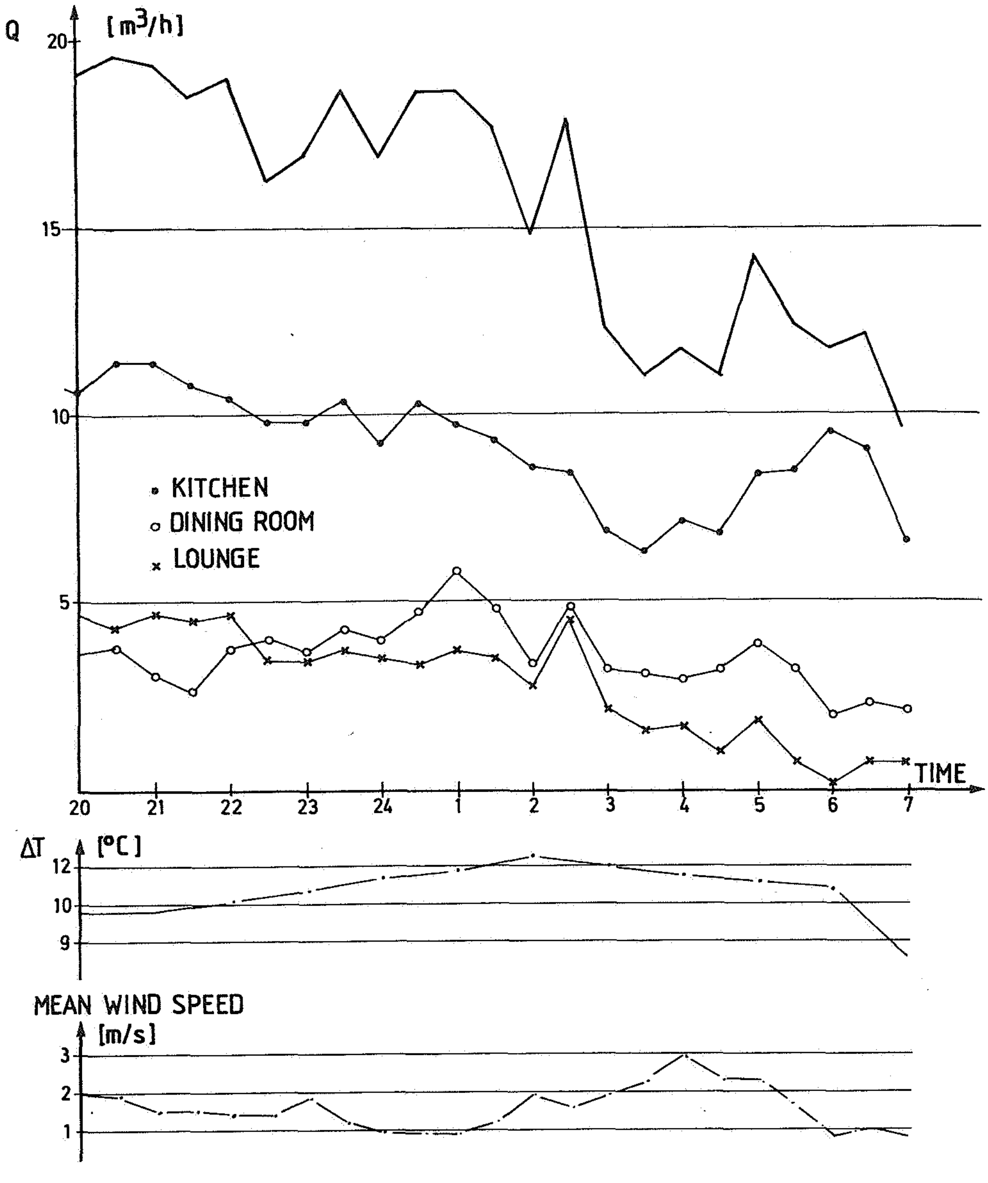

Figure 2.

