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EFFICIENCY OF GENERAL VENTILATION SYSTEMS IN RESIDENTIAL AND OFFICE BUILDINGS - CONCEPTS AND MEASUREMENTS

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ABSTRACT

This paper gives a presentation of the current research being carried out at NSIB with the aim of exploring the effectiveness of ventilation systems in controlling contaminant levels.

The key concepts used for quantifying the performance are; the age distribution of both air and contaminants. The air-exchange effectiveness and the average ventilation efficiency are derived from the age distributions. Measurements of the performance of different ventilation systems are given, expressed in terms of the key concepts above. Results from both single room applications and whole houses or buildings are reported.

INTRODUCTION

The volumetric flow rate of outdoor air supplied and the 'air-exchange rate', the latter commonly defined as the flow rate of outdoor air divided by the volume ventilated, have been the parameters commonly used for assessing the performance of general ventilation. The application of the flow rate and the 'air-exchange rate' as parameters is based on the assumption that both air and the contaminants are uniformly distributed throughout the whole ventilated space (complete mixing). However, this assumption is not always fullfilled, nor is complete mixing in general the most efficient principle of ventilation. The problem of quantifying the performance of ventilation systems raises the question of in what terms to express the following factors:

1. The distribution of the ventilation air in the room, i.e. where does it go, how fast and how much.
2. The time it takes to replace, i.e. exchange the air present in the room.
3. The factors that determine the dilution, distribution, and removal of a contaminant released in the room.
4. Expressions for the efficiency of air-exchange, dilution, and removal of contaminants.

A theoretical framework that deals with the above questions has been developed at NSIB. Details are given in ref.1 and ref.2. The approach applied is based on the following key concepts:

The distribution within the room of the outdoor air supplied is quantified by:

* The local net flow rate (purging flow rate) of air at an arbitrary point within the room.
* The age distribution of the air at the same point as represented by its statistical age distribution.

The distribution of a contaminant released within the room is quantified by:

* The local flow rate of a contaminant at an arbitrary point within the room. The age distribution of the contaminant at the same point, as represented by its statistical age distribution.

Only the mean value of the age distribution, i.e. the mean age, has any direct physical interpretation. The mean age of all air present in the ventilated space and the mean age of the air (or the contaminant) at a point within the space are relatively easy to measure with tracer gas technique. At present we do not possess any practical methods for measuring the local flow rates of air or contaminants. However, the local flow rates are amenable to theoretical analysis, and by knowing the mean age, the magnitude of the flow rates may sometimes be estimated, see equation (7). Furthermore, one can expect that the flow rates can be predicted by numerical models that solve the flow equations.

DEFINITIONS AND BASIC RELATIONS

The nominal time constant of a ventialtion system is defined as:

$$\tau_n = \frac{V}{q^t} \tag{1}$$

q^t = the total flow rate of outdoor air entering the ventilated space
V = the total volume.

The physical meaning of the nominal time constant is limited to be equal to the average residence time in the room 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 ventilated space 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 (ref.1, equation (69)):

$$\bar{\tau}_r = 2 \cdot \langle\tau\rangle \tag{2}$$

$\langle\tau\rangle$ = the mean age of the total volume of air present in the ventilated space.

The reciprocal of the nominal time constant

$$n = q^t/V = 1/\tau_n \tag{3}$$

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 flow rate of outdoor air (m^3/h) per total volume (m^3). Therefore, there is a common Scandinavian proposal to call n the specific flow rate. SI units for n is $((m^3/h)/m^3)$ or (room volumes/h). The air-exchange effectiveness is defined as:

$$\varepsilon_a = \frac{\tau_n}{\bar{\tau}_r} \cdot 100 \tag{4}$$

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 leavs the room (turn-over time):

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

$\dot{m}$ = the production rate of the contaminant.

The definition of the ventilation efficiency, $\langle\varepsilon\rangle^C$, is the traditional:

$$\langle\varepsilon\rangle^C = \frac{C_e(\infty)}{\langle C(\infty)\rangle} \cdot 100 \tag{6}$$

$C_e(\infty)$ = equilibrium concentration in the extract duct.

