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A Quantitative Estimate of the Accuracy of Tracer Gas Methods for the Determination of the Ventilation Flow Rate in Buildings

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The paper presents a quantitative estimate of the error of the decay and constant concentration method. A number of tests were carried out in an indoor test house located in the laboratory hall at the National Swedish Institute for Building Research. At the beginning of the paper the relevant meaning of the concept 'air-exchange rate' is discussed and an appropriate terminology is suggested. Then follows a presentation of the theoretical background, based on a multi-cell model, of the two tracer gas methods studied experimentally. Finally, the results obtained are given. Apart from the accuracy of the tracer gas methods, some results of studies of the effect on the infiltration rate due to different operation modes of mechanical ventilation systems are also presented.

NOMENCLATURE

A	total area of the building envelope
C	generic symbol for concentration
$C(\infty)$	equilibrium concentration
C_t	target concentration
$\mathbf{C}$	column vector consisting of cell (room) concentrations
$\mathbf{e}$	matrix exponential
$\mathbf{II}$	column matrix whose elements all are unity
K_P, K_I, K_D	constants for proportional, integral and derivation compensation, respectively
$\dot{\mathbf{m}}$	column vector consisting of injected flow rates of tracer gas into all the cells
N	number of tests, or number of recorded concentrations
n	specific flow rate of outdoor air ($n = q^t/V$)
$\mathbf{Q}$	flow matrix whose entries are flow rates between cells (rooms)
q^t	total flow rate of air
q_n^t	nominal total flow rate of air
q_m	measured flow rate of air
q_{mx}	mixing flow rate
s	parameter in transfer functions
V	total volume of system (building or room)
$\mathbf{V}$	diagonal matrix whose entries are the cell volumes.

Greek symbols

λ	exponent of the concentration decay curve at exponential decay
ΔP	pressure difference
ΔP_e	equivalent pressure difference
ΔT	temperature difference
ΔT_e	equivalent temperature
σ	standard deviation
$\bar{\tau}$	mean age of air
$\bar{\tau}_r$	replacement time for room air
τ_{mx}	time constant for mixing of released gas ($\tau_{mx} = V/q_{mx}$)
τ_n	nominal time constant ($\tau_n = V/q^t$)
τ	τ-matrix in the mass balance equation ($\tau = \mathbf{Q}^{-1}\mathbf{V}$).

Other symbols

$\langle\ \rangle$	Mean in the whole system (building or room)
$\langle\ \rangle_4$	Mean of conditions occurring in four rooms (living room, bedroom, kitchen, and hall).

INTRODUCTION

KNOWLEDGE of the total flow rate of air is often the missing link in energy balances of buildings. We possess different experimental procedures, based on tracer gas, for determining the total flow rate. Examples of methods in use are: decay method, constant concentration and constant flow. However, very little is known about their accuracy in multi-cell applications. This is probably because determination of their accuracy requires an independent and accurate knowledge of the flow rate. In the literature there are some reports on the accuracy. Hitchin and Wilson [1] in a survey article, estimated that the accuracy of the decay method should be about 15%. Sherman *et al.* [2] presented a qualitative error analysis of different experimental procedures. Sandberg and Fracastoro [3] have, based on measurements in a two-room indoor test house, made quantitative estimates of the accuracy of the decay method. They found the accuracy in an empty house to be about 10%.

TERMINOLOGY

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:

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

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where

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

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 [4, equation (69)]

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

where

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

The reciprocal of the nominal time constant

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

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 RHS of equation (3), the total flow rate of outdoor air ($m^3\ h^{-1}$) per total volume (m^3). Therefore, there is in Scandinavia a proposal to call n the specific flow rate. SI units for n are ($m^3\ h^{-1}$) m^{-3} or room volumes h^{-1}.

By complete mixing of the air we mean an airflow pattern in the house characterized by the following two conditions:

- The local mean age of the air at all points in a house is equal to the nominal time constant.
- The local net flow rate of air (purging flow rate) at all points within a room is equal to the total flow rate of outdoor air entering the house.

Complete mixing is an ideal flow pattern that we try to establish by using mixing fans.

By uniform mixing of the air within a region, we mean a situation in which the mean age of the air is the same at each point, but differs from the nominal time constant, τ_n. By complete mixing of tracer gas, we mean a situation at which the tracer gas concentration is the same at each point.

A multi-cell model

In [5] a multi-cell model was described, based on the key concepts of mean age of air and local net flow rates (purging flow rate of air). The starting point in the model formulation is the flow matrix **Q**, consisting of the total flow rates of air between the rooms (cells). The sum of the elements in a row (say No. i) of **Q** is equal to the flow rate of outdoor air entering cell i. In an analogous manner the sum of all elements in a column (say No. j) of **Q** is equal to the total flow rate of air transferred directly from the cell j to outdoors. By assuming that there are no totally isolated cells, we can conclude that the flow matrix **Q** is non-singular, and therefore that the inverse $\mathbf{Q}^{-1}$ of the flow matrix always exists. The reciprocal of the diagonal elements in **Q** are the local net flow rates of outdoor air in each cell. We define a τ-matrix as:

$$\boldsymbol{\tau} = \mathbf{Q}^{-1}\mathbf{V} \tag{4}$$

where

V = diagonal matrix of cell volumes.

The sum of the elements in an arbitrary row, say row No. p, is equal to the mean age, $\bar{\tau}_p$, of the air in cell p.

The mass balance equation becomes:

$$\boldsymbol{\tau}\frac{d\mathbf{C}}{d\tau} + \mathbf{C} = \mathbf{Q}^{-1}\dot{\mathbf{m}} \tag{5}$$

where

C = column vector consisting of cell concentrations
$\dot{\mathbf{m}}$ = column vector consisting of injected flow rates of tracer gas in the cells.

The decay from a given initial concentration distribution **C**(0) is governed by:

$$\mathbf{C}(\tau) = \mathbf{C}(0)\mathrm{e}^{-\boldsymbol{\tau}^{-1}\tau} \tag{6}$$

where

$\boldsymbol{\tau}^{-1}$ = inverse of the τ-matrix.

With continuous injection the equilibrium concentration, $\mathbf{C}(\infty)$, attained if governed by:

$$\mathbf{C}(\infty) = \mathbf{Q}^{-1}\dot{\mathbf{m}}. \tag{7}$$

At complete mixing the system of equation (5) is turned into the single equation:

$$\tau_n\frac{dC}{d\tau} + C = \frac{\dot{m}}{q^t}. \tag{8}$$

The decay method

The tracer decay method is by far the most widely used method for measuring the total flow rate of air. Even though this method is well known and extensively used throughout the world, we will here once again scrutinize the basic assumptions behind the method and the limitations of it.