Natural Ventilation Results for an overnight run showing the total air flow into the house (solid line) and the flows to individual rooms.

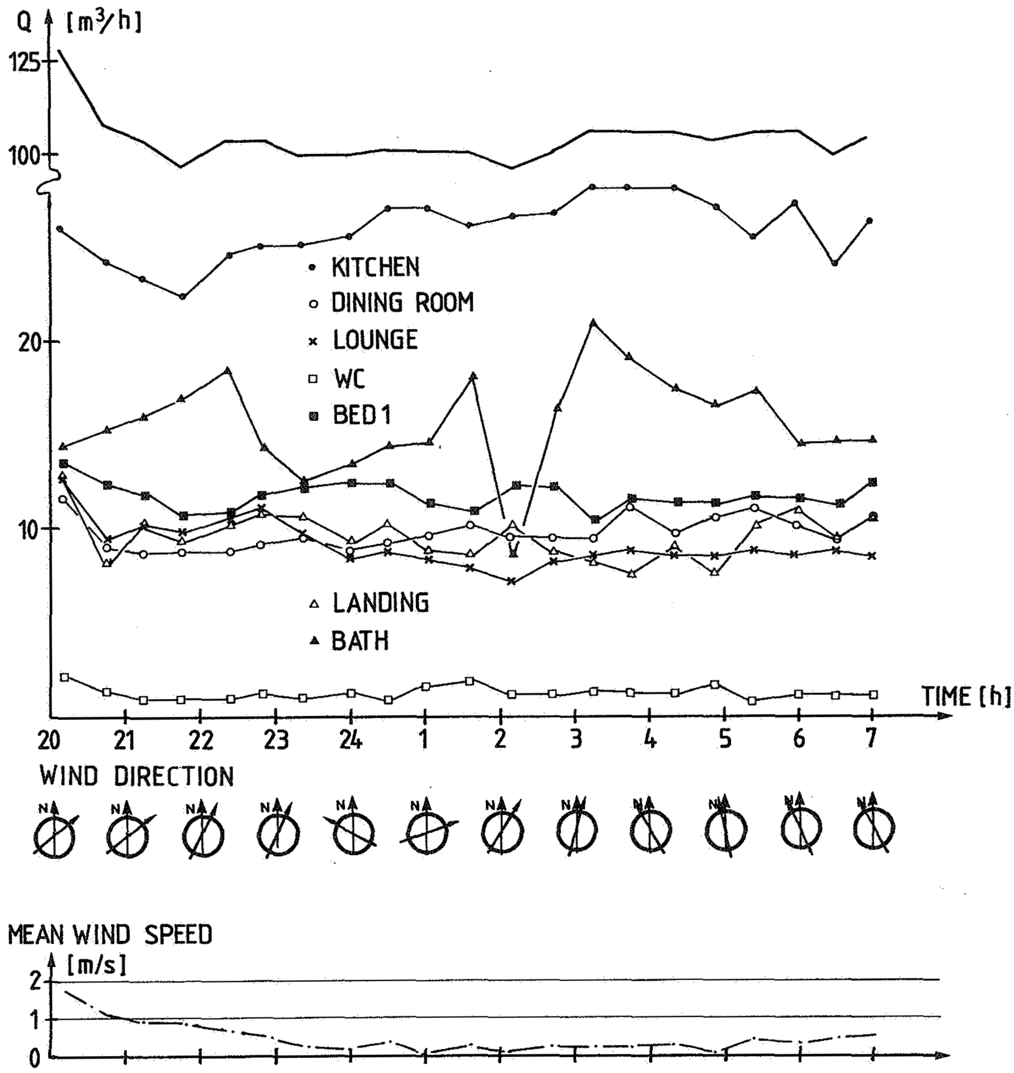

Figure 3.

Mechanical extract ventilation results for an overnight run showing the total air flow into the house (solid line) and the flows to individual rooms.