The definitions of the efficiencies given above are in accordance with those currently proposed in Scandinavia.

At an arbitrary point, p, we can expect the following relation to hold between the net flow rate of air, U_p, and the local mean age of the air, $\bar{\tau}_p$, (ref. 1 page 89 or ref.2 page 229).

$$U_p < \frac{\tau_n}{\bar{\tau}_p} q^t \quad (\text{when } \bar{\tau}_p > \tau_n) \tag{7}$$

That is to say that the region surrounding the point is stagnant in the sense that it is not 'flushed' by the total air flow supplied.

MEASUREMENTS IN AN OFFICE ROOM

Measurements have been carried out in a room measuring (width x length x height) = 3.6 x 4.2 x 2.5 m. The room was ventilated by a combined mechanical supply- and extract system. Both the supply and the extract terminals were located at the back wall. The room was both cooled and heated by the ventilation air. As a light contaminant, with similar properties as tobacco smoke, a mixture (density 1.14 kg/m^3) of N_2O and He was used. The contaminant was released in the centre of the room at a height of 1.2 m above floor level. The performance of the following three principle ventilation schemes were monitored; supply air terminal - extract air terminal; ceiling - ceiling, ceiling - floor, floor - ceiling. The results are presented in figure 1. The mean age of the air (□), the mean age of the contaminant (X), and the contaminant exposures (O) are shown. All values have been divided by the value recorded in the extract terminal. That is to say that the mean age of the air has been divided by the nominal time constant, τ_n, the mean age of the contaminant by the turn-over time, τ_e^C, and finally the concentration has been divided by the equilibrium concentration in the extract, $C_e(\infty)$. Each ventilation scheme was tested at three conditions; isothermal, heating, and cooling (ΔT is the temperature difference (^oC) between the supply air and the extract air). The flow rate amounted to 76 m^3/h which corresponds to a nominal time constant of 0.50 h and a specific flow rate of 2 room volumes/h. If we first scrutinize the age distribution of the air we notice that there are two extreme cases. In the first extreme case, ceiling - ceiling system and heating give rise to a direct short-circuiting of air between the supply and the extract air terminals. The time it takes on average to replace the air present in the room is 2 x 0.67 = 1.13 h. The second extreme occurs with a floor to ceiling system and cooling. We now obtain a fast evacuation of the air in the room. As seen from the figure, it now only takes on average 2 x 0.39 = 0.72 h to replace the air in the room. The ceiling to floor system gives rise to a comparatively rapid exchange of the air at heating. However, the evacuation of the contaminant is now delayed. First, due to its bouyancy, it goes upwards, and then it is forced, due to the location of the extract air terminal, to move downwards. Ref.3 gives, for the same ventilation systems as above, results from the release of contaminants with both greater and approximately the same density as air.

MEASUREMENTS IN A TEST HOUSE

The tests reported in this section were carried out in a test house located in the laboratory hall at the Institute. The house and the measuring system belonging to it is designed for studies of the performance of whole-house ventilation systems. The house has five 'rooms', the total volume is 176 m^3, and the floor area is 70 m^2. 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. Each test consisted of three runs:

1:st rum:

* Measurement of the flow rate of outdoor air to each room by the use of the constant concentration method.
* Measurement of the mean age of air in each room and the mean age of all air in the house.

2:nd run:

* Measurements of the transfer to other rooms of a short burst of tracer gas released into the kitchen.

3:rd run:

* Measurements of the transfer to other rooms of a short burst of tracer gas released into the bedroom.

Immediately before and after each run the temperature in each room and pressure difference between each room and the laboratory hall are measured. The flow of air between the rooms through the doorways is visualized by releasing smoke around the doorways, see Appendix. Figures 2a and 2b show an example of a result obtained with a combined mechanical supply- and extract system in operation. The tests were undertaken with all internal doors closed. The tests were carried out at a nominal flow rate, q_n^t, equal to 88 m^3/h, which corresponds to a nominal time constant of 2.0 hours and a specific flow rate of 0.5 house volumes/h. The air was supplied to the living room (about 54% of the total flow rate and to the bedroom. The air was extracted from the kitchen (about 68% of the total flow rate) and the bathroom. Figure 2a first gives the inflow of outdoor air, q_m, to each room as predicted by the constant concentration method. The results 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.