Tracer gas is released into the space. Mixing fans are used in order to create complete mixing. At the state of complete mixing equation (8) holds. Starting from the initial concentration $C(0)$, and with no injection of gas ($\dot{m} = 0$), the solution of (8) is the familiar expression

$$C(\tau) = C(0)\, e^{-\tau/\tau_n}. \tag{9}$$

The decay follows a simple exponential with the exponent equal to $1/\tau_n$. This method therefore, gives the ratio of the total flow rate to the building volume, which is used in turn to calculate the total flow rate by multiplying it by the volume of the building.

However, the occurrence of furniture and cupboards will diminish the ventilated volume to less than the volume of the building.

In that case, the method gives the ratio of the total flow rate to the active volume. The active volume is difficult to measure and must be estimated. A natural choice is to set the active volume equal to the volume of the building. However, this is a source of error whose magnitude is so far more or less unknown.

A second error that occurs is that we do not achieve

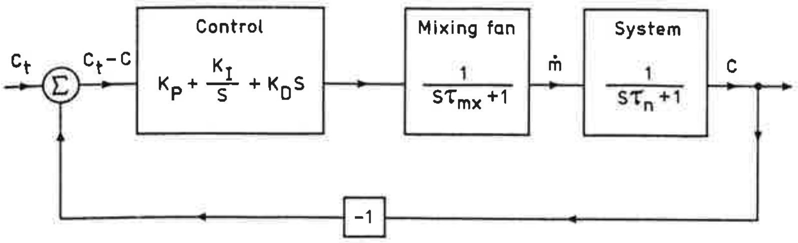


Fig. 1. Block diagram of the constant concentration method.

complete mixing. The concentration decay is then governed the matrix equation (6) above.

In a lin–log plot of the concentration vs time, we then obtain a graph which is curved at the beginning, but after a certain time period becomes a straight line. The straight part of the graph is called the exponential part. The exponent of the exponential part we denote by λ. In Sandberg [5] it was shown that the following relation holds:

$$\min \bar{\tau}_p \leqslant \frac{1}{\lambda} \leqslant \max \bar{\tau}_p \tag{10}$$

where

$\bar{\tau}_p$ = mean age in cell No. p.

That is to say, the magnitude of the reciprocal of the slope of the exponential part lies between the smallest mean age of air occurring in any cell, and the largest mean age of air occurring in any cell. This demonstrates that the slope reflects the average conditions occurring in the system and not the local ones.

This is of great practical importance for the decay method because, as we will see further on, it is difficult to create complete mixing in a whole building. Although we are using mixing fans, the mean age of the air will be different from room to room. In those rooms where the air enters the mean age of the air will be less than the nominal time constant, τ_n. In other rooms, the mean age will be greater than the nominal time constant. However, the slope will reflect the mean for the whole building. Therefore, if the mean value for the whole building is close to the nominal time constant, then we can expect the reciprocal of the slope to give quite an accurate estimate of the nominal time constant.

THE CONSTANT CONCENTRATION METHOD

In the constant concentration method, the release of gas into each room is controlled in such a way that the concentration is kept constant (= the target concentration). If we denote the target concentration by C_t, then the equilibrium concentration can be expressed as:

$$\mathbf{C}(\infty) = C_t \cdot \mathbf{I} \tag{11}$$

where

$\mathbf{I}$ = column vector whose elements are unity.

After inserting equation (11) into equation (7) the latter can be rearranged as:

$$\mathbf{Q} \cdot \mathbf{I} = \frac{1}{C_t} \dot{\mathbf{m}}. \tag{12}$$

The LHS in equation (12) is a vector consisting of the row sums of the elements in the flow matrix **Q**. Each row sum is, as we know from the discussion above, equal to the flow rate of outdoor air entering the cell with the same number as the row number, Therefore, the flow rate of outdoor air to cell No. i, q_i, predicted by the method, is given by:

$$q_i = \frac{1}{C_t} \dot{m}_i \tag{13}$$

where

$\dot{m}_i$ = release rate of gas into cell No. i.

A block diagram of a system with a negative unit feedback for controlling the concentration in each cell (room) is shown in Fig. 1. The control system has proportional (K_P), integral (K_I), and derivative (K_D) compensation. The transfer function for each part of the system is given in the figure. The controlled system has two time constants. First we have the time constant, τ_{mx}, for the mixing of the tracer gas within the room.

