

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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EXPLORATION OF VENTILATION STRATEGIES IN DOMESTIC HOUSING.
THEORY AND EXPERIMENTAL RESULTS

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SYNOPSIS

The performance of whole-house mechanical ventilation systems was explored in an full-scale indoor test house (volume 176 m³). A range of parameters were monitored:

- * The pressure distribution
- * The inflow of outdoor air to each room, the mean age of air in each room and the air-exchange effectiveness
- * The spread of a 'contaminant' released respectively in the kitchen and in the bedroom.

The tests were undertaken both with the internal doors closed and with the internal doors open. Both mechanical extract system and balanced (combined) systems were tested. The tests were undertaken for a specific flow rate equal to 0.5 house volumes/hour (total flow rate 88 m³/h). The fundamental concepts used are defined at the beginning of the paper. The concepts are in accordance with those currently proposed in Scandinavia. In particular the relevant meaning of the concept air-exchange rate is discussed. Then follows a short description of the test house and the measuring procedures adopted. Finally, the results obtained are given.

1. Purposes of a ventilation system

The most general purposes for ventilating a dwelling with 'fresh' air are:

- * The removal of 'contaminants' originating from the building fabric and from people and their activities.
- * Temperature control.

Only the first task will be considered in this paper. For a given 'contaminant' source the concentration attained at an arbitrary region in the whole house is governed by the following two factors:

- * How much of the 'contaminant' that passes through the region.
- * How much 'fresh' outdoor air that passes through the region.

The transfer of a 'contaminant' and 'fresh' air to a region can be more or less related to each other. The degree of relation depends on the type of 'contaminant' source we have. At one extreme end of the state we have a passive 'contaminant' generated everywhere in

the house, and with the same and constant rate. In this case the 'contaminant' levels are fully controlled by the distribution of the air. At the other extreme end we have a point source releasing a 'contaminant' with e.g. a density that differs from the density of the air. In the closest neighbourhood of the source the spread of the 'contaminant' is more or less independent of local air motions. However, when the 'contaminant' has become sufficiently diluted with air it will start to follow the local air motions.

In domestic housing, unlike the situation in industrial premises, there is seldom any specific 'design contaminant' with known characteristics. Therefore the designer of a ventilation system for a residential building does not normally know in advance which pollutants the ventilation system is to remove.

In our approach to the evaluation of the performance of different ventilation schemes we have chosen the following criteria:

- * The efficiency in the distribution of the supplied air and the air-exchange efficiency.
- * The concentration levels caused by a uniform source in the kitchen and in the bedroom respectively.

2. Terminology and theoretical background

We will make a distinction between the total flow rate of outdoor air entering a house, and the infiltration. Infiltration is the difference between the total flow rate of outdoor air entering a house, and the flow rate of outdoor air provided by a mechanical ventilation system.

The nominal time constant, τ_n , of a ventilation system is defined as:

$$\tau_n = \frac{V}{q^t} \quad (1)$$

where:

- q^t = The total flow rate of outdoor air entering the house
- V = The total volume of the house.

The physical meaning of the nominal time constant is limited to be equal to the average residence time in the house of the air supplied. That is to say, that each unit of volume of the supplied flow rate q^t will on average stay in the house for a time period equal to the nominal time constant. However, this does not imply that the air present in the room is replaced (exchanged) at the same rate. The time, $\bar{\tau}_r$, it takes on average to replace the air present in the room is equal to (Sandberg and Sjöberg¹, equation 69).

$$\bar{\tau}_r = 2 \cdot \langle \bar{\tau} \rangle \quad (2)$$

where:

$\langle \bar{\tau} \rangle$ is the mean age of the air in the room.

The reciprocal of the nominal time constant

$$n = \frac{q^t}{V} = 1/\tau_n \quad (3)$$

is often called the air-exchange rate.

In view of equation (2), this is a misleading terminology. The physical meaning of n is, as is literally expressed in the right-hand side of equation (3), the total volume of outdoor air (m^3/h) per total volume (m^3). Therefore, there is in Scandinavia a proposal to call n the specific flow rate. SI Units for n is ($\text{m}^3/\text{h}/\text{m}^3$) or (room volumes/h).

The air-exchange effectiveness is defined as:

$$\varepsilon_a = \frac{\tau_n}{\bar{\tau}_r} \times 100 \quad [\%] \quad (4)$$

The theoretical upper limit for the air-exchange effectiveness is 100%. Complete mixing of air gives rise to an air-exchange effectiveness equal to 50%.

The following relation holds between the stationary room-average concentration $\langle C(\infty) \rangle$ and the mean age of the 'contaminant', τ_e^C , when it leaves the room (turn-over time)

$$\langle C(\infty) \rangle = \tau_e^C \frac{\dot{m}^C}{V} \quad (5)$$

where:

\dot{m} is the 'contaminant' production rate.

The ventilation efficiency, $\langle \epsilon \rangle^C$, is defined as ($C_e(\infty)$ = conc. in the extract):

$$\langle \epsilon \rangle^C = \frac{C_e(\infty)}{\langle C(\infty) \rangle} \times 100 \quad (6)$$

The right-hand side in the above relation may be expressed in terms of the turn-over time for the 'contaminant' time constant as:

$$\langle \epsilon \rangle^C = \frac{\tau_n}{\tau_e} \times 100 \quad (7)$$

3. Description of test house

3.1 General

All the tests reported in this article were carried out in the test house shown in figure 1a. The house is located in the laboratory hall at the Institute. The house has five 'rooms' (see figure 1b), a total volume of 176 m^3 , and the floor area is 70.2 m^2 . One short wall of the house consists of the existing south wall of the laboratory hall. Against the short wall at the opposite end of the house there is a cooling chamber. The air temperature in this chamber can be reduced to -25°C . Both above and below each internal door there are adjustable gaps. The air movement in the doorways is shown by releasing smoke. To enable inspection from outside there are several strips of glass in the building envelope. The house is heated by electric radiators, or by heating the supplied ventilation air. Pressurization of the house to 50 Pascal pressure difference gave rise to a specific flow rate of 0.8 house volumes/h through the building envelope.

3.2 Flow rates and ventilation systems

The tests were carried out at a nominal flow rate q_n^t equal to 88-89 m^3/h , which corresponds to a nominal time constant of 2.0 hours, and a specific flow rate equal to 0.5 house volumes/h.

The air was always extracted from the kitchen (about 68% of the total), and the bathroom. When the extract system was in operation