Finally the mean age of the air in each room is given as a percentage of the nominal time constant. Figure 2b gives the results obtained from releasing a contaminant in the kitchen and the bedroom. First is given the recorded time integrated exposures, D_p, divided by the time 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 flow conditions, have obtained with a continous release of contaminant, see ref.1 page 187). On the right-hand side of the figure is given the fraction (m/m_s) of total amount of contaminant released (m_s), that was extracted from the kitchen and bathroom respectively. We see from figure 2b, that when the contaminant is released in the kitchen it does not spread to other rooms because air is directly extracted from the kitchen and the door is closed. On the other hand, when the contaminant is released in a room with no extraction, such as the bedroom, it spreads throughout the whole house. Further results, from the test house, are given in ref.4.

CONCLUSIONS

The examples of the measurements of the performance of ventilation systems, expressed in terms of the concepts presented in the paper, show that:

* The age distributions provide a good insight into how the air and the contaminants spread within a ventilated space. This in turn opens new research possibilities for a systematic evaluation of what factors determine the contaminant levels in a ventilated space.
* By applying the concepts, air-exchange effectiveness and ventilation efficiency, we can compare the performance of general ventilation systems in controlling contaminant levels.

This research is in its very beginning. A better understanding of the spread of contaminants in the boundary layer flow along the surfaces in a room is necessary. A real research challenge remains; namely methods for measuring the local net flow rate of air at an arbitrary point in a ventilated space.

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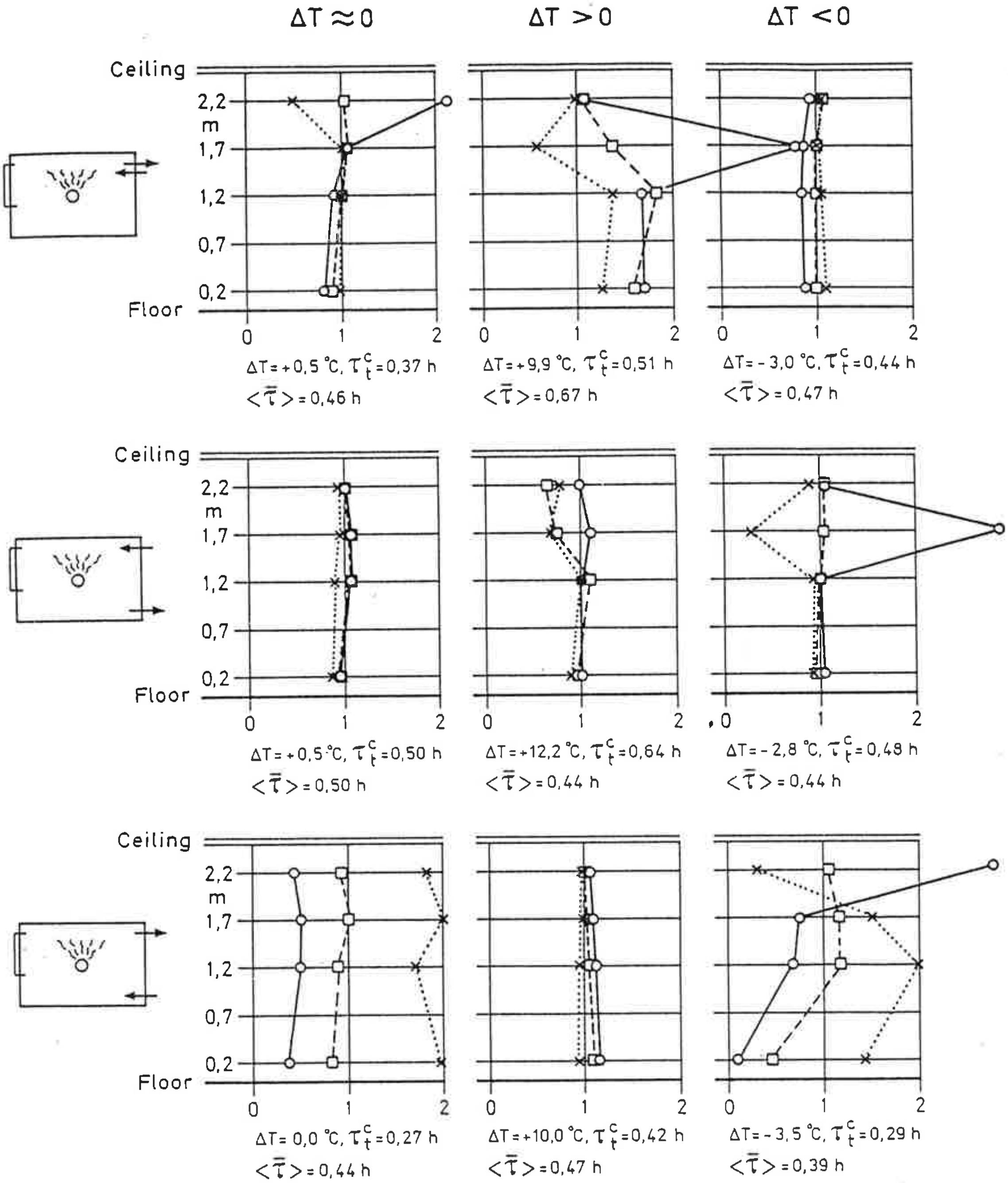