$$\tau_{mx} = \frac{V}{q_{mx}} \tag{14}$$

where

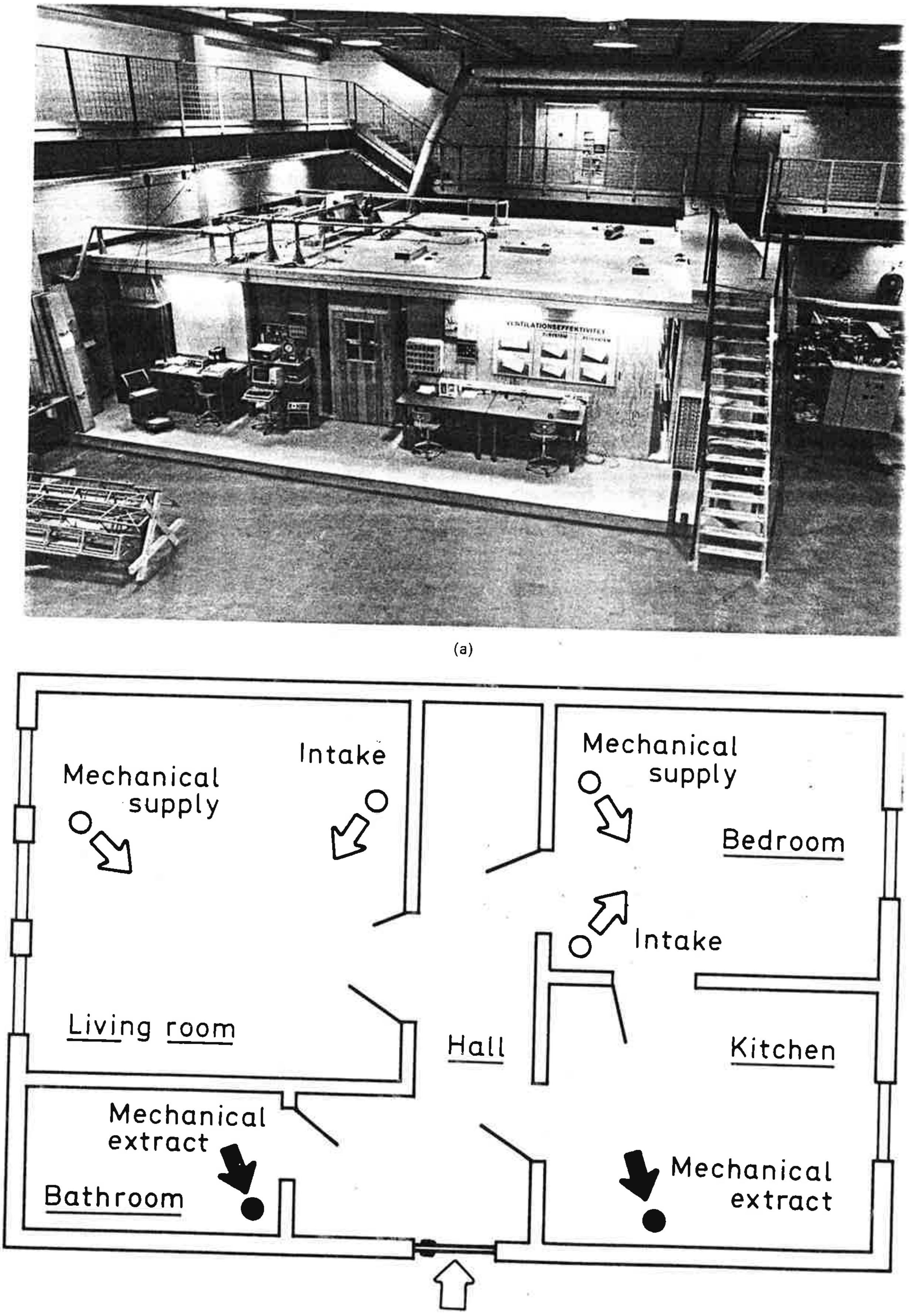
q_{mx} = internal flow rate created by the mixing fans plus other internal sources.

The flow rate set up by a small mixing fan (electrical power 35 W) can be estimated to lie in the range 1000–2000 $m^3 h^{-1}$. This will give rise to a time constant for mixing in the range 0.5–3 min.

The second time constant is the nominal time constant for the ventilation, τ_n, which is based on the flow rate of outdoor air entering the system. For dwellings, the nominal time constant lies in the range 1–4 h.

DESCRIPTION OF TEST HOUSE AND EXPERIMENTAL METHOD

All the tests reported in this article were carried out in the test house shown in Fig. 2. The house is located in the laboratory hall at the Institute. The house has five 'rooms' a total volume of 175.7 m^3, and the floor area is 70.2 m^2. One short wall of the house consists of the existing south



(a)

(b)

Fig. 2. The test house.

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 Pa pressure difference gave rise to a specific flow rate of 0.8 house volumes h^{-1} through the building envelope.

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 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. The measuring and control sequence was as follows:

1. Temperature.
2. Pressure.
3. Constant concentration method.
4. Decay of concentration.
5. A repeat measurement of temperature and pressure.

The whole sequence was controlled by a computer which also starts and stops the mixing fans. In the tests reported here the mixing fans were running during the constant concentration mode and during the decay. From the temperature measurements an equivalent temperature difference across the building envelope is calculated as:

$$\Delta T_e = \sum\left(\frac{A_i}{A}\right)|\Delta T_i| \qquad (15)$$

where

ΔT_i = temperature difference across surface No. i of the building envelope
A_i = area of surface No. i of the building envelope
A = total area of the building envelope.

In an analogous manner an equivalent pressure difference ΔP_e is calculated. In the constant concentration mode the target concentration, C_t, is equal to 50 ppm. The concentration in each room is sampled at a time interval of 120 s. The measured concentration is compared with the target concentration and, if necessary to maintain the target, a calculated amount of gas is injected in a short burst. For each room, the amount of gas injected is summed over a time interval of 30 min. The predicted flow rate of outdoor air to each room is calculated from equation (13). From the concentrations recorded during the decay, the mean age of air in each room is calculated by taking the total area under the curve and dividing it by the initial concentration.

Furthermore, the exponent in the exponential decay part of the curve is obtained by a least-square fit. The tests were carried out at three different nominal total flow rates q_n^l: low (48 m^3 h^{-1}), medium (94 m^3 h^{-1}), and high (242 m^3 h^{-1}). The flow rates in the ducts were measured by orifice plates. The corresponding specific flow rates, n, expressed in house volumes h^{-1} were 0.28, 0.54 and 1.38, respectively. The air was always extracted from the kitchen (about 55% of the total), and the bathroom. When the extract system was in operation two 100-mm-diameter intake holes in the ceiling were opened. One intake was in the living room ceiling, and the other intake was in the bedroom ceiling; see plan of house in Fig. 2. When the balanced system was in operation the air was supplied to the living room and the bedroom. The points of supply are indicated as mechanical supply in Fig. 2.

RESULTS

The decay method

The basic idea behind the decay method is to create complete mixing throughout the whole house. To see if this condition could be met, repeated tests with different numbers of mixing fans in operation were carried out. The total number of mixing fans in operation were two, six and 10, respectively. With only two fans in operation, one was placed in the living-room and the other in the bedroom. With six fans in operation, two were placed in the living-room and one in each of the other rooms. Finally, with a total of 10 fans in operation three were placed in the living-room, one in the bathroom, and two fans in each of the remaining three rooms. During the tests the door to the bathroom was closed, as is usually the case in field trials, while the other internal doors were open.

The average age of the air, $\langle\bar{\tau}\rangle_4$, in the living-room, bedroom, kitchen and hall, was obtained by taking the arithmetic mean of the mean age recorded in each individual room. In an analogous manner an arithmetic mean $\langle 1/\lambda\rangle_4$ was calculated of the reciprocal, $1/\lambda$, of the slope of the decay curve. The standard deviation of the mean age, $\sigma_{\bar{\tau}}$, and the reciprocal of the slope for these four rooms is presented in Table 1, and Figs. 3 and 4. We observe that complete mixing is not created.