6.3.1 Natural Ventilation - No Heating

The measured ventilation efficiency is typical of that found for a low fresh air flow rate, that is, a very even ventilation efficiency implying even-mixing[3].

In these circumstance the final slope of the decay curve is equivalent to the ventilation rate.

The obseved value of the slope of the decay curve was -0.048. This implied a flow rate of 11.5 m^3/hr into the house (volume 240m^3). This result agrees well with the constant concentration results, Figure 2 (p 10).

6.3.2 Natural Ventilation - With Heating

The ventilation efficiency for this condition is higher than the previous case, Table 1 (p 8). The efficiency is almost constant again implying an even mixing through the house. The low efficiencies for the toilet and bathroom may be because these rooms were on the leeward side of the house and on the upper floor and so were subjected to a dominant flow direction from the house. The average wind speed during the decay was about 1.5 m/s and the final slope of the decay curve was -0.2. The constant concentration result immediately prior to the decay was 0.3 ach with a 2.5 m/s wind. Again, the agreement is reasonable and encouraging.

6.3.3 Mechanical Extract Ventilation - No Heating

A higher ventilation efficiency than the previous 2 results, an even distribution typical of a mechanical extract system, and the final slope, -0.433, agreed well with a constant concentration determination, Table 1 (p 8).

The rooms extracted from had the highest ventilation efficiencies. This is as expected and as found for the 2-roomed test structure.

6.4. Discussion

The two techniques so far discussed allow us to know where the fresh air gets into a house and how well that fresh air is subsequently distributed. The fresh air entry points are widely distributed since fresh air enters all rooms of the house, although not all results are depicted in figures 2 & 3 and in general, the mixing within the house is complete, although slowly achieved in some instances. An alternative interpretation of the eveness of the ventilation efficiency throughout the house is that exposure to an homogeneous pollutant would be even. The next section discusses the effect of introducing a pollutant into one room of the house.

6.5. Injection at a Point Followed by Decay

Results are presented in Table 2 (p 14) for 4 house conditions, injection into the Kitchen with and without heating and injection into Bedroom 3 with and without heating.

There are several things noticeable. Firstly the integrated exposures without heating are greater than those with, reflecting the higher ventilation rates in the latter case. Secondly, the source room always has the highest integrated exposure, not surprisingly. Thirdly, the results without heating show a greater differential exposure between floors than those with heating. The results with heating have almost equal integrated exposures outside the source room. This implies an efficient mixing of the air within the house. Fourthly, results without heating show that within a particular floor the mixing is more efficient than between floors. The heating system is designed to provide differential temperatures between living and sleeping rooms and this mechanism aids the mixing between floors.

6.5.1 Interpretation of Results

These integrated exposures can be used to predict the stationery concentration of any point pollutant source, in any room and can be used to highlight differences in exposure in different parts of the house, in a given set of weather conditions.

TABLE 2 INJECTION AT A POINT FOLLOWED BY DECAY

SOURCE ROOM HEATING	KITCHEN OFF	KITCHEN ON	BEDROOM 3 OFF	BEDROOM 3 ON
Kitchen	47.8	33.6	23.1	32
Dining Room	38.1	24.7	20.9	31.8
Lounge	38.9	24.3	19.6	36.8
Hall	44.2	25	20.4	35.8
Landing	24	23.9	35.1	40.4
Bedroom 1	23.4	23.4	40.5	35.6
Bedroom 2	23.2	23.6	40.2	35.8
Bedroom 3	23	22.6	48.1	40.8
Bedroom 4	23.8	24.1	40.9	40.4
Toilet	23.7	23.8	41.4	38.5
Bathroom	23.7	22.7	37.9	36.1
Wind speed ms^{-1}	2.0	3	1.0	2.5-3.6
Wind direction	SW-WSW	NNE	E-SE	NNW

All entries are in units of $m^3h/10^3$ at 20°C unless otherwise indicated.