Fig. 1 The mean age of the air (□) and the contaminant (X) plus the contaminant exposures (O). All values are divided by the value recorded in the extract terminal.

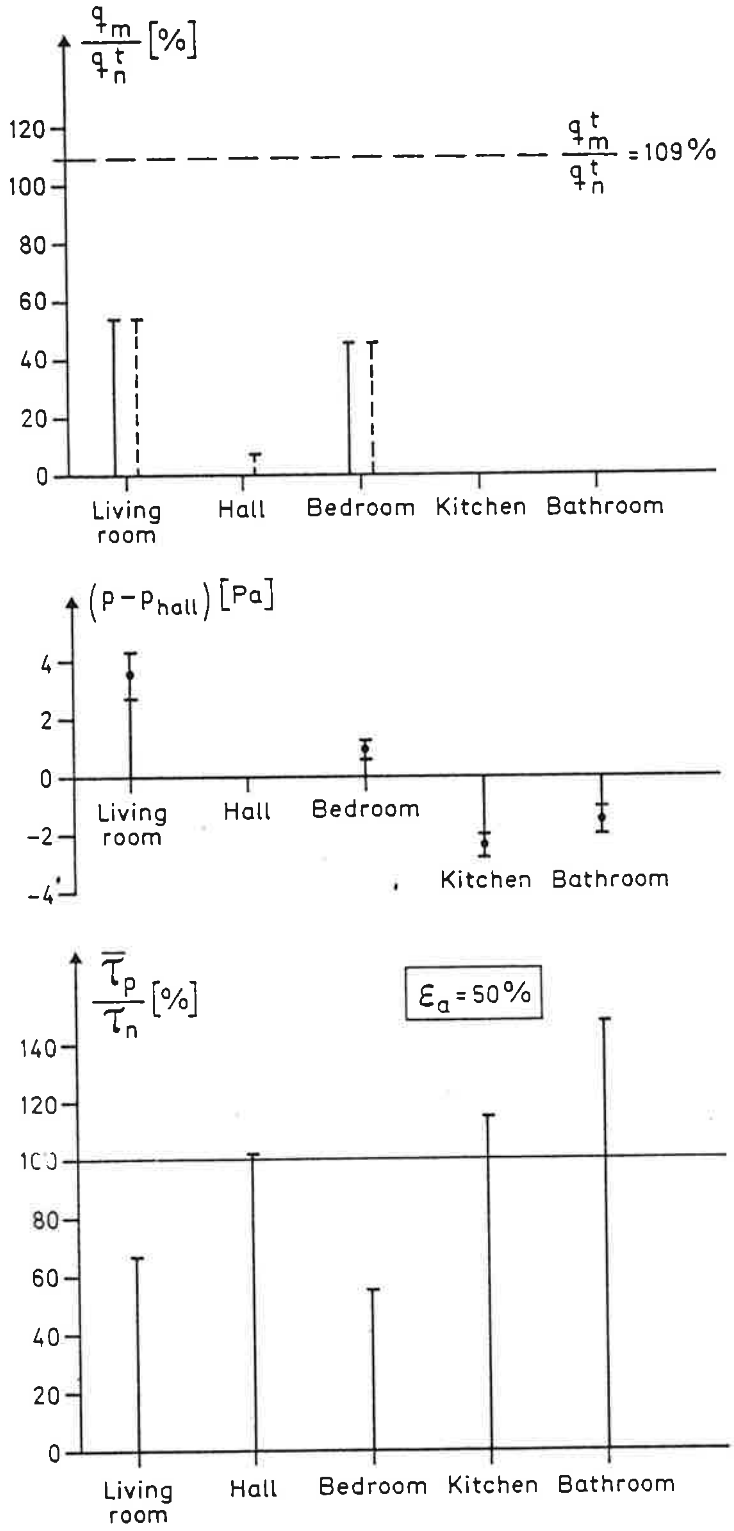


Fig. 2a Combined system and internal doors closed. Supplied air, pressure distribution and mean age of air. The flow set by the mechanical supply is denotet by (———).