The variation in mean age between the rooms is quite large, while for the reciprocal of the slope the variation is smaller. With increased flow rate the variations diminish. This is due to the increased mixing induced by the supplied flow rate itself. The opening areas of the supply air registers of the balanced system, and of the intakes of the extract system, are kept constant. Subsequently the momentum flow is increased as the flow rate is increased. By comparing

Table 1. The standard deviation $\sigma_{\bar{\tau}}$ of the mean age of air and the standard deviation $\sigma_{1/\lambda}$ of the reciprocal of the slope

Specific flow rate (house volumes h^{-1})	Extract system		Balanced system	
	$\sigma_{\bar{\tau}}$	$\sigma_{1/\lambda}$	$\sigma_{\bar{\tau}}$	$\sigma_{1/\lambda}$
$n = 0.28$	24% $N = 7$	13% $N = 7$	24% $N = 4$	8% $N = 4$
$n = 0.54$	14% $N = 7$	8% $N = 7$	24% $N = 4$	9% $N = 4$
$n = 1.38$	10% $N = 7$	6% $N = 7$	14% $N = 4$	3% $N = 4$
	16% $N = 21$	9% $N = 21$	21% $N = 12$	7% $N = 12$

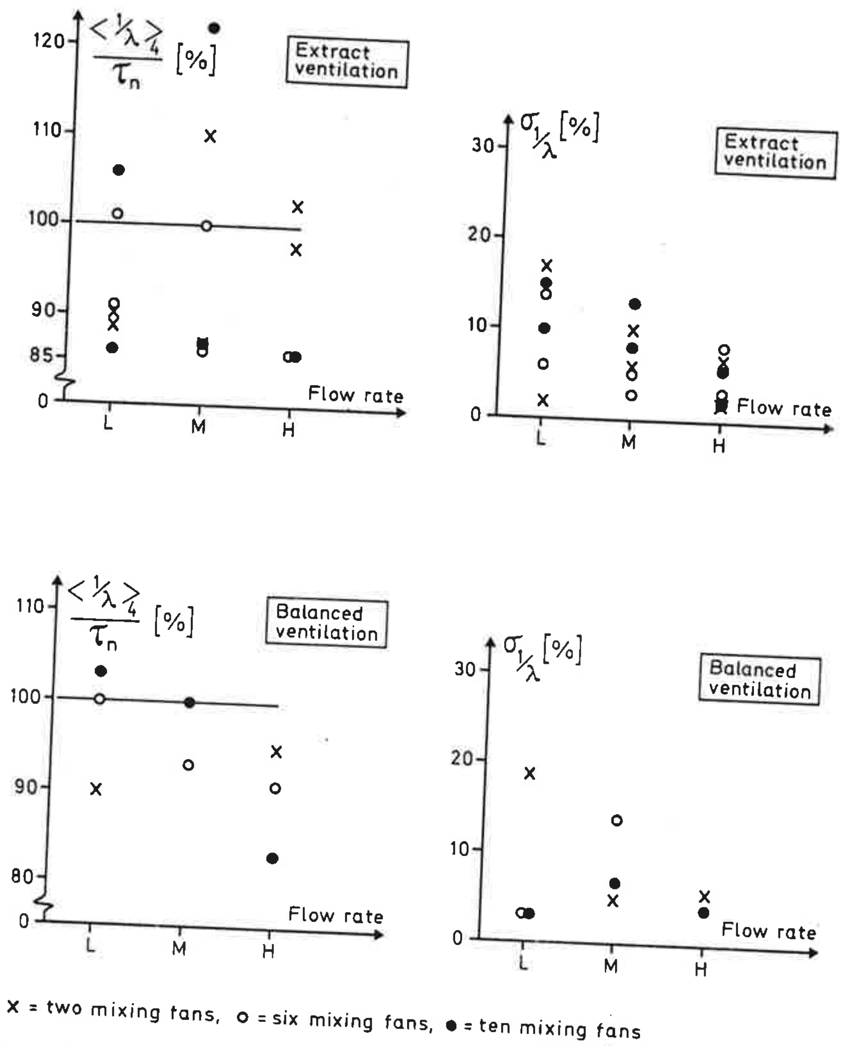


Fig. 3. Measured reciprocal, $1/\lambda$, of the slope of the decay curves. Flow rates (house volumes h^{-1}): L ($n = 0.28$), M ($n = 0.54$), H ($n = 1.38$).

the balanced and the extract system, we observe that we obtain larger variations, at the same flow rate, when the balanced system is in operation. With the balanced system in operation the supply of air is concentrated to two points only, while with the extract system in operation the supply of air is more spread out.

The accuracy of the decay method is given in Table 2. Because the extract system, contrary to the balanced systems, maintains a constant flow rate free from disturbances, the estimate of the accuracy is based on tests with only the extract system in operation.

Two measuring strategies have been explored. The first

Table 2. The estimated accuracy obtained from tests with the extract system in operation

Specific flow rate (house volumes h^{-1})	Decay method		Constant concentration method
	$\frac{\langle 1/\lambda \rangle_4 - \tau_n}{\tau_n}$	$\max \frac{[(1/\lambda - \tau_n)]}{\tau_n}$	$\frac{q_m^t - q_n^t}{q_n^t}$
$n = 0.28$	8% $N = 7$	13% $N = 7$	8% $N = 8$
$n = 0.54$	14% $N = 7$	19% $N = 7$	5% $N = 8$
$n = 1.38$	11% $N = 7$	17% $N = 7$	5% $N = 8$
	11±6% $N = 21$	16±7% $N = 21$	6±3 $N = 24$