Figures 4 - 9 (pp 16 - 21) show the actual tracer gas concentration in various rooms plotted against time. Figures 4,5,6 (pp 16 - 18) present the results for injection in the kitchen without and with heating. There are interesting differences between the two cases. Without heating, it takes 5 hours for the bedroom concentrations to reach their peaks, about 10 ppm. With heating, the bedroom peaks, of 18 ppm, are reached in 1.5 hours. This illustrates the movement of air between floors promoted by the differential heating of the ground and first floors and by the stack effect.

Figures 7,8,9 (pp 19 - 21) show the effect of injection into Bedroom 3 without and with heating. Without heating, it takes nearly 4 hours for the ground floor rooms to reach their peak concentrations. With heating, the peaks are reached after about 1.5 hours.

The complexity of the graphs illustrates the importance of this method of interpretation in unravelling the complex phenomena interacting.

7. Conclusions

By using the area beneath the plot of concentration against time it has been possible to draw several conclusions regarding behaviour of hypothetical homogeneous and point pollution sources within the house. We have shown that, with internal doors open, the mixing within a floor is generally very good. The mixing between floors is better when the house is heated than when not heated. These conclusions are only strictly valid under the weather conditions encountered.

The Autovent system has been shown to be very versatile and adaptable to several different experimental configurations. The experimental approaches towards the problem of measuring the quality of internal house air have proved successful and we hope that others will be encouraged to develop them further.

8. Acknowledgements

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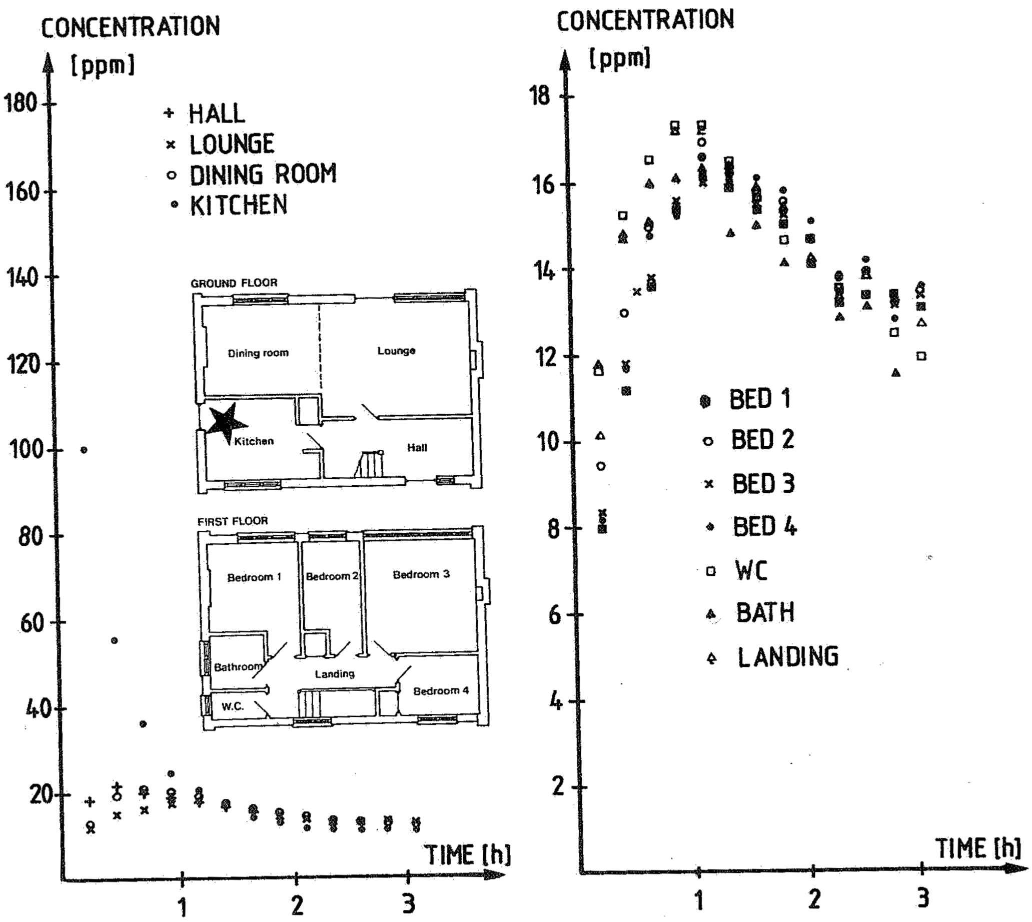