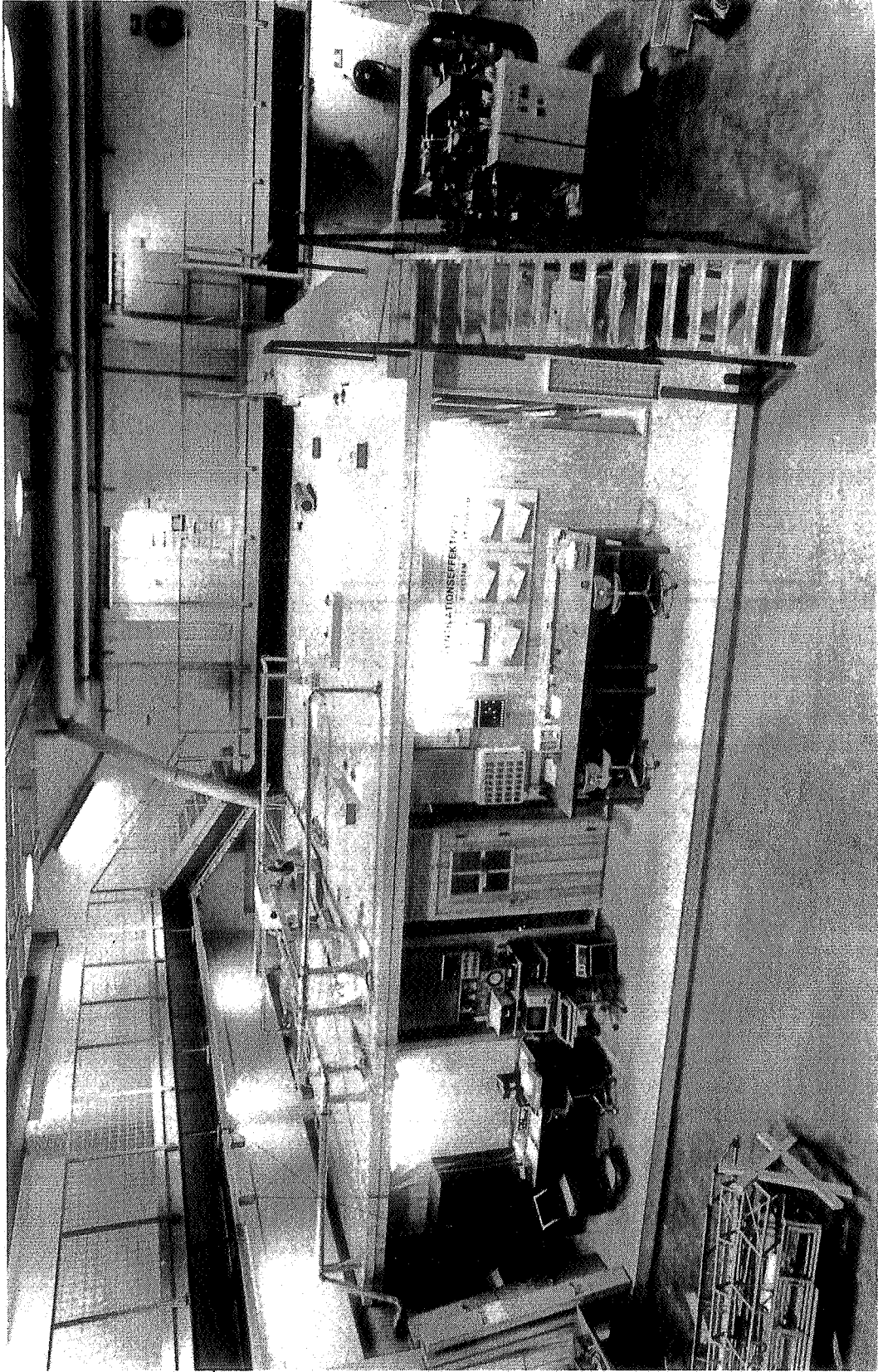


Figure 1a. The test house

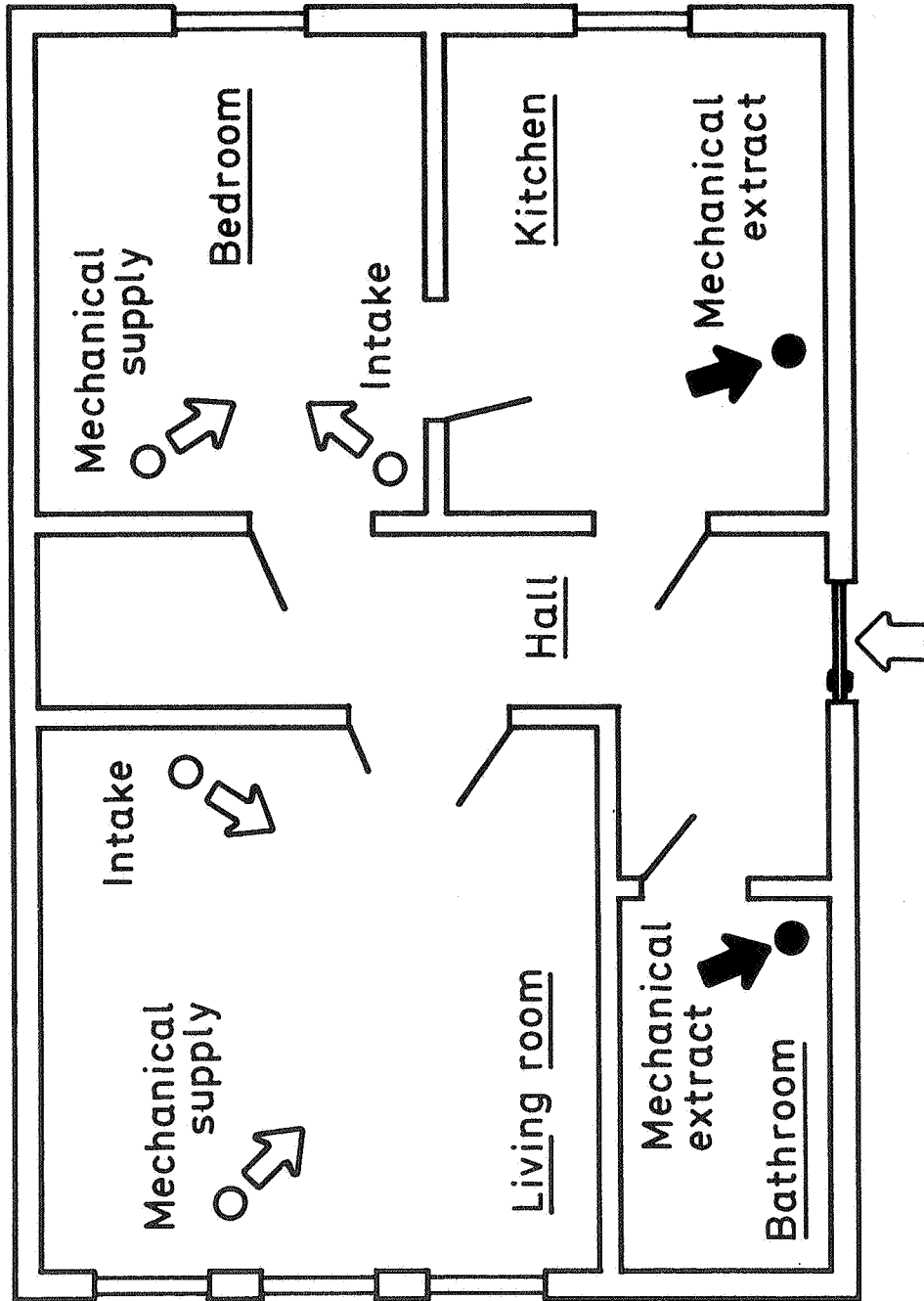


Figure 1b. Plan of test house

two 100 mm diameter intake holes in the ceiling were opened. One intake was in the living room ceiling, and the other intake in the bedroom ceiling (see plan of house in figure 1b). When the balanced ventilation was in operation the air was always supplied to the living room (about 54% of the total), and to the bedroom. The points of supply are indicated as mechanical supply in figure 1. The supply air was always taken from the laboratory hall while the air extracted from the test house was dispersed outdoors.

4. Experimental procedure

The following quantities were monitored in each room:

- * Room air temperature at 0.2 m above the floor, and 0.2 m below the ceiling
- * The pressure (relative to the laboratory hall) in the middle of the room
- * Gas concentration in the middle of the room.

Tracer gas (N_2O) was released in each room directly into the air stream created by the mixing fan. The temperature in the laboratory hall and the outdoor temperature was continuously monitored. The pressure difference between outdoors and the laboratory hall was also recorded. Three runs were made for each situation. The measuring and control sequence in each run was as follows:

1:st run:

1. Temperature
2. Pressure
3. Start of mixing fans and release of gas into each room
4. Constant concentration method to determine the flow rate of outdoor air to each room
5. Stop of gas-release and mixing fans
6. Decay of concentration to determine the mean age of in air in each room and the mean age of all air present in the house
7. A repeat measurement of temperature and pressure.

2:nd run:

1. Temperature
2. Pressure
3. Release of 3.6 liter of tracer gas in the kitchen (during the whole release period the mixing fan in the kitchen is running and the door to the kitchen is closed)
4. Recording of gas concentration to determine the transfer of 'contaminants' to other rooms
5. A repeat measurement of temperature and pressure.

3:rd run:

The same procedure as in the 2:nd run except that now 3.6 liter of gas is injected into the bedroom.

In order to check the zero drift of the analyzer the gas concentration in the ambient air was recorded before and after each run.

From the concentration readings during the decay of concentration in the 1:st run, the mean age of air in each room, $\bar{\tau}_p$, is calculated by taking the total area under the curve and dividing it by the initial concentration. The mean age of all air present in the room $\langle \bar{\tau} \rangle$ is calculated by taking the normalized first moment of the concentration readings in the extract duct.

From the concentration readings during the 2:nd and 3:rd run, the total dosage, D_p (= the time integrated exposure), of the gas in each room is calculated. From the concentration readings in the extract duct, the mean age, τ_e^C , of the 'contaminant' when it leaves the room is calculated.

From the pressure measurements, an equivalent pressure difference, Δp_e , across the building envelope is calculated as:

$$\Delta p_e = \sum_i \left(\frac{A_i}{A} \right) |\Delta p_i| \quad (8)$$

where:

Δp_i = Pressure difference across surface no i of the building envelope

A_i = Area of surface no i of the building envelope

A = The total area of the building envelope.