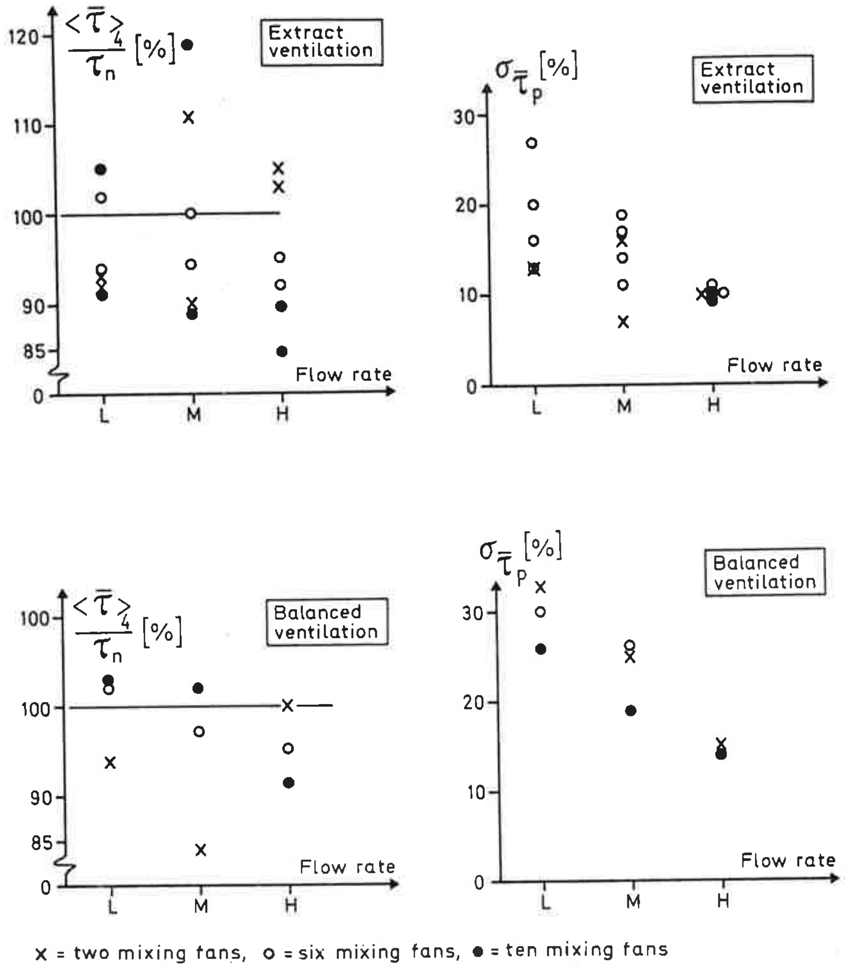


Fig. 4. Measured mean age of air, $\bar{\tau}$. Flow rates (house volumes h^{-1}): L ($n = 0.28$), M ($n = 0.54$), H ($n = 1.38$).

is based on the arithmetic mean of the reciprocal of the slope obtained from the living-room, bedroom, kitchen and the hall. The second measuring strategy is a 'worst case' situation, based on measurements from one room only. The room with the greatest deviation from the nominal time constant has been selected in each test. The accuracy of the method based on data from four rooms is 10.8±6.2% while with data from one room only and the 'worst case' situation the accuracy is 16.2±6.8%. These figures are based on data from a total of 21 tests. It should again be stressed that these accuracies only hold for the active volume divided by the total flow rate. To determine the total flow rate we must also determine the active volume. This is an extra source of error that will give an accuracy for the total flow rate which is poorer than the figures above.

The constant concentration method

The advantages of the more expensive constant concentration method are claimed to be as follows:

- The prediction of the total flow rate with a high degree of accuracy.
- The prediction of the flow rate of air entering each separate room.
- The prediction of the time-dependent flow rate of air.

The evaluation of the first point above is presented in Table 2. The conditions during the tests were the same as when the accuracy of the decay method was determined. All internal doors were open except the door to the bathroom. Based on a total number of 21 tests the accuracy obtained is 6.0±3.2%. Three tests with all internal doors closed were also carried out. Then the accuracy improved and became 1%.

When it comes to the second point above (i.e. the distribution of the air entering the house) it is more difficult to evaluate the accuracy. Examples of predictions of the distribution of the incoming air to individual rooms from runs with the balanced system are presented in Fig. 5, and from runs with the extract system in operation in Fig. 6. In Figs. 5 and 6 the left-hand columns are from tests with *all* internal doors *open*, while the right-hand columns are from tests with *all* internal doors *closed*. The horizontal line of short dashes in each of the figures indicates the ratio between the predicted total flow rate and the total nominal flow rate.

Due to the location of the supply registers of the balanced system, and the location of the openings when the extract system was in operation, we know that the bulk of air enters the living-room and the bedroom. However, from the results obtained for the open-door case, we see that quite a large inflow of outdoor air into the hall is

