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Introduction

Calculating the concentration levels of pollutants in occupied spaces has many applications. One is the estimation of the dose caused by pollutant sources located inside or outside the building. The location of the air inlets and outlets in the building can also been chosen in the best possible way by concentration calculation. Further, the connection between the airtightness of the building and the indoor air quality can in certain situations be evaluated in this way.

The methods used today for estimating the concentration levels in a building are quite rough. The calculation is usually based on the multi-chamber theory and some model for evaluating the air flow rates between adjacent rooms. Simple procedures for calculating the flows through an open doorway are needed because the numerical methods are far too complex and time consuming for this purpose. The flow through vertical and horizontal openings has been lately studied quite intensively (1,2,3,4) and several improvements have been developed. The international ANNEX 20 project also contains a task called "New algorithms" studying among other things, the flow through large openings.

The problems in these very simple approaches mainly arise in the calculation of flow rates between the zones. Not only the temperature difference and the dimensions of the doorway affect the flows. The real flow pattern inside a room is an extremely complicated phenomenon and often has a strong influence on the flows between adjacent rooms. The air flows transport heat from one room to an other and affect the mean temperature and the vertical temperature gradient in the rooms. The temperature difference between the rooms and further the temperature gradient have, on the other hand, an influence on the flows, and so on.

Three models are in fact needed to master the whole problem: the first to calculate the thermal behaviour of the building, the second to calculate the air infiltration, exfiltration and ventilation air flows, and the third to calculate the internal circulating flows and pollutant transport. These three models must be connected to each other in a suitable way and the calculation requires several iterations between the models. So far nobody has reported any experience using such a combination. This is, however, only a question of time, because all the necessary knowledge already exists.

The aim of this study was to determine, to what extent it is possible, using simple calculation algorithms, to estimate the concentration histories in a real dwelling when different kinds of disturbances affect the air flows in the system. The methods used here have proved fairly reliable in laboratory conditions (5). In situ conditions are, however, changing all the time and are much more difficult to handle.

Measurement arrangements

The environment of the measurements was a dwelling in a semi-detached house, Fig. 1., on the south coast of Finland. The dwelling contained two bedrooms, a hall, a living room, a dining room and a kitchen. Further there was a WC, a bathroom and a sauna. The total area was 79 m^2 and the total volume 198 m^3. The space heating was provided by electric radiators located under the windows in each room. The ventilation system was a mechanical exhaust system with fans in the kitchen and the bathroom.

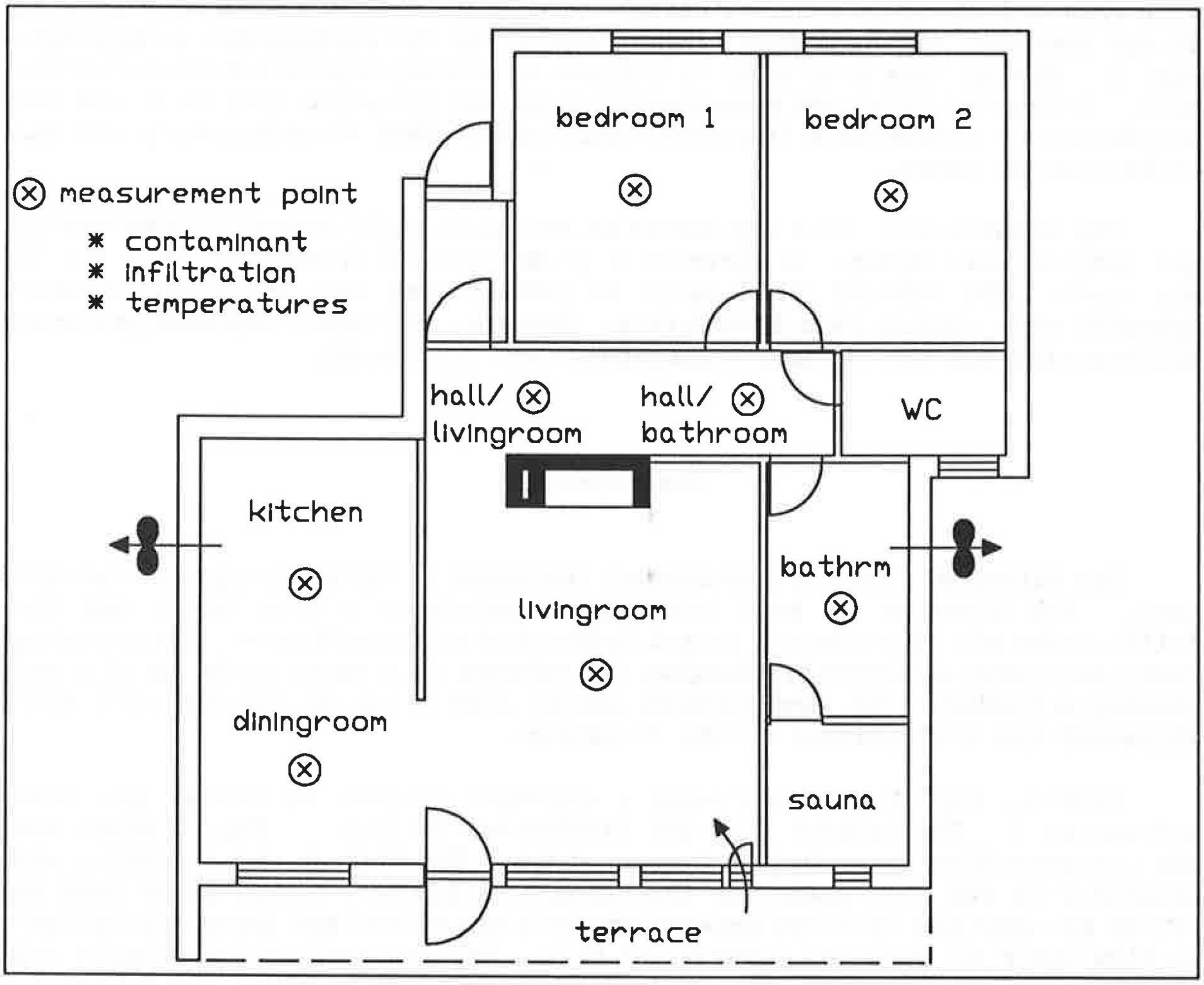

Fig. 1. Layout of the dwelling and the sampling points.