The flow of air between the rooms through the doorways is visualized by releasing smoke around the doorways.

5. Results

5.1 Extract system

Figures 2a-2b (Case: Internal doors open) and fig 3a-3b (Case: Internal doors closed) show the results from the extract system. Fig 2a and 3a give the results concerning the supplied air and internal pressure distribution. First is given the inflow of outdoor air (q_m) to each room as predicted by the constant concentration method. The result is presented as a percentage of the nominal total flow rate, q_n^t (the flow rate set by the mechanical system). The internal pressure distribution is given as the pressure difference between each room and the pressure recorded in the hall, ($p - p_{hall}$). The pressure distribution presented constitutes an average of six repeated measurements. The equivalent pressure difference, Δp_e (see equation (8)), across the building envelope is also presented. Finally, the mean age of the air, $\bar{\tau}_p$, in each room is given as a percentage of the nominal time constant.

Figures 2b and 3b give respectively the results obtained from releasing a 'contaminant' in the kitchen and in the bedroom. First is given the integrated exposure, D_p , recorded, divided by the integrated exposure, D_s , in the source room. This ratio is equal to the ratio between the equilibrium concentrations we should, under identical release and air flow conditions, have obtained with a continuous release of 'contaminant'. On the right-hand side part of the figures is given the fraction (m/m_s) of total amount of 'contaminant' released (m_s) extracted from the kitchen and bathroom respectively.

In figure 3b, case source in kitchen, this fraction has not been presented because the predicted amount of 'contaminant' that left the house was greater than the released amount of 'contaminant'. This effect can probably be explained by an offset of the baseline caused by a drift of the gas analyzers zero level.

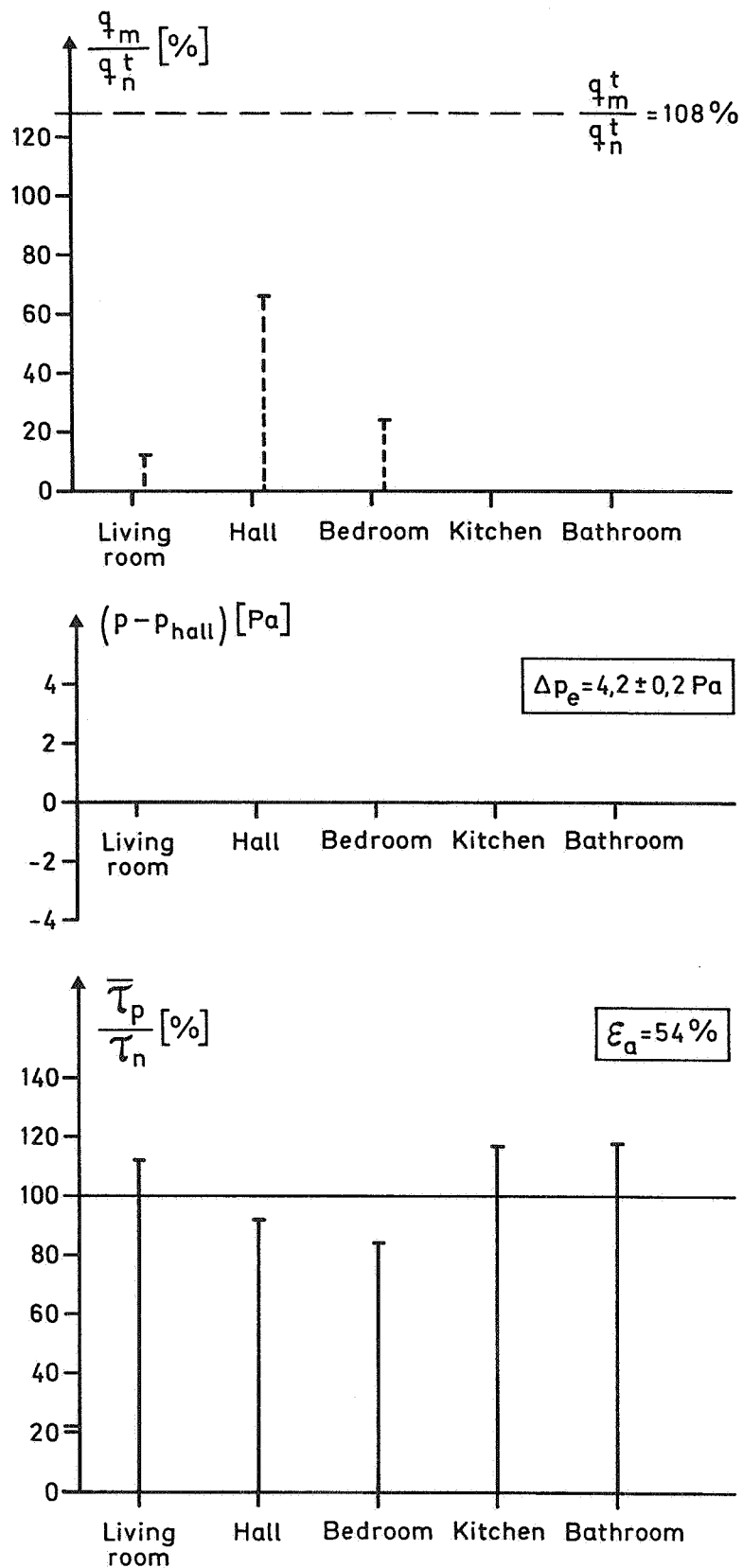


Figure 2a. Extract system and internal doors open. Supplied air, pressure distribution and mean age of air.