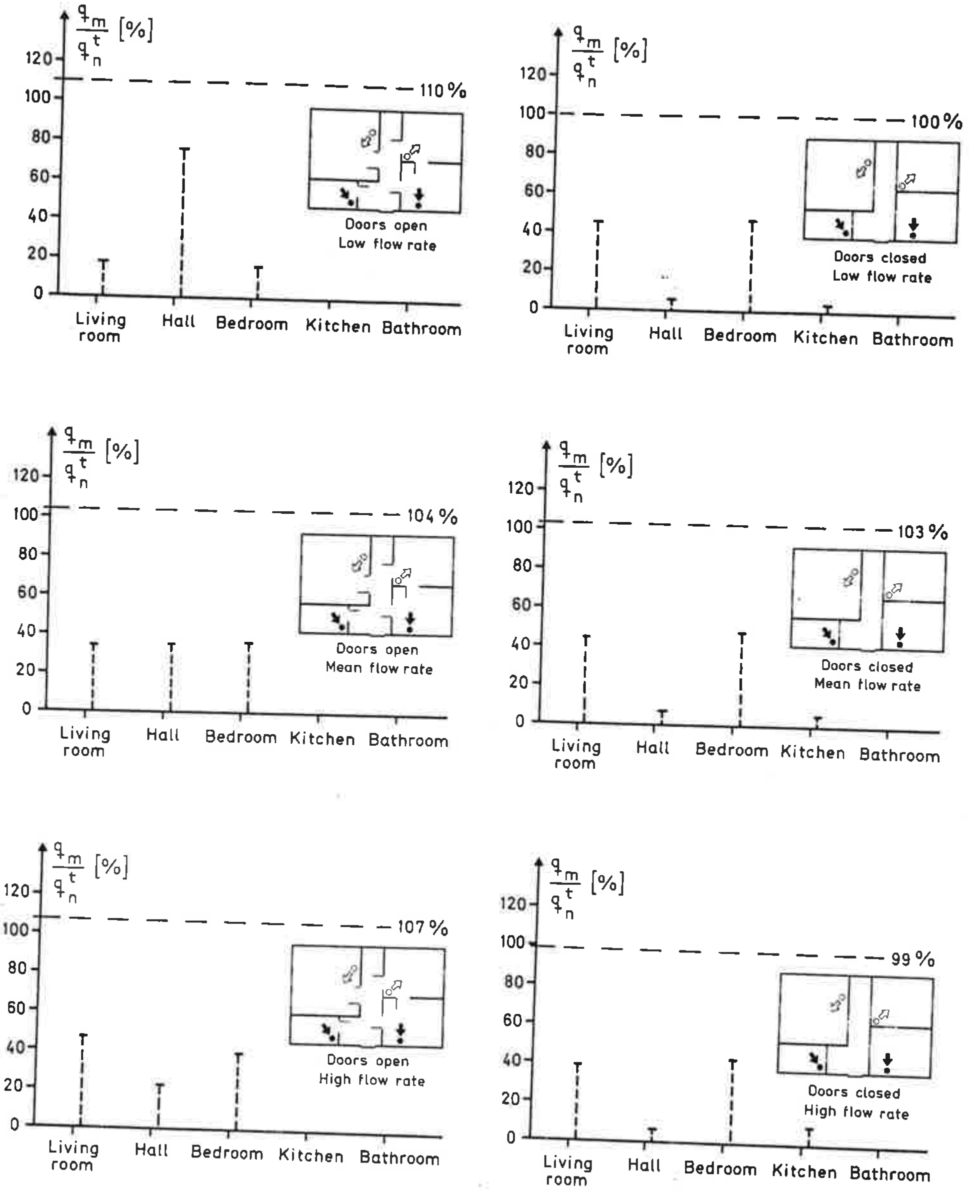


Fig. 5. The constant concentration method. Extract system. Examples of predicted flow rates ---.

predicted. What happens is that a part of the air that enters the living-room and the bedroom flows directly towards the hall. This inflow of air into the hall from the neighbouring rooms is predicted as direct inflow of outdoor air into the hall. Therefore if we aim at locating which rooms the outdoor air first enters we do not obtain the correct information. On the other hand if we are more concerned about the air quality it is perhaps wrong to claim that the method does not predict the correct distribution of incoming outdoor air. In spite of the fact that the outdoor air first comes to the living-room and the bedroom, it is more or less 'unused' outdoor air that flows towards the hall. Or to put it another way, there is a certain ambiguity in defining what is incoming fresh outdoor air. When all the internal doors are closed the situation is clearer, and as seen in Fig. 5 for the predicted distribution, is close to the correct one.

Figure 7 shows the response of the method to a step change in the total flow rate. The ventilation system in operation is an extract system.

The predicted value constitutes an average over a time period of 0.5 h. With no integral control we obtain a steady-state error. By adding an integration term to the control algorithm the steady-state error disappears. However, we still have quite large oscillations around the correct value. By finally adding a derivation term the predicted flow rate quite neatly follows the step change. However, it takes a time period of approx. 1.5 h to rise to the final flow rate. This demonstrates that the method is too slow to predict fast changes in total flow rates occurring when, for example, a window is opened.

The instantaneous concentrations were measured during the step changes in total flow rates. An example of the recorded concentrations are shown in Fig. 8. Table 3

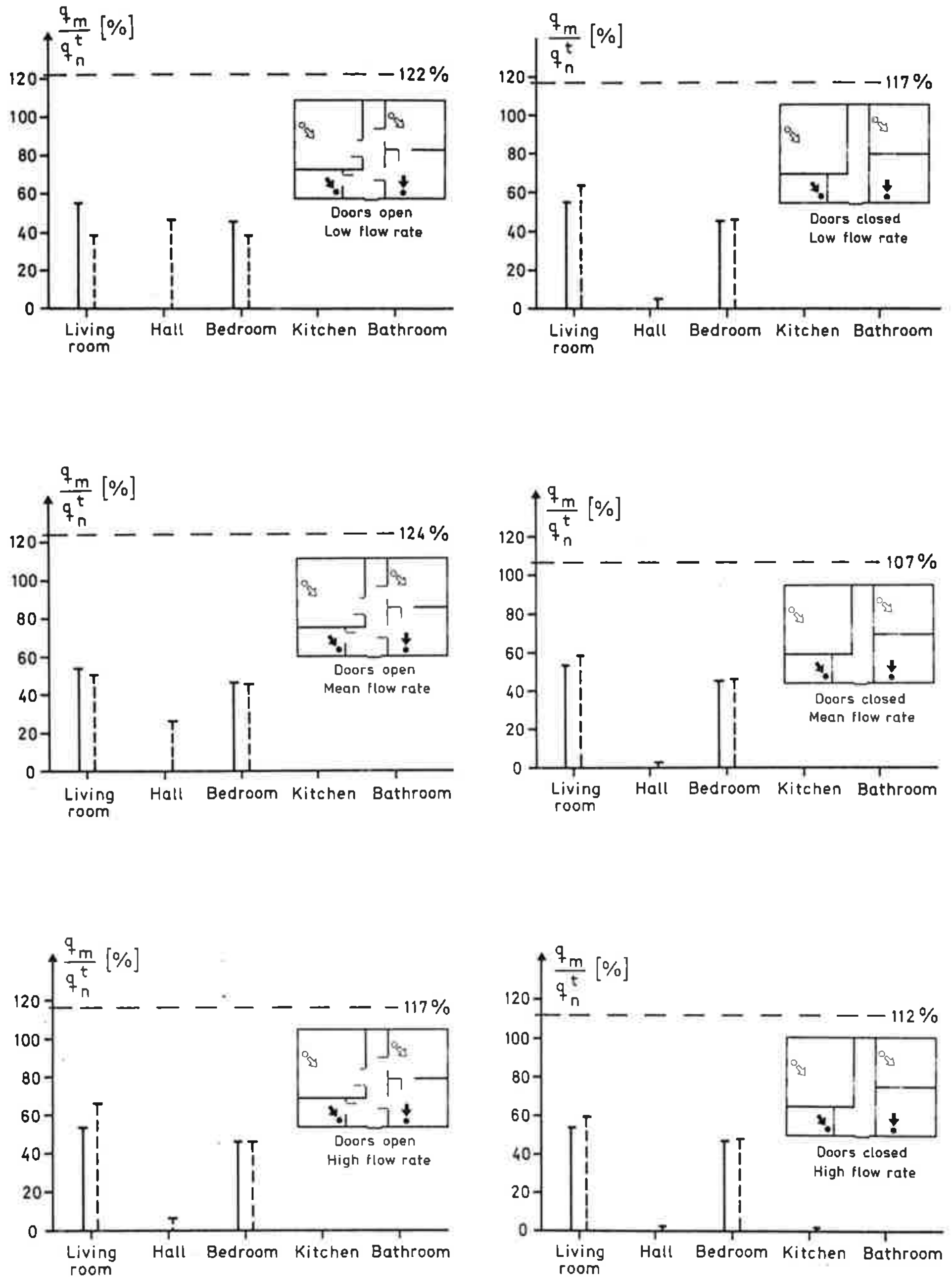


Fig. 6. The constant concentration method. Balanced system. Examples of predicted flow rates ----. The mechanical supply is denoted by ——.