All the doors were wide open during the measurements except the door between the hall and the bathroom and the door between the hall and the WC, which were closed, having only a narrow opening down by the threshold. The air change rate at 50 Pa was measured to be about 3 ach. The pressure differential over the building envelope was 6...8 Pa and the outdoor temperature was approximately +2 ^{o}C during the whole measurement period. The measurements were carried out during March 1989.

The contaminant transport was simulated by using CCl_2F_2 as the tracer gas. A constant release of tracer gas was injected through a rotameter into the plume of the radiator in bedroom no 1. The concentrations were measured using an IR-analyser. Eight sampling points in the middle of each room at a height of 1.5 m were used, Fig. 1. A slightly unhomogeneous concentration distribution was observed in the room where the injection took place. The plume raised the tracer towards the ceiling and caused a higher concentration in the upper part of the room. This was, however, a better alternative to letting the tracer sink to the floor because of its high density. The concentration distributions in the other rooms were satisfactorily uniform.

The constant concentration method was used to measure the infiltration flow rates. The SF_6 target concentration was 80 ppb and the concentrations were measured with a gas chromatograph. The eight sample points were located in the same way, in the middle of the room, as in the contaminant simulation, Fig. 1. Mixing fans were used to achieve a uniform concentration distribution. Because of this, the measurement of the infiltration flow rates and the simulation of contaminant transport could not be done simultaneously and had to be done in turns.

The temperatures were monitored at the same eight points as the tracer gas samples were taken. A thermistor probe with an inaccuracy of ± 0.1 ^{o}C was used. The exhaust flow rates in the kitchen and the bathroom were measured with orifice type flow meters. Further, the indoor/outdoor pressure differential and the outdoor temperature were monitored.

Measurements

Two different cases of contaminant transport in the dwelling are reported here. The duration of both cases was approximately nine hours and the infiltration air flows were measured before and after each case. The unsteady conditions were achieved by changing the exhaust flow rates or by opening and closing a window. The temperatures inside also crept up and down and thus increased the unsteadiness of the situation.

CASE 1, Fig. 2, started with a constant release of tracer gas into bedroom no 1. The exhaust from the kitchen was 40 l/s. Fig. 2 shows how the concentrations grew in the step-up stage. The highest concentration was naturally in the room where the injection took place. On the other hand no tracer got into the bathroom because the door was closed and the unidirectional flow under the door was towards the hall. The temperature differences and the net air flows drove the tracer into the other rooms. After six hours the exhaust was changed to the bathroom using the same flow rate as before. The concentration in the bathroom increased very fast as the direction of the flow changed. A slight change in the other concentrations could also be noticed. The measured mean temperatures and infiltration air flows are presented in Table 1.

Table 1. The measured mean temperatures [^{o}C] and mean infiltration air flows [l/s] during the observation periods.

CASE 1 **Exhaust from the kitchen 40 l/s**

	bedr1	bedr2	hall/WC	bathr	hall/lr	livingr	diningr	kitchen
Temp	21.4	19.7	20.5	21.2	20.5	20.8	20.7	20.8
Flow	2.4	2.4	5.9	12.5	5.9	5.3	5.3	0.3

Exhaust from the bathroom 40 l/s

	bedr1	bedr2	hall/WC	bathr	hall/lr	livingr	diningr	kitchen
Temp	21.7	20.1	20.8	20.5	20.8	20.8	20.7	20.8
Flow	1.7	1.7	5.6	16.3	5.6	4.5	4.5	0.1

CASE 2 **Exhaust from the kitchen 20 l/s and the bathroom 20 l/s, window closed**

	bedr1	bedr2	hall/WC	bathr	hall/lr	livingr	diningr	kitchen
Temp	21.3	19.6	20.5	19.7	20.5	20.4	20.3	20.5
Flow	2.4	2.4	5.9	12.5	5.9	5.3	5.3	0.3

Exhaust from the kitchen 20 l/s and the bathroom 20 l/s, window open

	bedr1	bedr2	hall/WC	bathr	hall/lr	livingr	diningr	kitchen
Temp	21.2	19.6	20.2	19.5	20.2	20.4	20.2	20.4
Flow	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0

CASE 2, Fig. 3, began, like the former case, with a step-up of the tracer gas also injected into bedroom no 1. This time the exhaust was 20 l/s both from the kitchen and from the bathroom. The concentrations increased fast and settled down after a few hours. The low concentration in the bathroom was due to the rather large infiltration into the sauna and the bathroom. After about four hours a window, height 1.67 m and width 0.18 m, was opened for 30 minutes in the livingroom. The pressure difference between indoors and outdoors fell to some tenths of a pascal and practically all the infiltrated air came in through the window. This caused a remarkable increase in the concentration in the bathroom and some minor changes in the other rooms. This sequence was repeated after four hours and caused approximately the same changes in the concentrations. The temperatures seemed to change very little during the opening period even though the outdoor temperature was only +2 ^{o}C. A much more drastic effect was expected. The reason for this was that the cold air sank to the floor and the temperature sensors on a height of 1.5 m could not detect any change.