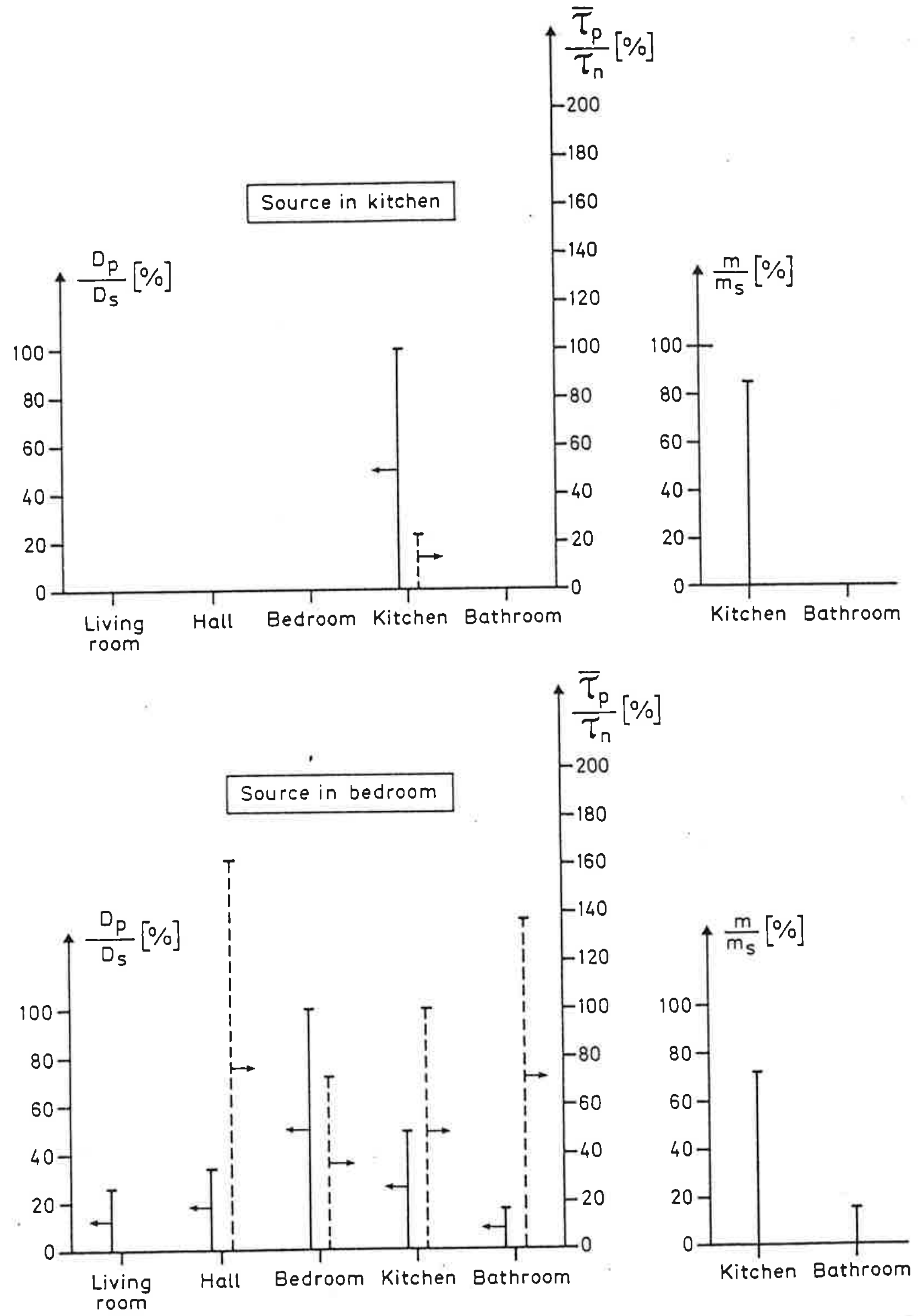
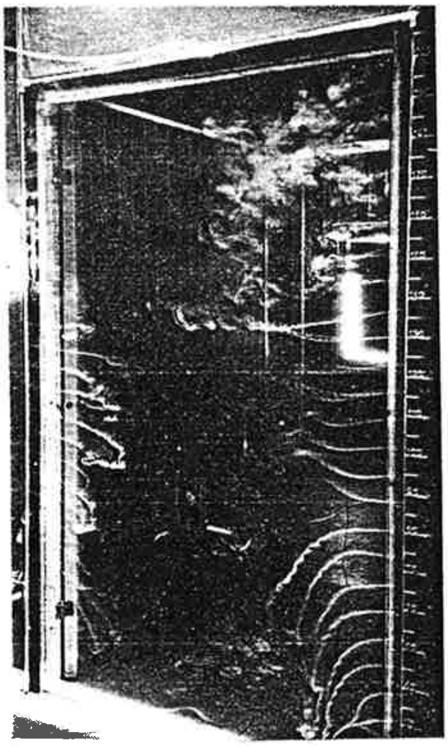


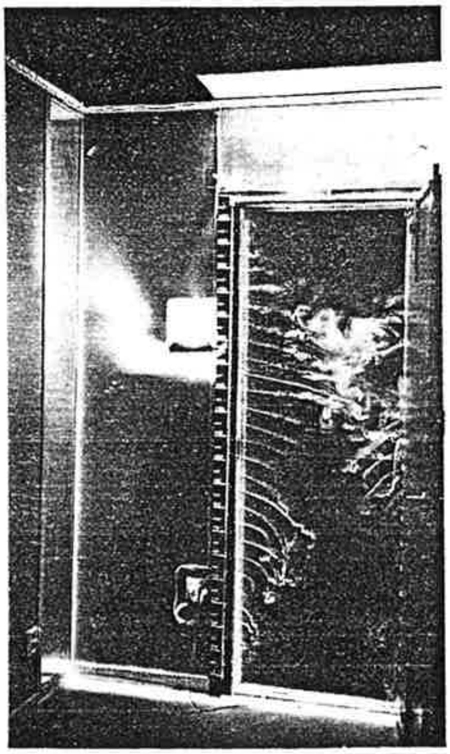
Fig. 2b Combined system and internal doors closed. 'Contaminant' exposures and mean age of air.

APPENDIX

Flow visualization. All pictures taken from the hall.



Door between hall and living room



Door between hall and bathroom