Table 3. Mean concentration in ppm and standard deviation in each room during the step changes in total flow rates presented in Fig. 7

Case	Control algorithm	Living-room	Hall	Bedroom	Kitchen	Bathroom
1 $N = 240$	$K_P = 0.10$ $K_I = 0.00$ $K_D = 0.01$	49.9±2.8	50.3±2.7	49.9±2.0	50.0±1.4	50.1±1.0
2 $N = 240$	$K_P = 0.05$ $K_I = 0.001$ $K_D = 0.0$	50.0±2.9	50.3±2.0	50.0±2.3	50.0±1.4	50.5±1.2
3 $N = 240$	$K_P = 0.05$ $K_I = 0.0004$ $K_D = 6$	49.9±1.6	50.3±1.2	49.9±1.3	50.0±0.7	50.0±0.6

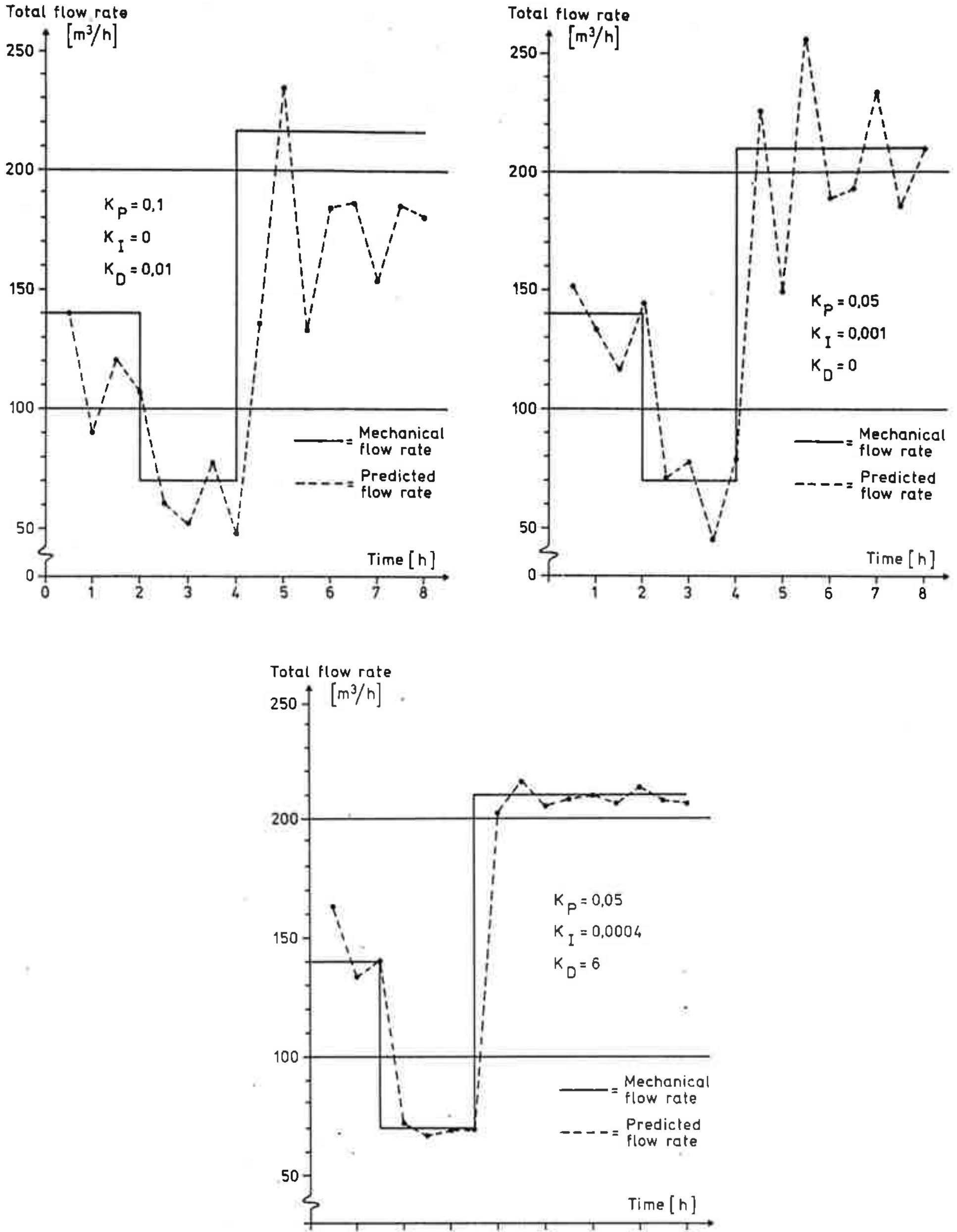


Fig. 7. The constant concentration method. Response to step changes in total flow rate.

gives the mean concentration and the standard deviation for the three cases in Fig. 7. The mean concentrations in each room in case 3 are close to the target concentration of 50 ppm.

The effect on the infiltration rate due to different operation modes of mechanical ventilation

The tests reported in Figs. 5 and 6 give insight into the effect on the infiltration rate due to the pressurization of individual rooms and whole house by mechanical ventilation. In each test the pressure drop across the building envelope was monitored before and after the test. Tables 4 and 5 give for the cases reported in Figs. 5 and 6 the monitored pressure drop (in Pa) between each room and the laboratory hall.

Infiltration should be reduced by greater pressurization of individual rooms or the whole house. If we compare Figs. 5 and 6 we see that the extract system, as expected, gave rise to a systematically lower infiltration rate than the balanced system. For both systems we observe that the infiltration rate is lower when the interval doors are closed compared to when the internal doors are open. It should be stressed that in these tests the balanced system was run with an exact balance between the supplied flow rate and the extract flow rate. In practice, the systems are run with a slight underbalance in the sense that more air is mechanically extracted than is mechanically supplied.