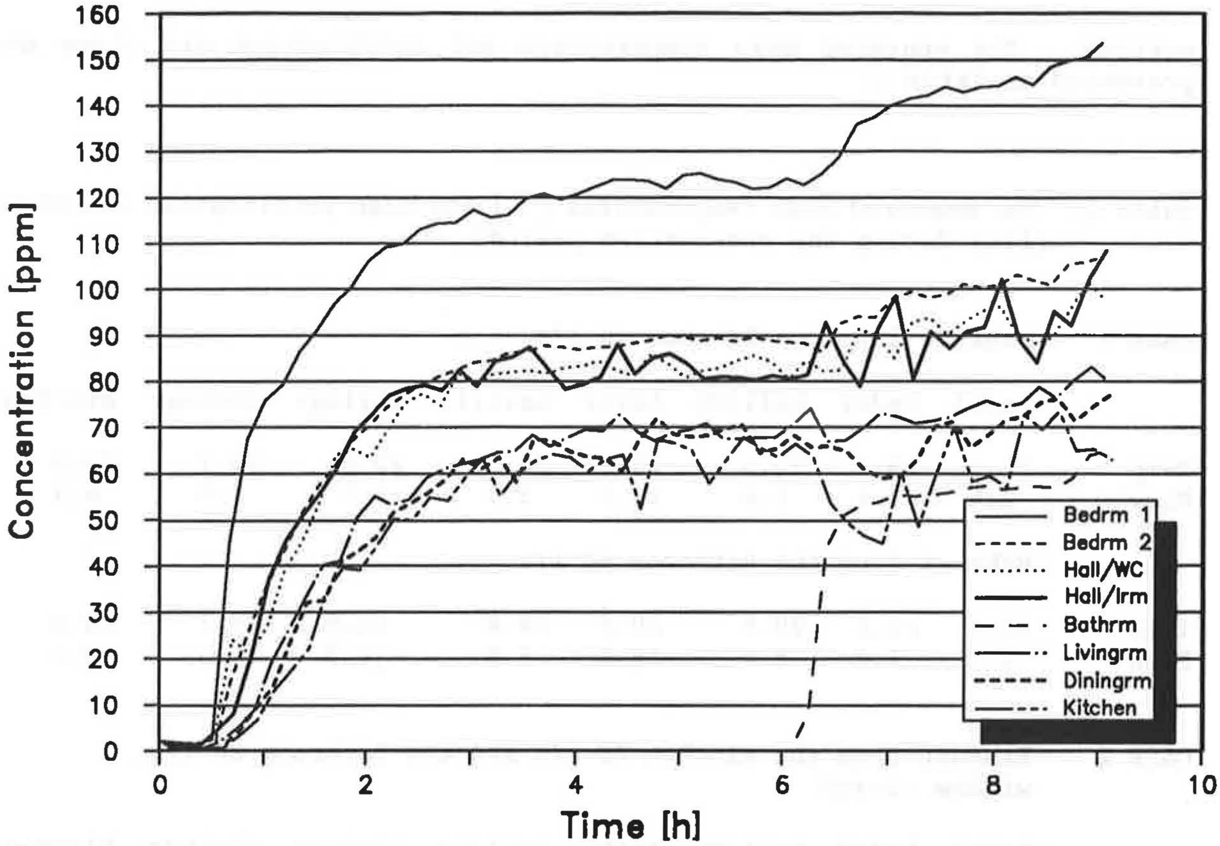

Fig. 2. CASE 1, measured concentrations

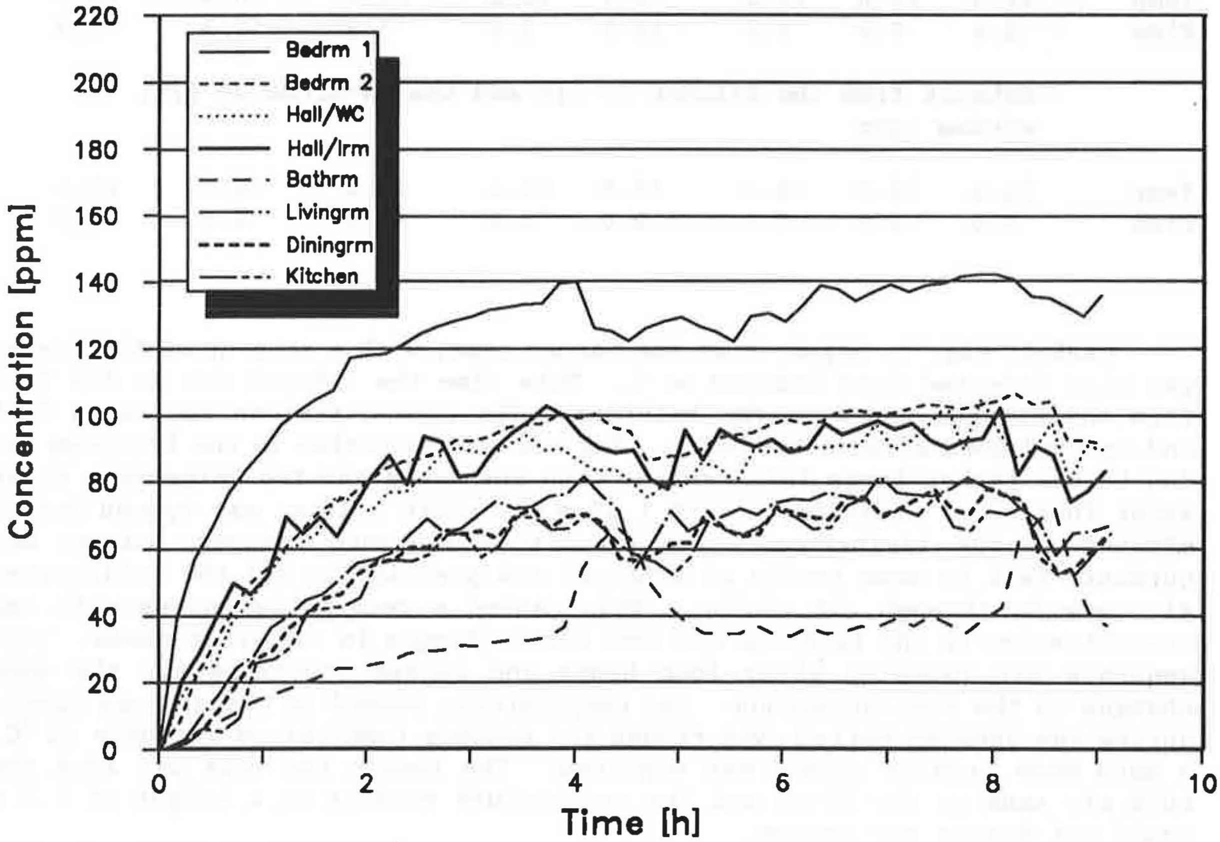

Fig. 3. CASE 2, measured concentrations.

Calculations

The calculation of the concentration histories was made using the MULTIC code (6). This code contains an analytical solution of the vector matrix differential equation of the multizone system combined with a simple analytical model for the estimation of the circulating air flows through the doorways. The input data were the temperatures, volumes, exhaust flow rates and initial concentrations of the zones and the net flow rates of air between the zones. A description of the internal contaminant sources was also included in the input data. The output data contained the concentration histories. The code can be applied to conditions usually existing in dwellings. The major restriction is for the present that all the zones must be horizontally adjacent. Because of the analytical algorithms, the calculation time is very short and large systems can be handled without any difficulties.