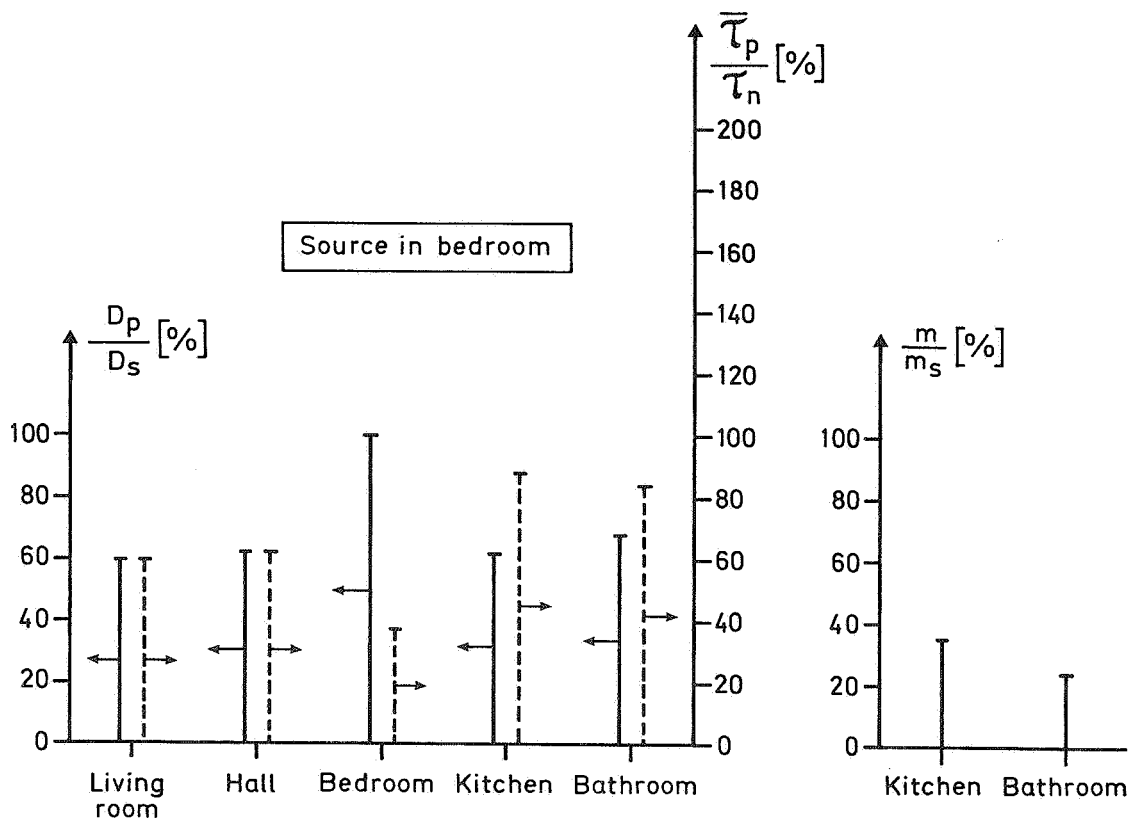
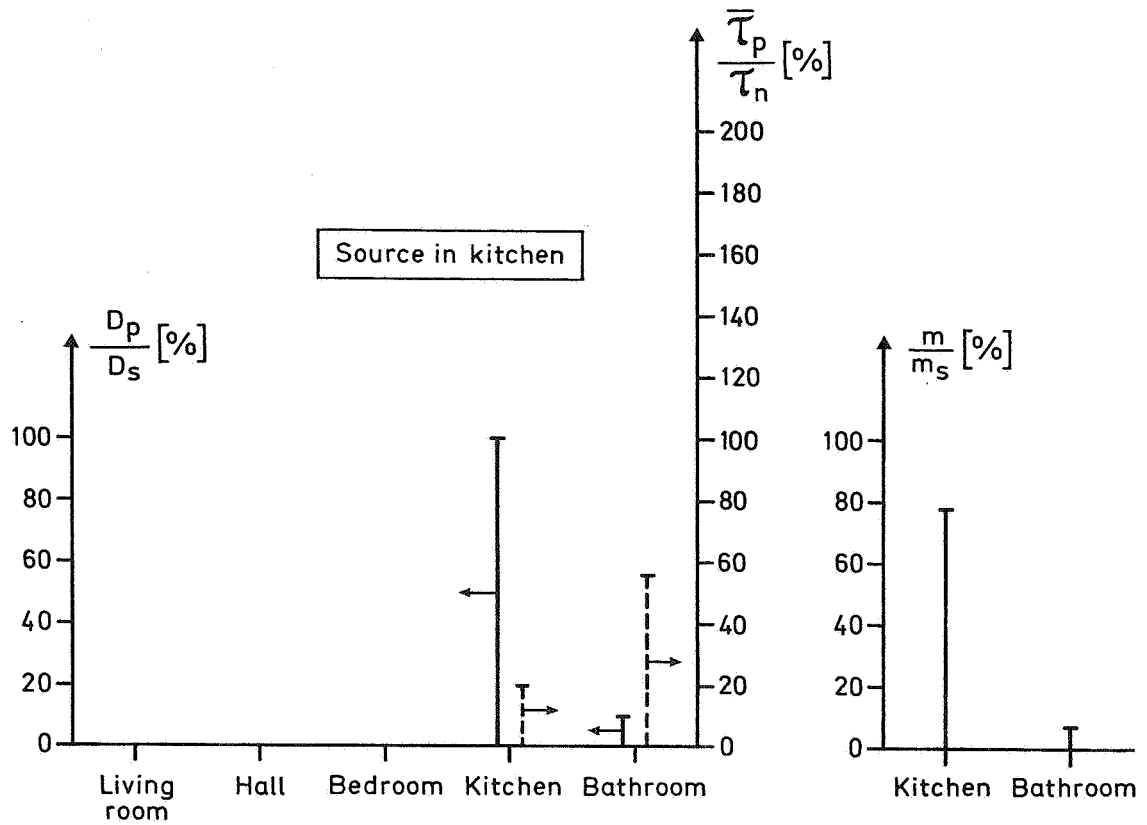


Figure 2b. Extract system and internal doors open. 'Contaminant' exposures and mean age of 'contaminant'.

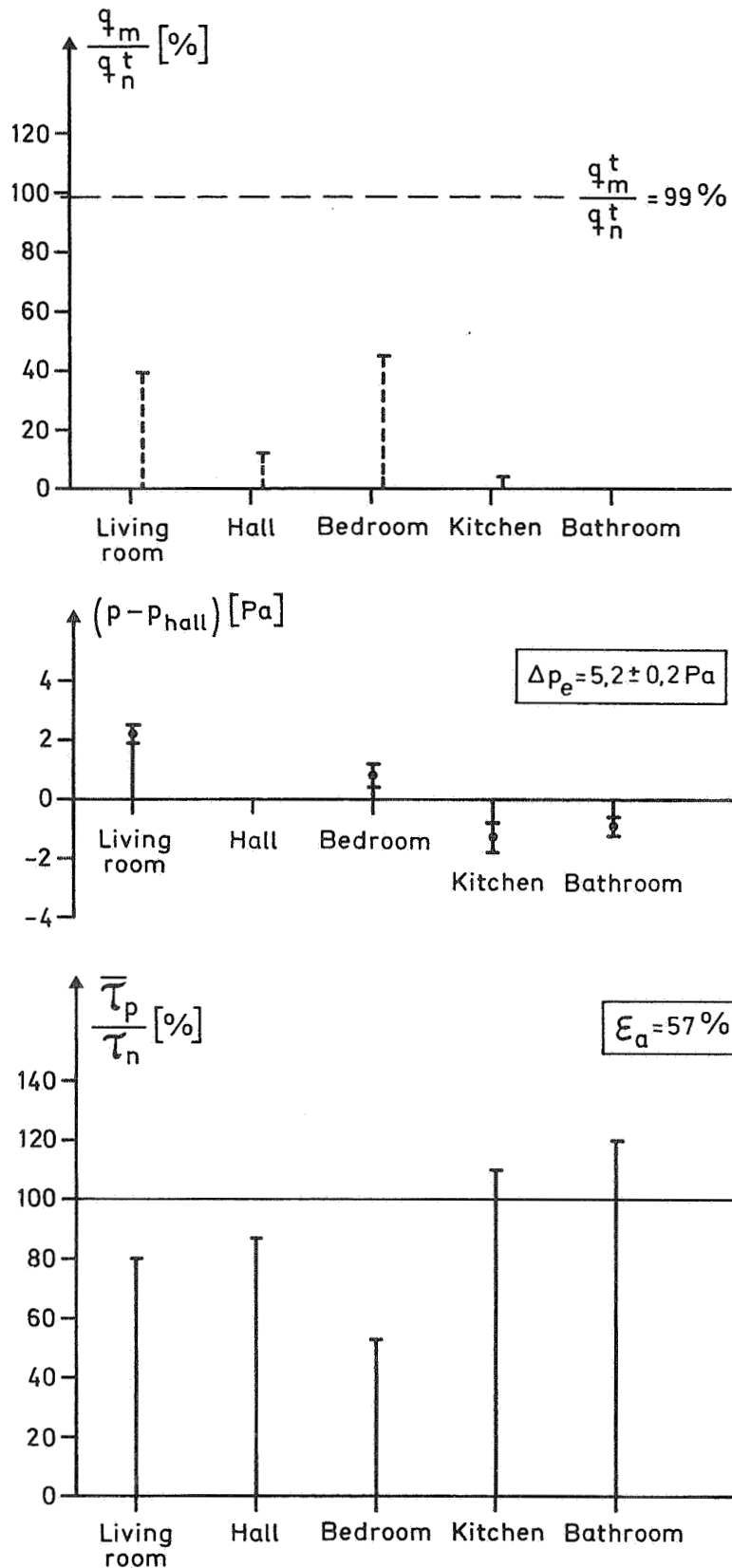


Figure 3a. Extract system and internal doors closed. Supplied air, pressure distribution and mean age of air.