Figure 6.

Injection in the Kitchen, House Heated.
Results for Ground Floor Rooms

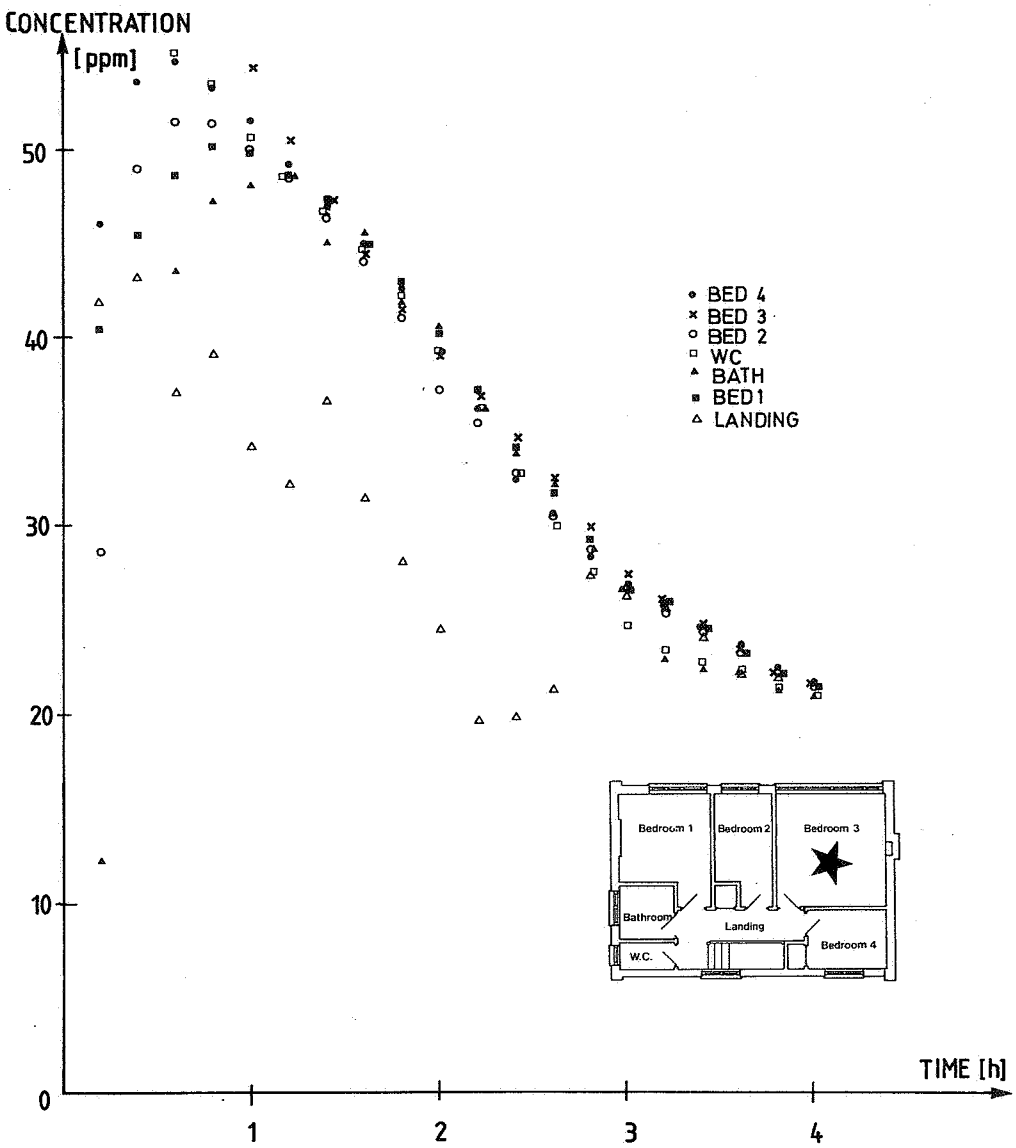