The first step in making the calculations is to select the zones. The most sraightforward solution is to put each room in one zone. This is a good approximation as long as the room is large enough in relation to the doorway. In the dwelling under consideration the doorways between the bedrooms and the hall were of normal size, height 2.02 m and width 0.80 m. The other open doorways, however, were considerably larger. In fact the living room and the dining room were one space without any doorway at all and they may be treated as one zone. The possibility of dividing the hall into two zones is also obvious because of its elongated shape. To find out the effect of the zone selection, two different alternatives were chosen for the basis of the calculations. One system contained eight zones and the other six zones, Fig. 4.

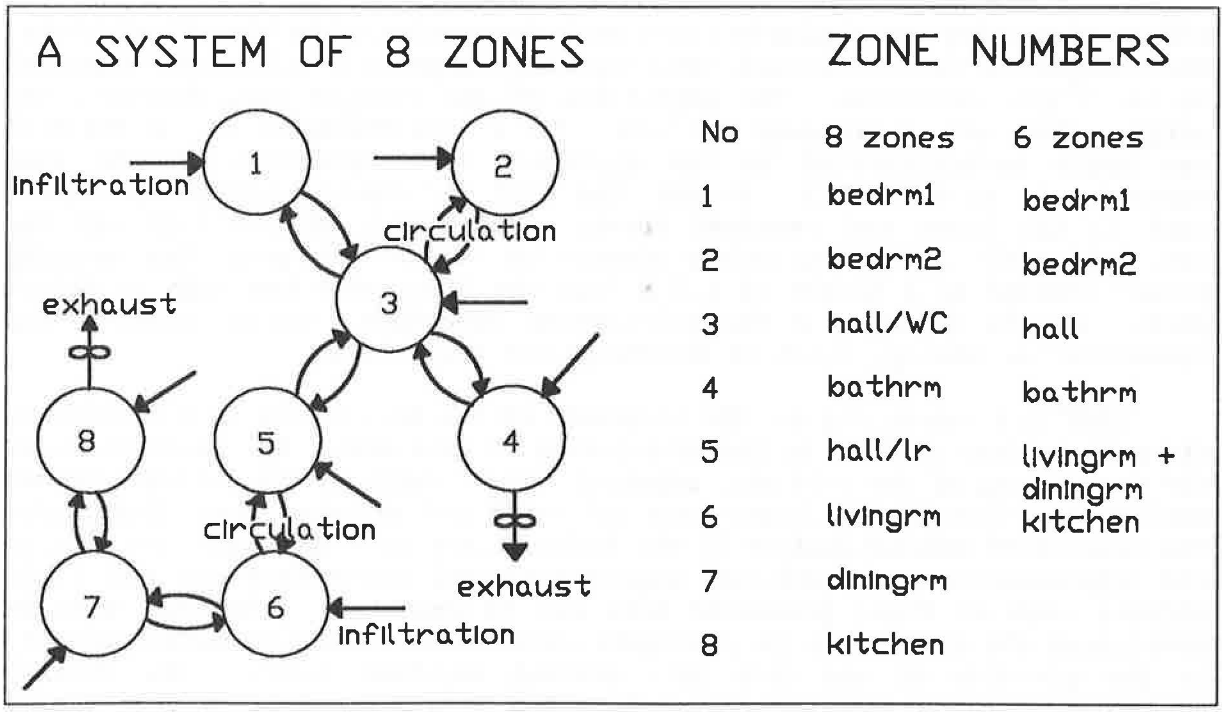

Fig. 4. Different alternatives for zone selection.