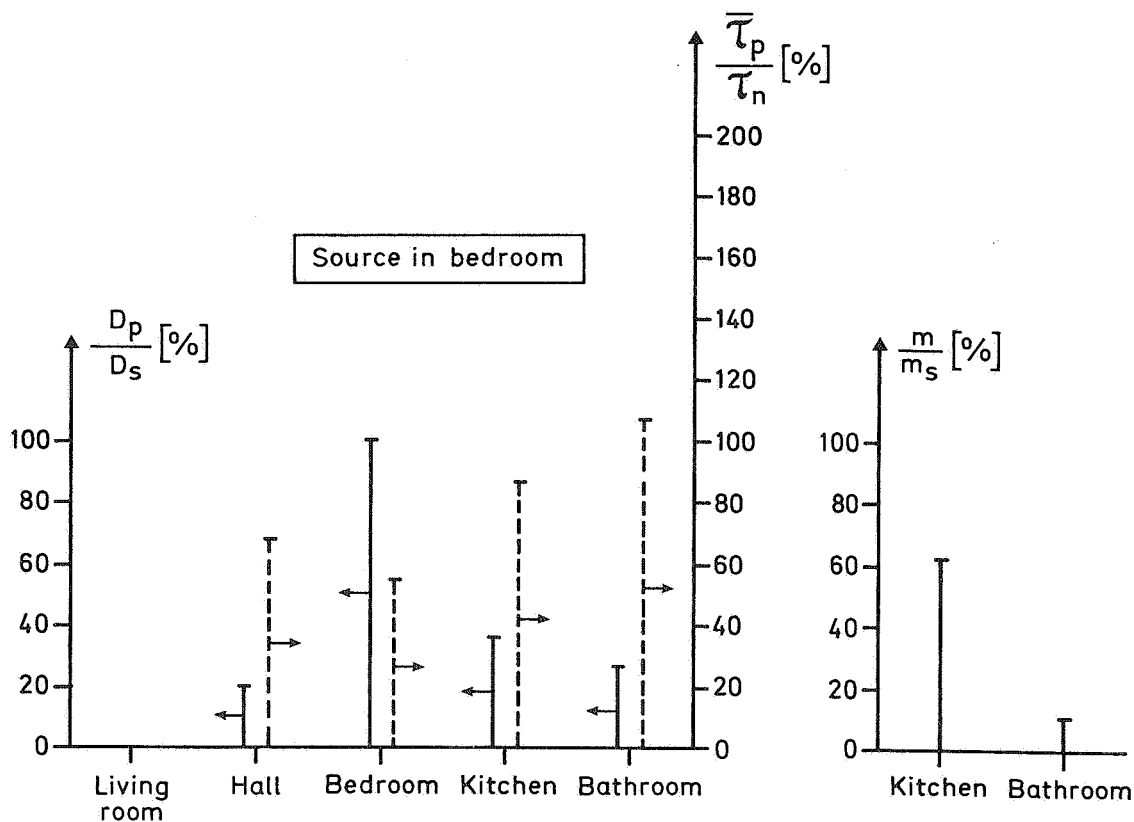
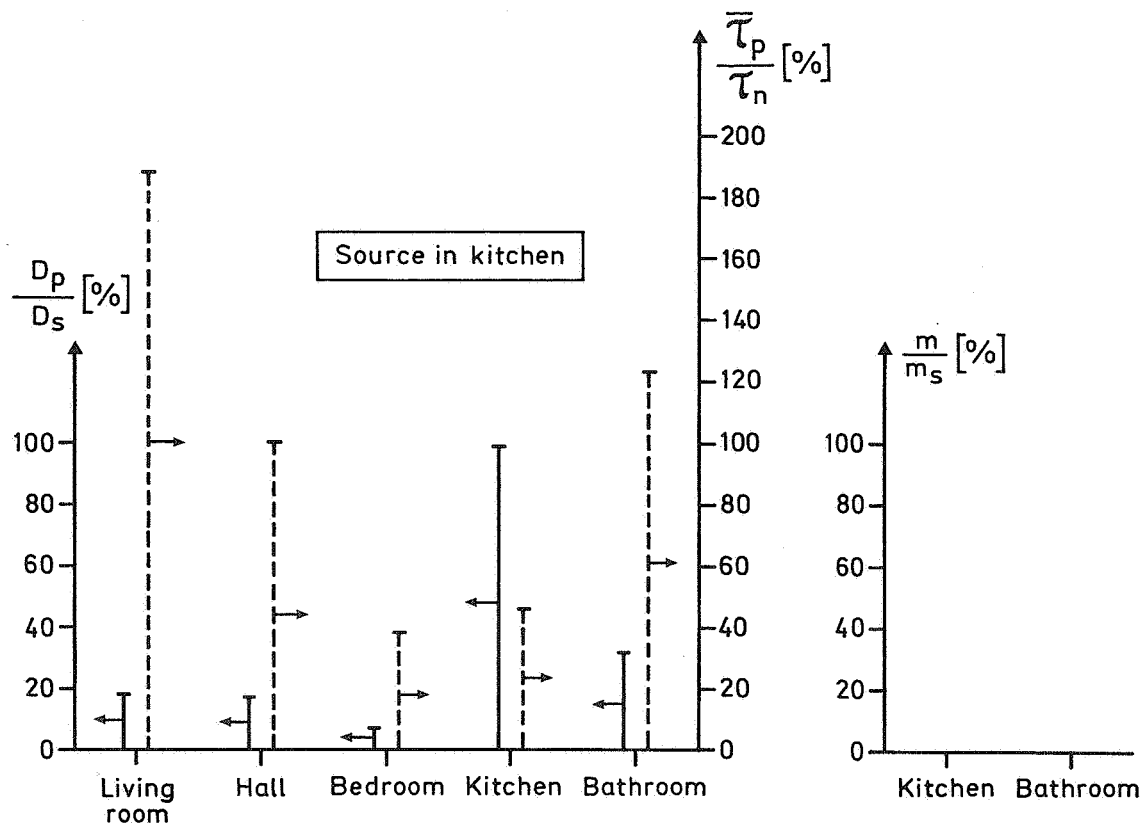


Figure 3b. Extract system and internal doors closed. 'Contaminant' exposures and mean age of 'contaminant'.

This focuses on the problem of making absolute measurements with this pulse technique.

First, concerning the results on the air distribution, we see that closed internal doors give rise to a slight increase in the air-exchange efficiency compared to the case with the internal doors open. This is in accordance with results reported earlier from experiments in a small two room test house, see Sandberg².

With the internal doors open quite a large inflow of outdoor air to the hall (64% of the total flow rate) is predicted. When the doors are closed the predicted inflow of air to the hall drops to 12% of the total inflow. This is fully in accordance with the properties of the constant concentration method, see discussion in Sandberg and Blomqvist³. The constant concentration method essentially predicts the inflow of 'fresh' air to each room. 'Fresh' air can come to a room from the neighbouring rooms and not only directly from outdoors. 'Contaminant' released in the kitchen is less dispersed than 'contaminant' released in the bedroom. This is what one should expect since air is extracted from the kitchen. Even when the doors are open almost all 'contaminant' released in the kitchen is also extracted from the kitchen. The rest of the 'contaminant' flows direct towards the bathroom. No concentration is recorded in the middle of the hall. This is due to the layout of the house with the bathroom located directly opposite the kitchen.

4.2 Balanced system

Figures 4a-4b (Case: Internal doors open) and figures 5a-5b (Case: Internal doors closed) shows, in similar manner as in section 4.1, the results from the balanced system.

We see from the figures that qualitatively we have the same results as for the extract system.

4.3 Comparison between the extract and balanced system

If we have a very low infiltration rate through non-purpose provided openings, that is to say a very tight building envelope, then we should not expect any greater differences in internal air move-