Figure 7.

Injection in Bedroom 3, House Heated
Results for First Floor Rooms

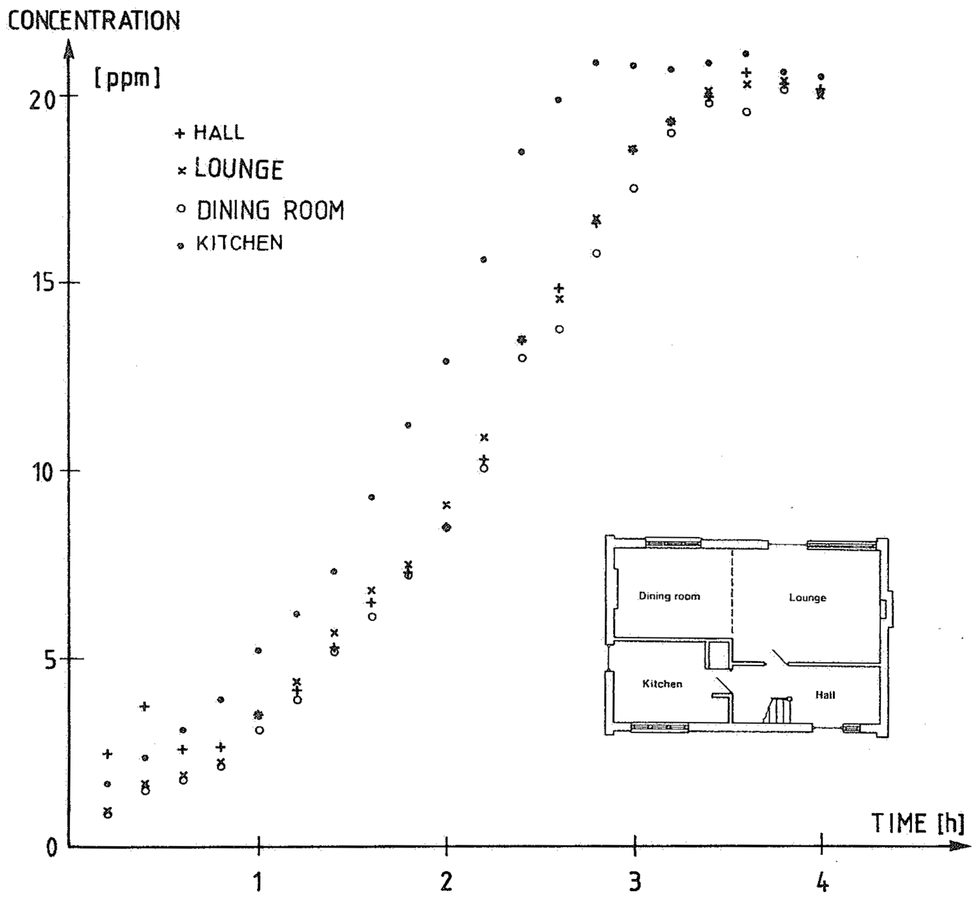

Figure 8.