The calculations were made at intervals following the changes in the exhaust and infiltration air flows and temperatures. As the volumes of the zones were used the total volumes of the spaces decreased with the volumes of the furniture and fittings. The results are shown in Figs. 5...8.

Analysis

CASE 1, 8 zones, Fig. 5. On comparing the measured and the calculated concentrations, two things are clear. First, the calculated levels are to some extent too high. Second, the calculated concentrations at both ends of the hall differ considerably, though the measured concentrations are almost identical. Obviously the model of the hall is not functioning in the right way. The mixing of air between both ends of the hall is much stronger than predicted by the algorithm. There is no doorway between these zones, the air circulates effectively for some reason or an other and evens out the temperature difference, which is in turn the main driving force in the algorithm. Mainly for this reason the other concentration levels are also inaccurate. Dividing the hall into two zones was not therefore very succesful.

CASE 1, 6 zones, Fig. 6. Here the measured and calculated concentrations were quite similar during the whole period of nine hours. The hall, which plays a very important role in the system, functioned better as one zone, and this was reflected on all the other concentrations. The livingroom and the diningroom also worked well as one zone. The effect of changing the exhaust point was slightly overestimated by the calculations, however, the levels were quite near the measured concentrations.

CASE 2, 8 zones, Fig. 7. The first impression in this case is that the effect of opening the window was very much overestimated by the calculations. The changes in the calculated concentrations appared at the right time and in the right direction. The magnitudes of the changes are, however, too large. There are two reasons for this. First, the mixing of air in the hall was again underestimated by the algorithm with approximately the same consequences as in CASE 1. Second, the cold air coming through the window sank to the floor and remained there. The mixing of the cold air was extremely small during the thirty minutes the window was open. The sampling points located at a height of 1.5 m from the floor were too high to detect much. On the other hand the calculation procedure assumed complete and instantaneous mixing, which is obviously not valid here.

CASE 2, 6 zones, Fig 8. The treatment of the hall as one zone eliminated the most serious problem in the calculation of this case. The other problem, the poor mixing of the cold air, remained. The results of the calculation are much better than in the former case but still not satisfactory. Especially the calculated concentrations in the bathroom are wide too high. As long as the approximations of uniform temperatures and concentrations are used, effects such as those presented here can be expected. The next step in developing the algorithms to calculate contaminant transport would probably be the division of one room into several vertical zones. The thermal behaviour of the system could also be taken into account using some simple model capable of calculating large systems relatively fast.