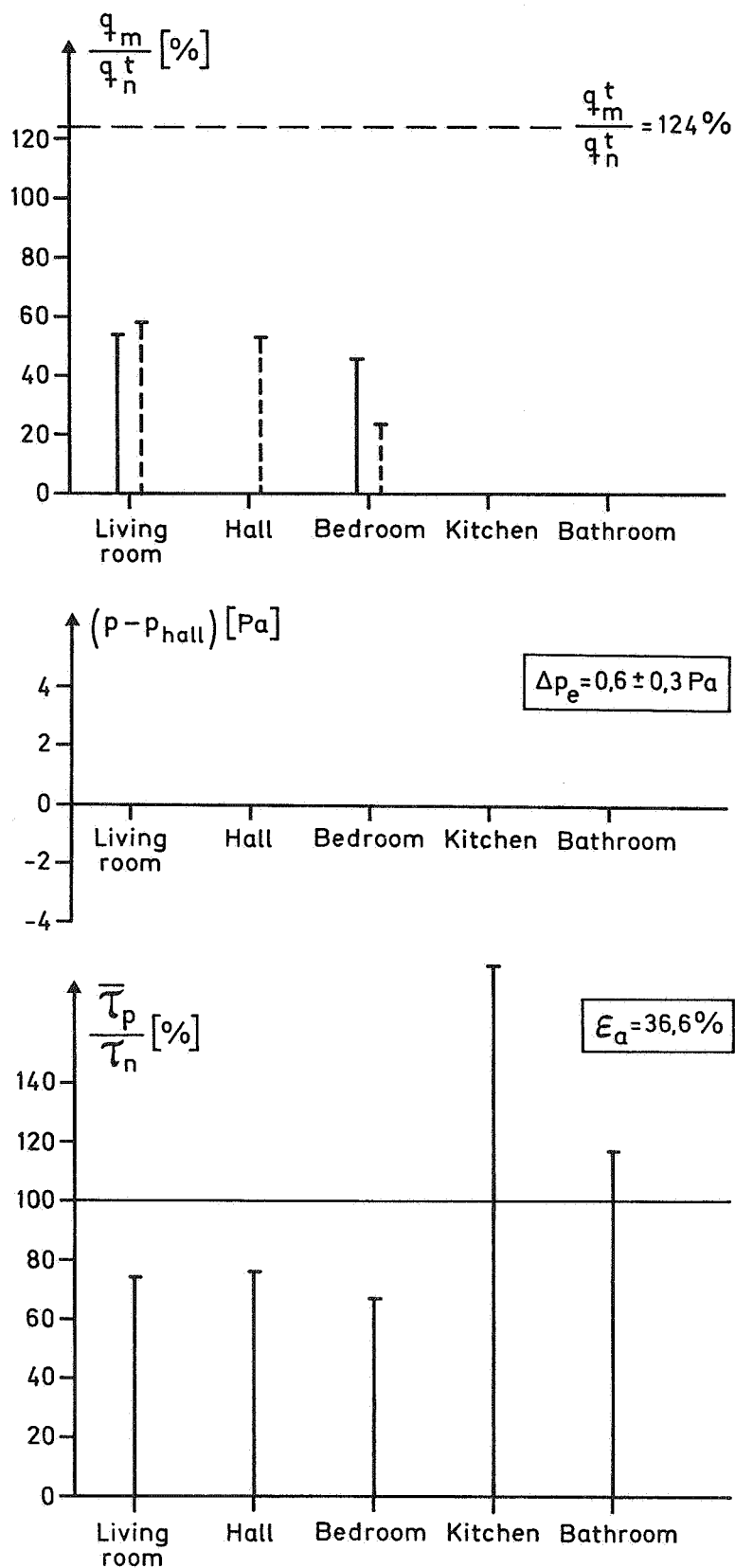


Figure 4a. Balanced system and internal doors open. Supplied air, pressure distribution and mean age of air. The mechanical supply is denoted by (—).

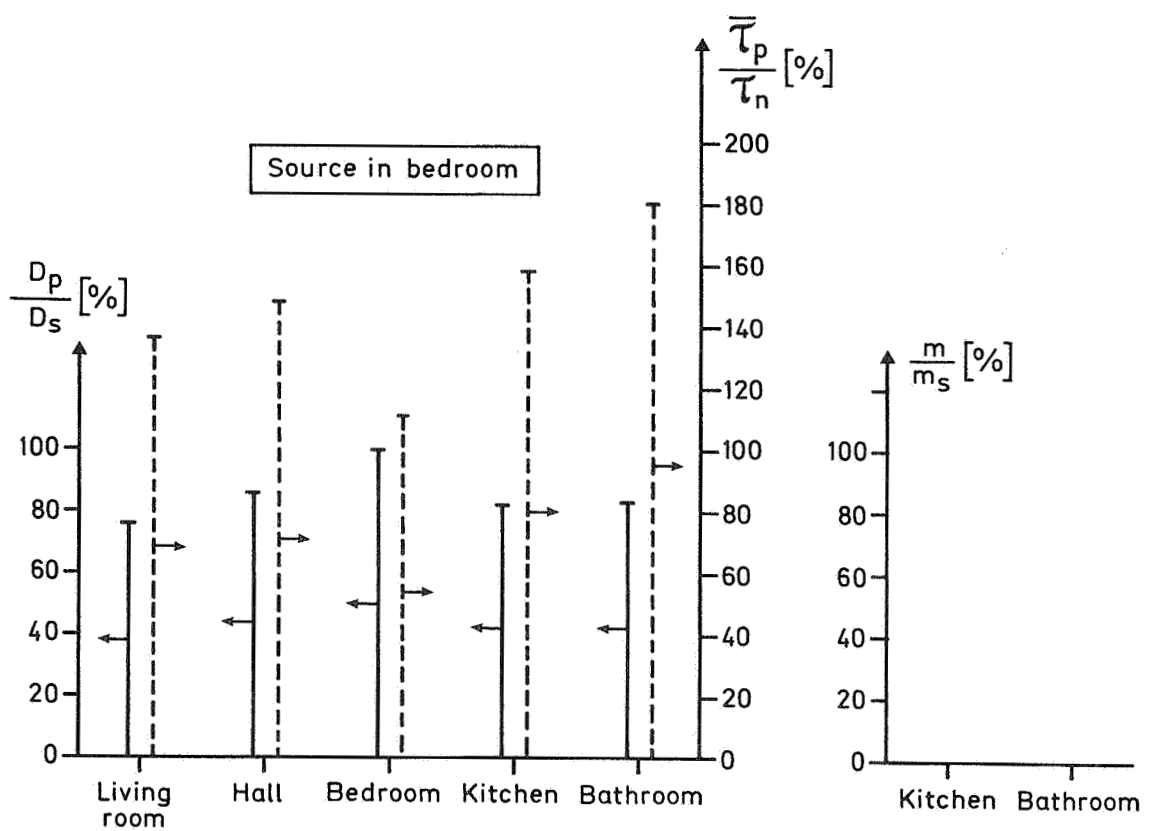
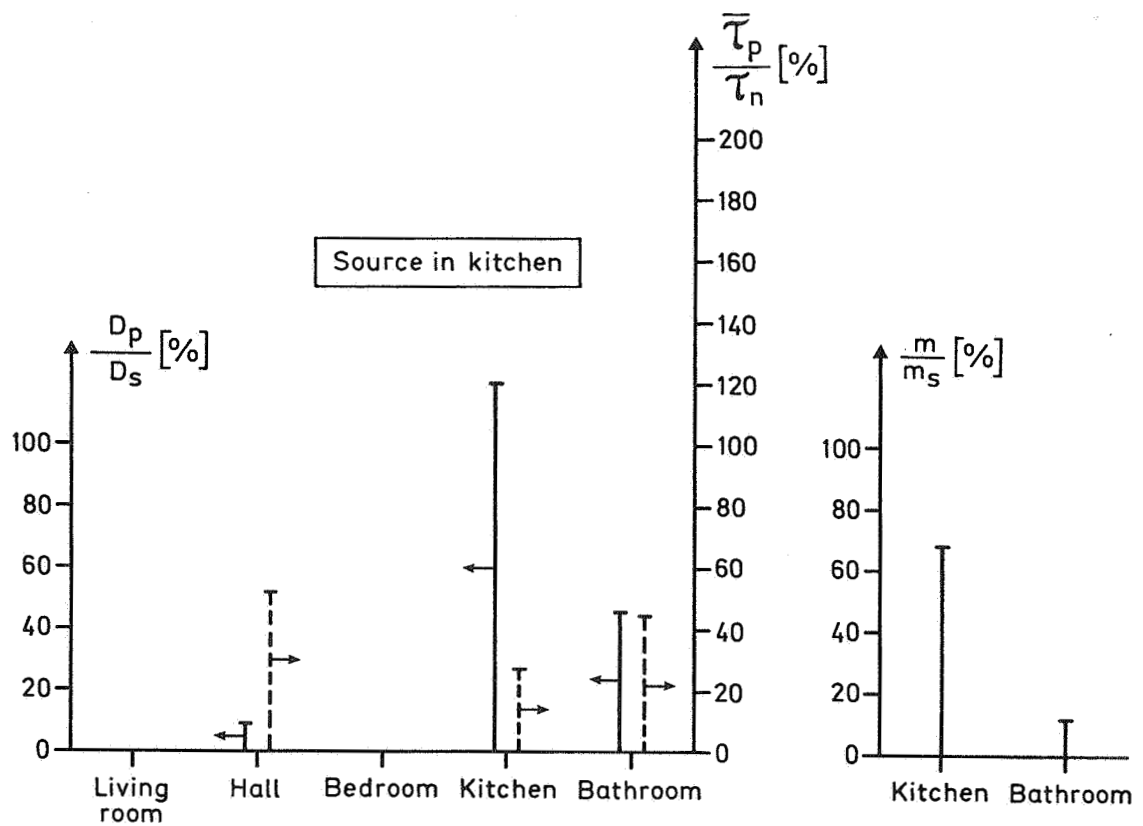


Figure 4b. Balanced system and internal doors open. 'Contaminant' exposures and mean age of 'contaminant'.