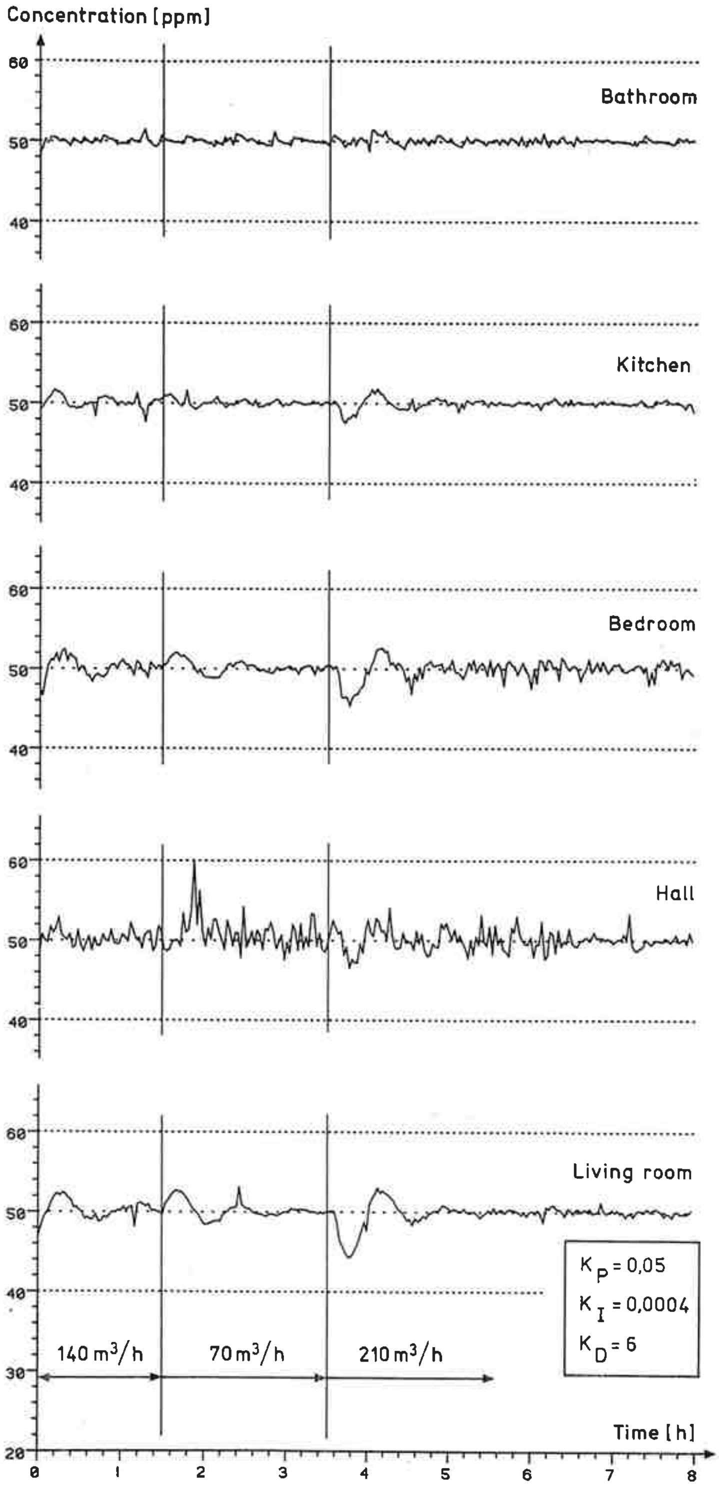


Fig. 8. The constant concentration method. Recorded instantaneous concentrations during a step change in total flow rate.

Table 4. Extract system. Pressure drop (Pa) between each room and the laboratory hall

Specific flow rate (house volumes h^{-1})	$n = 0.28$				$n = 0.54$				$n = 1.38$			
	All internal doors open		All internal doors closed		All internal doors open		All internal doors closed		All internal doors open		All internal doors closed	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Living-room	−1.2	−0.9	−0.8	−1.0	−3.4	−3.3	−2.2	−2.2	−14.5	−14.8	−9.8	−10.2
Hall	−1.1	−1.0	−1.8	−1.9	−3.1	−3.2	−4.9	−4.4	−14.4	−14.6	−20.8	−21.2
Bedroom	−1.0	−1.0	−1.4	−1.6	−3.3	−3.2	−4.0	−3.7	−14.1	−14.7	−18.1	−18.2
Kitchen	−1.0	0.9	−2.2	−2.4	−2.8	−3.1	−6.7	−6.1	−14.7	−14.7	−30.2	−30.8
Bathroom	−1.4	−1.1	−2.5	−2.7	−3.1	−3.2	−7.0	−6.4	−14.9	−14.7	−27.5	−28.0

Table 5. Balanced system. Pressure drop (Pa) between each room and the laboratory hall

Specific flow rate (house volumes h^{-1})	$n = 0.28$				$n = 0.54$				$n = 1.38$			
	All internal doors open		All internal doors closed		All internal doors open		All internal doors closed		All internal doors open		All internal doors closed	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Living-room	1.1	0.0	2.3	2.2	1.4	2.0	4.1	—	3.1	2.5	16.2	16.5
Hall	1.1	0.0	0.9	0.7	1.3	2.0	0.6	—	2.7	2.7	0.8	1.3
Bedroom	1.2	0.1	1.1	1.0	1.5	2.0	1.3	—	3.0	2.8	3.0	3.5
Kitchen	1.3	0.1	0.2	0.2	1.6	2.1	−1.3	—	3.0	3.0	−9.2	−8.5
Bathroom	1.2	0.0	−0.2	0.0	1.3	2.0	−0.7	—	2.8	2.9	−5.7	−4.6

CONCLUSIONS

Tests were carried out in an unoccupied and unheated five-room indoor test house with no furniture. By using two, six and 10 desk fans, respectively in no case did we achieve complete mixing in the house. The standard deviation of the mean age of air between rooms amounted to 24% at the lowest flow rate, while at the highest flow rate the standard deviation was reduced to 10%. This reduction at the highest flow rate is caused by the increased momentum flow of the supply air. The variation from room to room in the exponent of the exponential decay curves shows less variation than the variation in mean age. This is so because the exponent reflects an average value of the decay rate for the whole house. Ten mixing fans did not prove to be better than using only six fans. Therefore as a rule of thumb for an ordinary house, two mixing fans in the largest room and one in each of the other rooms would seem to be sufficient.

In the case of the decay method two measuring strategies were explored. By taking the mean value of the slope in four rooms the accuracy obtained was 11±6%. Based on measurements in one room only, and a 'worst case situation', i.e. the room with the largest deviation from the true value, the estimated accuracy was 16±7%. The accuracy of the decay method refers to the ratio between estimated volume of the test house and the total flow rate. We can expect the accuracy of the decay method in predicting the total flow in an occupied house to be poorer.

Based on a total of 21 repeated tests, the accuracy of the constant concentration method in predicting the total flow was found to be 6±3%. When all internal doors are closed, the flow rate to each separate room is predicted with a similar accuracy.

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