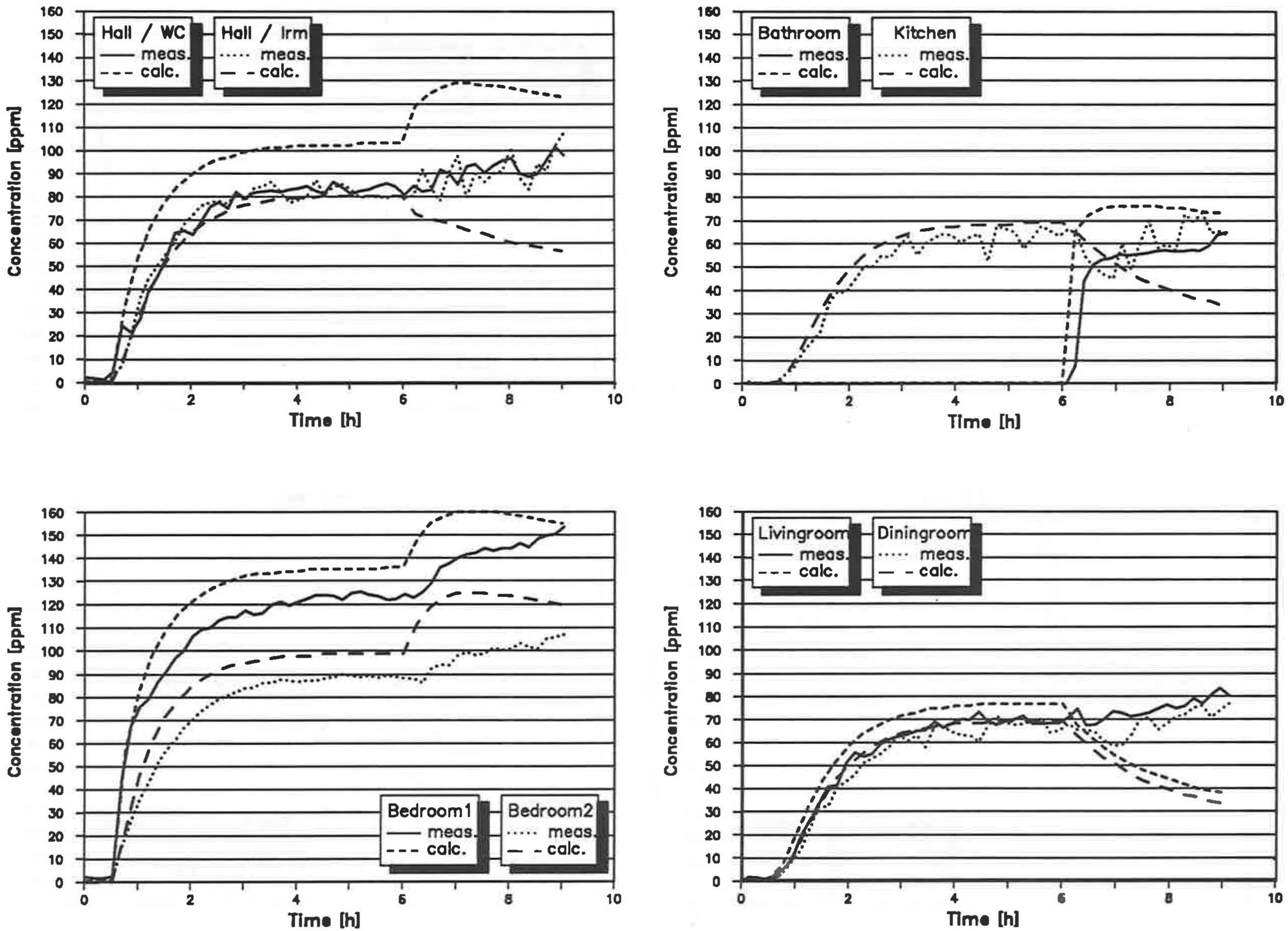

Fig. 5. CASE 1, 8 zones, measured and calculated concentrations.

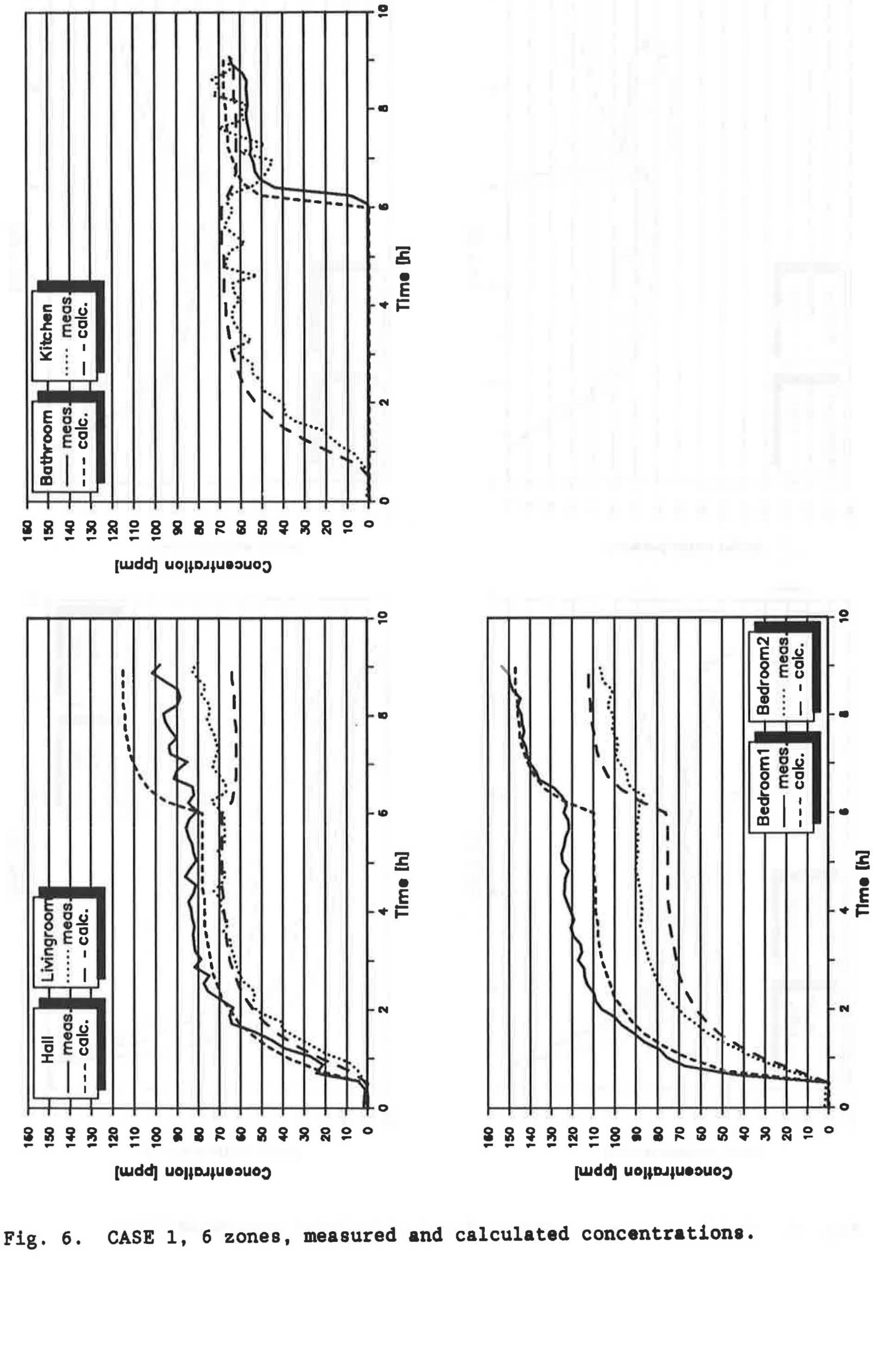

Fig. 6. CASE 1, 6 zones, measured and calculated concentrations.