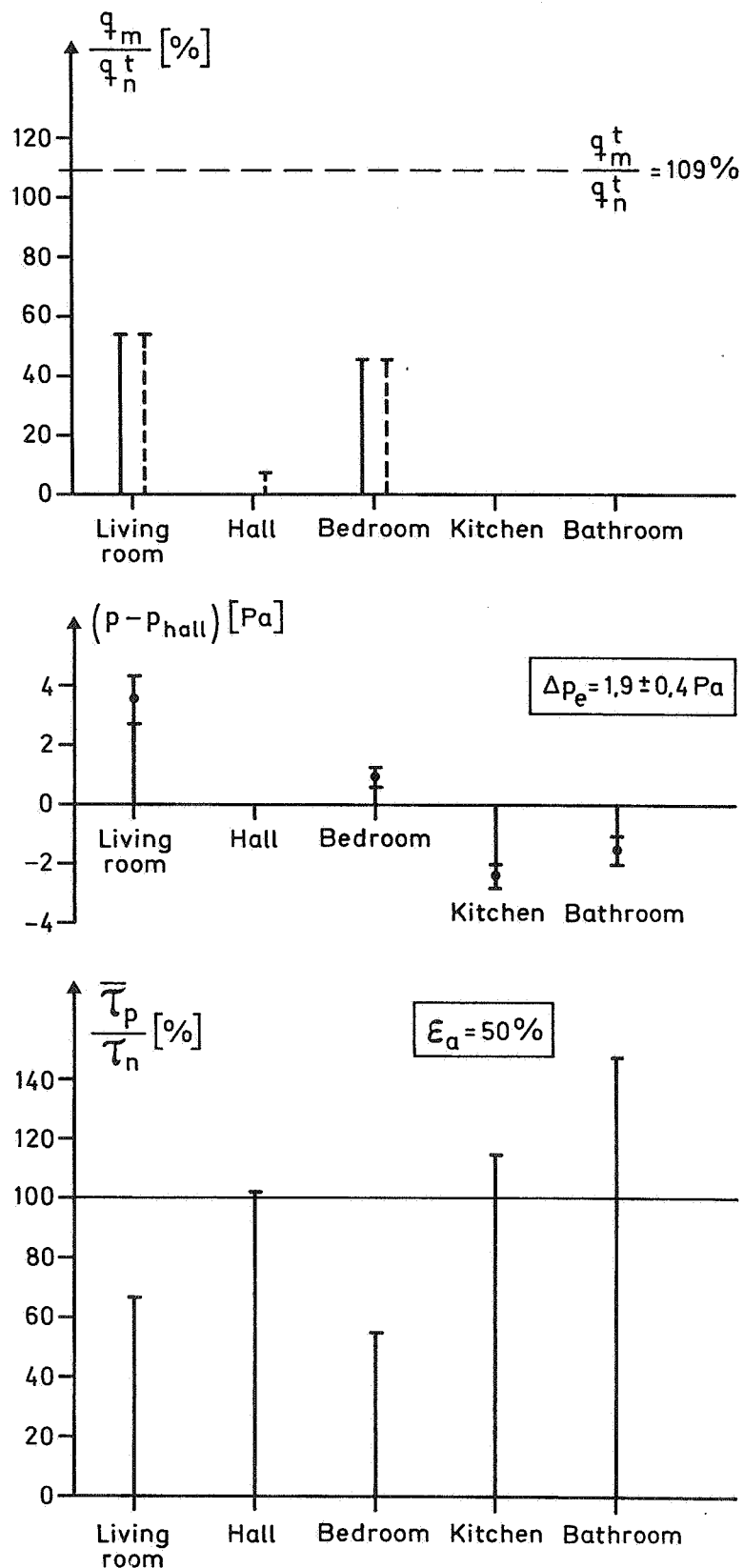


Figure 5a. Balanced system and internal doors closed. Supplied air, pressure distribution and mean age of air. The mechanical supply is denoted by (—).

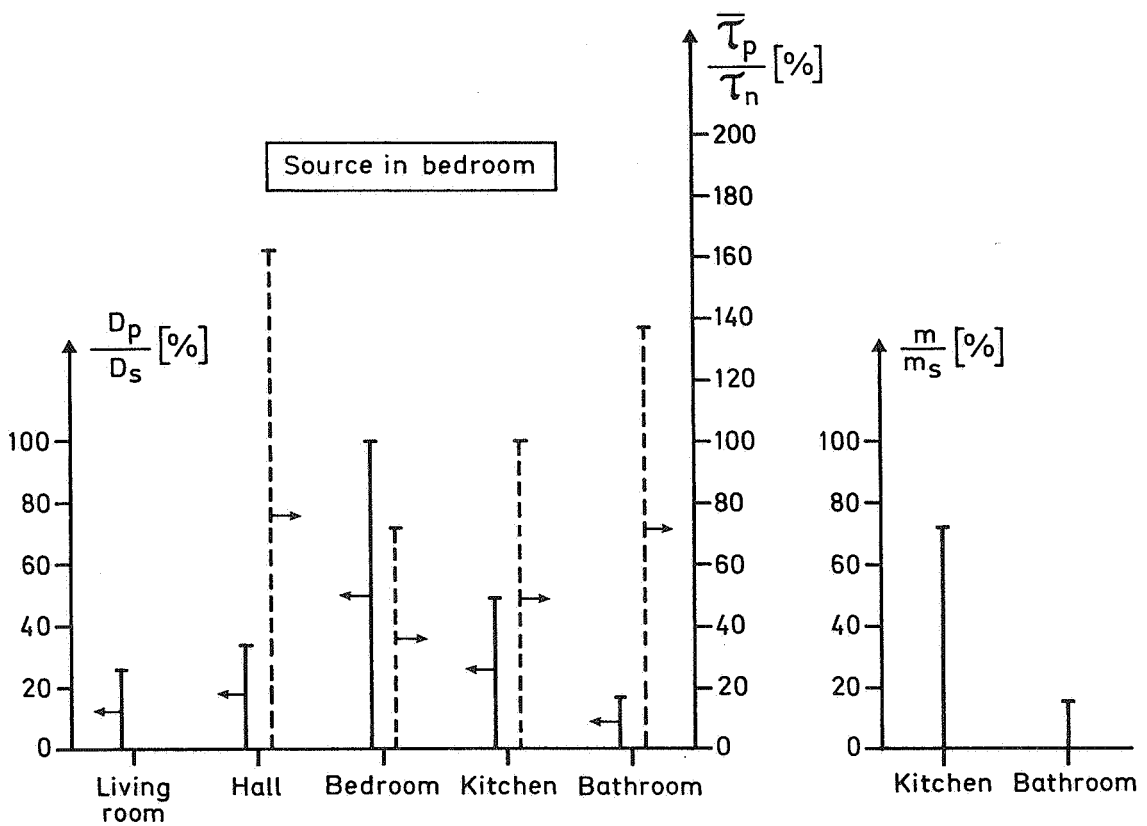
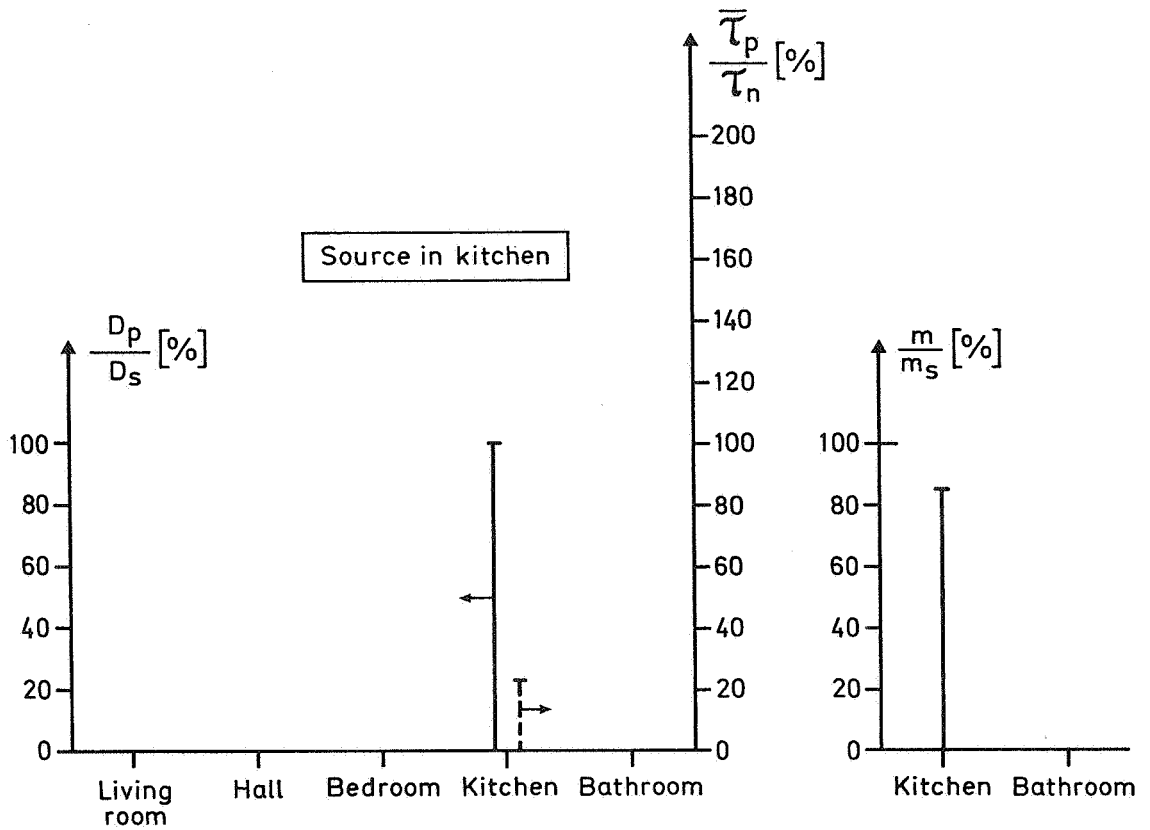