Injection in Bedroom 3, House Unheated
Plot of concentration against time for Ground Floor Rooms

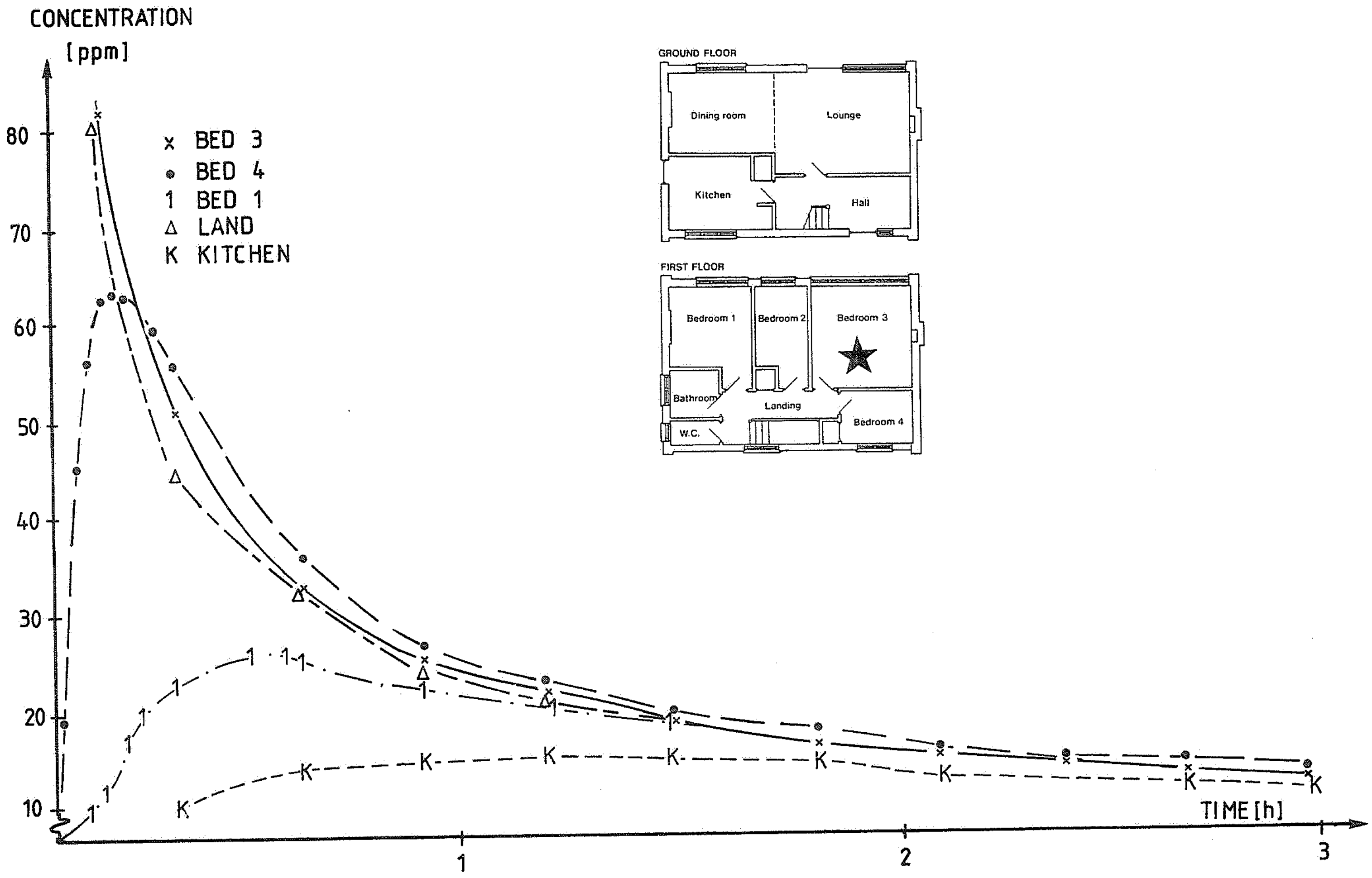

Figure 9. Injection in Bedroom 3, House Heated.
Plots of concentration against time for selected ground and First Floor Rooms

9. <u>References</u>

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