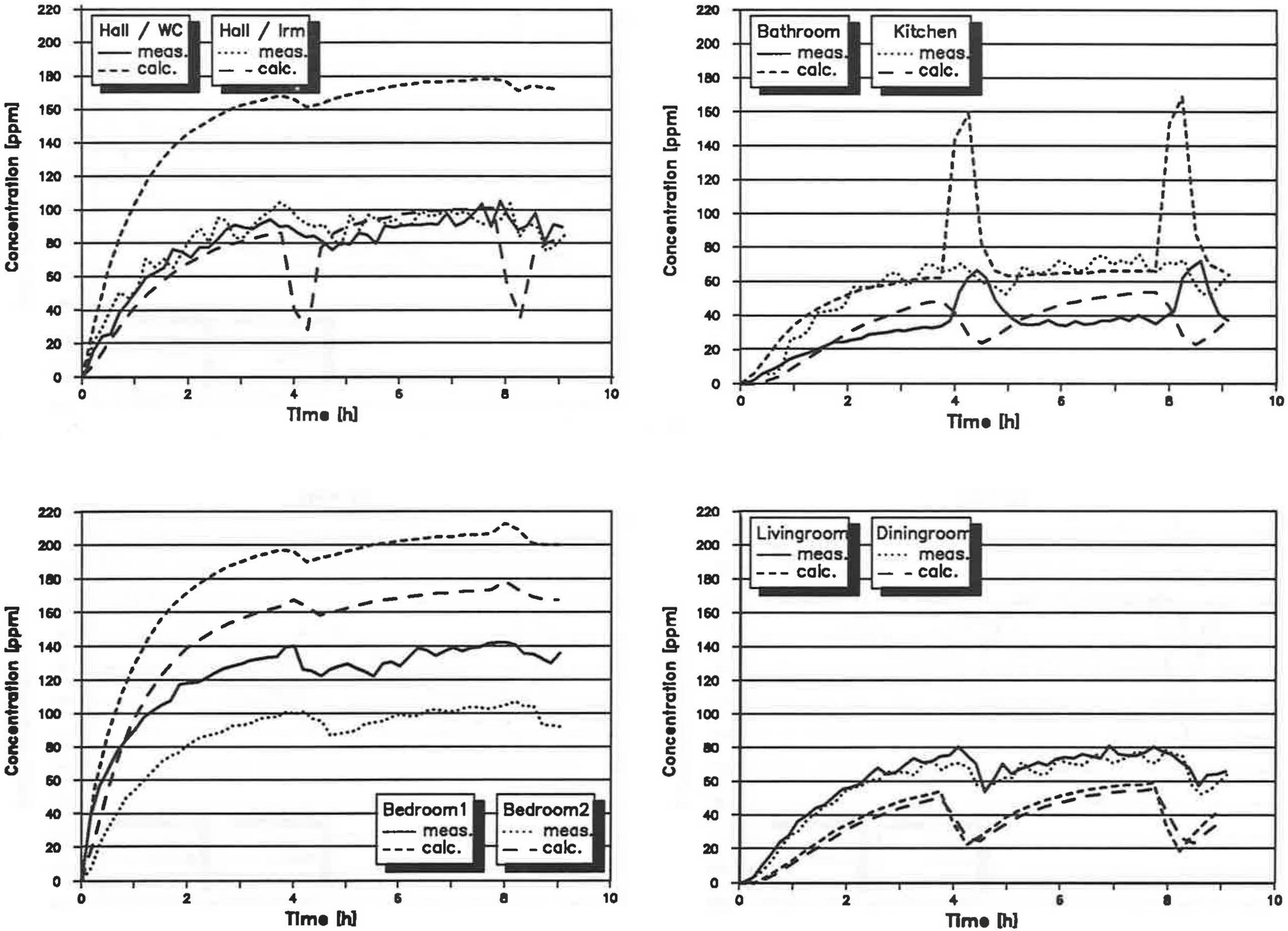

Fig. 7. CASE 2, 8 zones, measured and calculated concentrations.