Figure 5b. Balanced system and internal doors closed. 'Contaminant' exposures and mean age of air.

ments due either to mechanical extract system or balanced system. The prerequisite for this statement to hold is of course that we have the same nominal flow rate, that the intake and the supply points are at the same location, and that the air is extracted from the house at the same points on both occasions. The most pertinent data of performances recorded is summarized in table 1.

TABLE 1. Comparison between ventilation systems.
Parenthesis indicate closed door cases.

	Air-ex- change effective- ness	Source in kitchen		Source in bedroom	
		Ventilation efficiency	Mean age of contaminant	Ventilation efficiency	Mean age of contaminant
Extract ventilation	54% (57%)	380% (199%)	0.39 h (0.91 h)	123% (109%)	0.71 h (1.12 h)
Balanced ventilation	37% (50%)	389% (406%)	0.53 h (0.46 h)	58% (93%)	2.20 h (1.42 h)

The mean age of the 'contaminant' in the source room is a measure of how fast the 'contaminant' is evacuated from that room.

From table 1 we can see some differences between the systems. For a 'contaminant' released in the kitchen in a closed door case, the average ventilation efficiency becomes higher with the balanced system in operation. A possible explanation for this behaviour is that a somewhat greater positive pressure difference (see figure 5a) between the supply air room and the kitchen is created with the balanced system in operation. This prevents the spread of the 'contaminant' to rooms with a higher pressure. This gives rise to a low average 'contaminant' exposure in the whole house.

The difference in air-exchange effectiveness between the ventilation systems when the internal doors are open is difficult to explain. When the balanced system is in operation the mean age of the air in the kitchen becomes very great, see figure 4a. A repeat test with a balanced system and an open door case gave an air-exchange effectiveness equal to 51%. Even in this test the mean-age of air in the kitchen is much larger than in other rooms.

5. Conclusions

At the tested flow rate no greater systematic differences in performance between a balanced and an extract system could be found. This is what one should expect for a house as tight as the test house. For both systems the closed door case gave a slight higher air-exchange effectiveness.

'Contaminants' released in the kitchen in a closed door case were somewhat less spread to other rooms with the balanced system in operation compared to the case with the extract ventilation system in operation. This is probably an effect of somewhat greater pressure drop between rooms with the balanced system in operation.

With the doors open and release of 'contaminants' in the kitchen, the bulk of 'contaminant' (70-80% of the total) is extracted from the kitchen itself. The rest is only spread to the bathroom.

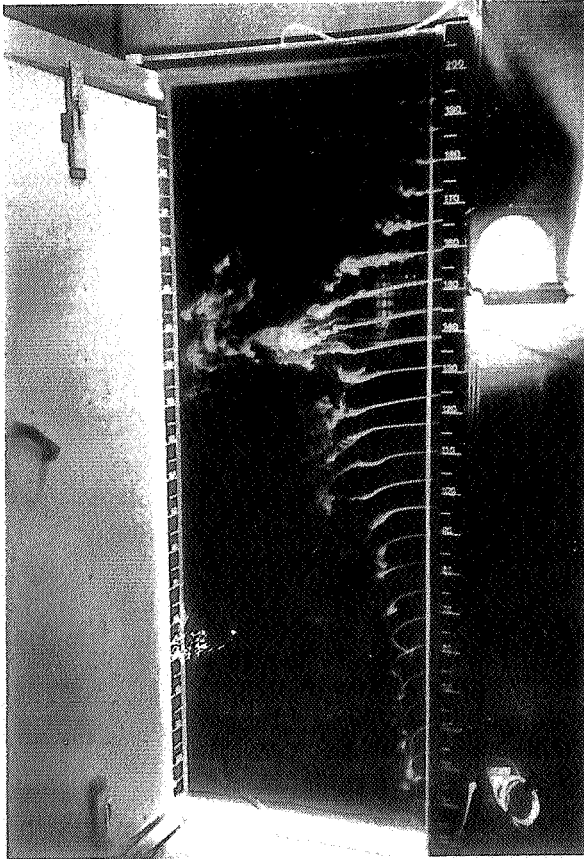
The tests reported here were undertaken for only one flow rate. Further tests at other flow rates must be undertaken in order to interpret the results obtained and to gain a better understanding of the properties of different systems. The balance between individual extract points and supply points should also be systematically varied.

Regarding the experimental technique, it was found that, even in a controlled environment such as the laboratory, it is often difficult to make estimates of absolute quantities such as e.g. the amount of 'contaminant' from different extract points. Drift of the analyzers zero level is one source of error.

6. References

1. Sandberg, M. and Sjöberg, M. 'The use of moments for assessing air quality in ventilated rooms'. Building and Environment, UK, Vol 18, 1983, pp 181-197.
2. Sandberg, M. 'The definition of ventilation efficiency and the efficiency of mechanical ventilation systems'. Proceedings 3rd AIC Conference, 1982.
3. Sandberg, M. and Blomqvist, C. 'A quantitative estimate of the accuracy of tracer gas methods for determination of the ventilation flow rates in buildings'. To appear in Building and Environment, UK, 1985.

APPENDIX



Flow visualization. Balanced ventilation. All pictures taken from the hall.

Door between hall and bedroom



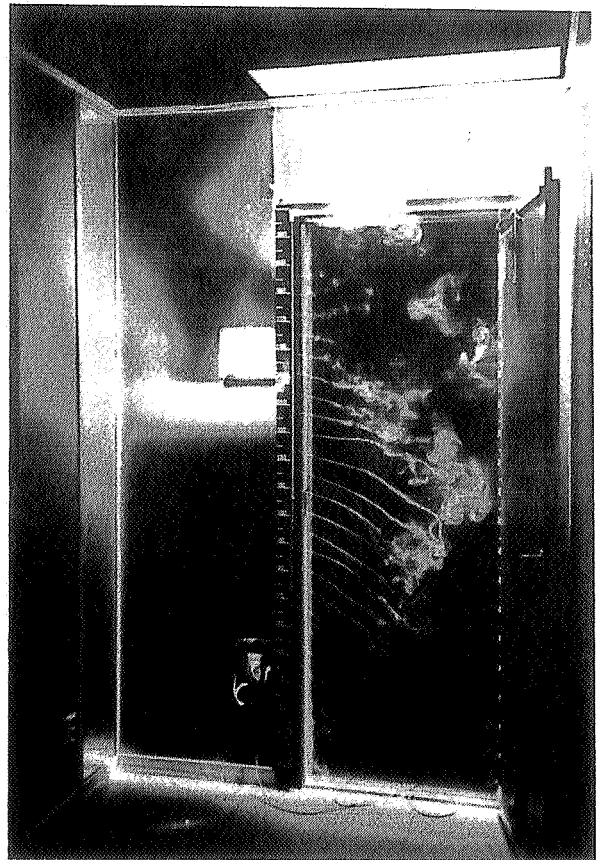
Door between hall and kitchen

APPENDIX



Flow visualization. Balanced ventilation. All pictures taken from the hall.

Door between hall and living-room



Door between hall and bathroom