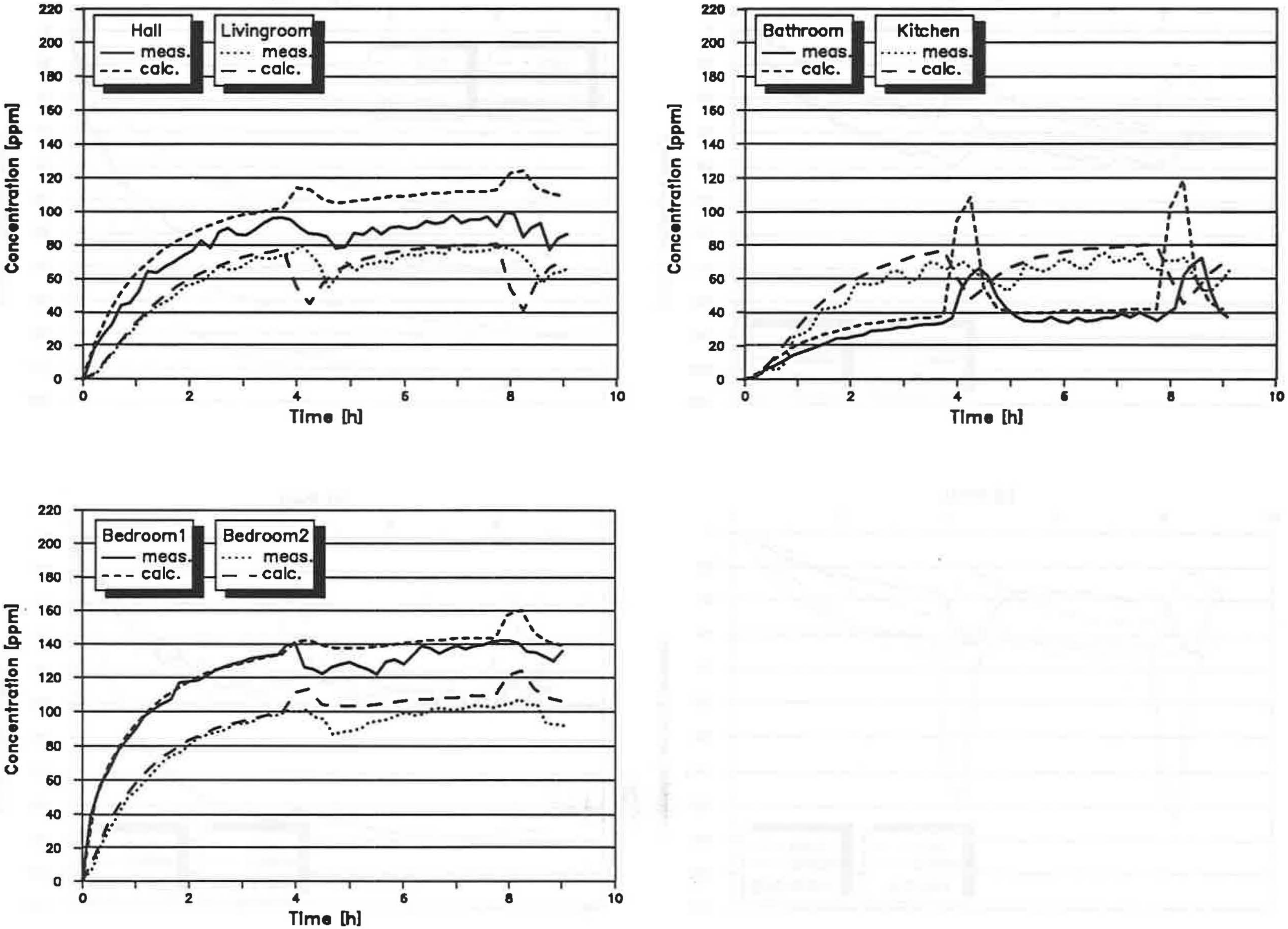

Fig. 8. CASE 2, 6 zones, measured and calculated concentrations.

To get a clearer picture of the performance of the calculation procedure in the different situations, a quantitative analysis was carried out. The relative error between the measured and calculated concentrations in each zone was calculated according to the equation

$$\text{(1)} \qquad \text{ERROR} = \frac{\int_0^T \frac{|C_c - C_m|}{C_m} dt}{\int_0^T dt}$$

where C_c and C_m are the calculated and the measured concentrations of one zone. The relative error for the whole system is simply the mean value of the errors for the individual zones, Table 2.

Table 2. The relative errors of the calculated concentrations

	zone number								
	1	2	3	4	5	6	7	8	all
CASE 1									
8 zones	0.12	0.19	0.34	0.14	0.68	0.19	0.19	0.19	0.26
6 zones	0.07	0.13	0.14	0.43	0.09	0.11			0.16
CASE 2									
8 zones	0.48	0.72	0.94	0.18	0.96	0.43	0.42	0.39	0.56
6 zones	0.05	0.09	0.20	0.24	0.08	0.29			0.16

Table 2. shows quite clearly that the system with eight zones was not a good choice. Using the system of six zones, the mean relative error of the calculated concentrations was 16 % in both cases.

Conclusions

A simple analytical procedure for calculating air flows through doorways combined with the multi-chamber theory could, after some further development, become a practical tool for evaluating contaminant concentrations in indoor spaces.

The main problems in this context seem to be the dividing the system into chambers and the violation of the basic approximations of the calculation in some cases.

The results indicate that the mixing of the air is usually quite effective in the individual rooms and no division into several zones is needed. On the other hand the results also show that the mixing of the air is very poor in some other situations when the temperature differences of the air are large enough.

The algorithms fo the calculation for the air flows in multi-zone systems should be developed further and connected with the estimation of the thermal behaviour of the building and the infiltration calculation.

References

(1) Haghighat F., Jiang Z., Wang J.C.Y., Natural convection and air flow pattern in a partitioned room with turbulent flow. ASHRAE Transactions 1989, vol. 95, pt 2.

(2) Riffat S.B., Measurement of heat and mass transfer between the lower and upper floors of a house. International Journal of Energy Research, vol. 13, no.2, pp. 231-241, 1989.

(3) van der Maas J., Roulet C.A., Hertig J.A., Some aspects of gravity driven air flow through large apertures in buildings. ASHRAE Transactions 1989, vol. 95, pt 2.

(4) Zohrabian A.S., Mokhtarzadeh-Dehghan M.R., Reynolds A.J., Marriott B.S.T., An experimental study of buoancy-driven flow in a half-scale stairwell model. Building and Environment vol. 24, no. 2, pp. 141-148, 1989.

(5) Sirén K.E., A procedure for calculating concentration histories in dwellings. Building and Environment vol. 23, no. 2, pp. 103-114, 1988.

(6) Sirén K.E., A computer program to calculate the concentration histories and some air quality related quantities in a multi-chamber system. Helsinki University of Technology, Institute of Energy Engineering, 1986.

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SUMMARY

The aim of the study was to determine, to what extent it is theoretically possible to estimate the concentration histories in a dwelling when different kinds of disturbances affect the air flows. The dwelling contained seven rooms and had a mechanical exhaust ventilation system. Tracer gas methods were used to simulate the contaminant transport and to measure the infiltration air flows. A constant release of tracer gas was injected into one of the rooms. Two different disturbances were applied. First the location of the exhaust was changed, second a window was opened and closed. The division of the system into six or eight zones affected the calculated concentrations considerably. The mixing of the air was usually quite effective in the individual rooms and no division into several zones was needed. Opening the window caused cold air from outside to sink to the floor. The mixing of the cold air was very poor. For this reason the calculation failed to some extent, because it used the approximation of perfect and instantaneous mixing. The calculation procedure does, however, have potential for development.