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COMPARISON OF TRACER GAS METHODS FOR MEASURING AIR FLOWS IN TWO ZONE BUILDINGS

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ABSTRACT

This paper discusses three methods for measuring interzonal air movements in two zone buildings:

1. initial injection of one tracer into a single room,
2. repeated injection of one tracer in two rooms,
3. initial injection of two tracers in two rooms.

The description of these methods includes an outline of the theoretical background, the presentation of suitable injection strategies and algorithms for the evaluation of the concentration profiles. A detailed error analysis using Monte-Carlo-Simulation shows the accuracy of these methods for a variety of cases, such as different magnitudes of the interzonal air flows and various measurement durations. The numerical results agree with tracer gas measurements conducted at a laboratory-scale physical model with two chambers.

1. INTRODUCTION

The knowledge of the air exchange between the interior and the exterior of a building (external air exchange) as well as between its individual rooms (interzonal air flow) is of great practical importance for its thermal, physical and hygienic characterization. Examples are the energy or the moisture balance of the building or the concentration of air pollutants in the interior. In passive solar buildings, the interzonal air exchange fulfills further important functions, such as convective heat transfer between the locations of solar gain, storage and use.

Unfortunately, air exchange is one of the least understood processes in building physics, since it is determined by a variety of parameters, which are not easily accessible. They include climatic parameters (e.g. wind velocity and temperature), building related parameters (e.g. shape and location of the windows) and behavior of the inhabitants. Theoretical calculations of air exchange rates are therefore difficult and unreliable. Accurate results for the quantity of air flows in a building can only be obtained by measurements. There are two principal measuring methods:

- pressurization methods,
- tracer gas methods.

Pressurization methods are suitable for leakage tests of a whole building or for measuring the external air exchange rate under standardized conditions (i.e. a fixed pressure difference between inside and outside). Tracer gas methods are capable of the determination of the external and the interzonal air flows under natural conditions.

Tracer gas methods for the measurement of the external air change rate are widely used in the field. They have been standardized in several countries [1,2]. Tracer gas methods for the measurement of interzonal air flows are still an area of research. Several laboratories have built multiple tracer gas systems, where a different tracer substance is used for each zone [3,...,9]. Various single tracer gas methods have been proposed [10,...,13] in order to avoid the simultaneous handling of multiple tracer gases. However, these methods are still in an early stage of development.

It is the purpose of this paper to compare several tracer gas methods for the measurement of interzonal airflows. Two single tracer and one multiple tracer gas method will be considered. This comparison is based on

- theoretical investigations,
- Monte Carlo simulation using synthetic data,
- air flow measurements using a small scale two zone building model with adjustable airflows.

The restriction to two zones simplifies the theoretical treatment and the experimental setup. It is adequate for the modelling of single family houses with a ground floor and an upper floor.

2. MEASUREMENT METHODS FOR THE AIR FLOW IN TWO ZONE BUILDINGS

2.1 Basic Equations

In order to measure the air flows between the zones of a building, it is necessary to distinguish at each moment of time between air that enters a certain zone from the outside or from a neighboring zone and air that has already been present in that zone. To this end, one marks the air in the zone under investigation with a tracer gas. The tracer concentration varies with time and tells at each moment the relation of "old air" to "fresh air".

Figure 1 describes this process in detail for a two zone building model. Two zones numbered 1 and 2 are interconnected with each other as well as with the outside air (0). Tracer gas is injected into each zone, resulting in a certain tracer gas concentration. Zones 1 and 2 are characterized by

V_i volume in m^3,

$c_i(t)$ tracer gas concentration (dimensionless),

$Q_i(t)$ tracer gas injection rate in m^3/h,

where i = 1,2. The outside air (zone 0) can be described by

$V_0 \rightarrow \infty$ infinite volume,

$c_0(t) = 0$ zero tracer gas concentration,

$Q_0(t) = 0$ no tracer gas injection.

F_{ij} denotes the air flow from zone i to zone j. Further we assume,

- the air flows do not vary with time: $F_{ij} \neq F_{ij}(t)$
- the total air flow into a zone is equal to the total air flow out of that zone:

  $$\sum_j F_{ij} = \sum_j F_{ji} ,$$

- the temperature (and thus the density of air) does not vary with time,
- the tracer gas concentration is uniform in each zone.

According to these assumptions, we can write the conservation of tracer gas in each zone as a volume balance:

$$V_1 \dot{c}_1(t) = - (F_{10} + F_{12})\, c_1(t) + F_{21}\, c_2(t) + Q_1(t) \qquad (1a)$$

$$V_2 \dot{c}_2(t) = F_{12}\, c_1(t) - (F_{20} + F_{21})\, c_2(t) + Q_2(t) \qquad (1b)$$

or with

$$F_{01} + F_{21} = F_{10} + F_{12} = - F_{11} \qquad (2a)$$

$$F_{02} + F_{12} = F_{20} + F_{21} = - F_{22} \qquad (2b)$$

as

$$V_1 \dot{c}_1(t) = F_{11}\, c_1(t) + F_{21}\, c_2(t) + Q_1(t) \qquad (3a)$$

$$V_2 \dot{c}_2(t) = F_{12}\, c_1(t) + F_{22}\, c_2(t) + Q_2(t) \qquad (3b)$$

Rather than expressing the air and tracer gas flows in absolute quantities, we can relate them to the volume of this zone

$$f_{11} = \frac{F_{11}}{V_1} = - \frac{F_{01} + F_{21}}{V_1} = - \frac{F_{10} + F_{12}}{V_1} , \quad f_{12} = \frac{F_{21}}{V_1} \qquad (4a,b)$$

$$f_{22} = \frac{F_{22}}{V_2} = - \frac{F_{02} + F_{12}}{V_2} = - \frac{F_{20} + F_{21}}{V_2} , \quad f_{21} = \frac{F_{12}}{V_2} \qquad (4c,d)$$

$$q_1(t) = \frac{Q_1(t)}{V_1}, \quad q_2(t) = \frac{Q_2(t)}{V_2} \qquad (5a,b)$$

and obtain

$$\dot{c}_1(t) = f_{11}\, c_1(t) + f_{12}\, c_2(t) + q_1(t) \qquad (6a)$$

$$\dot{c}_2(t) = f_{21}\, c_1(t) + f_{22}\, c_2(t) + q_2(t) \qquad (6b)$$

or in matrix notation

$$\dot{\underline{c}}(t) = \underline{\underline{f}}\ \underline{c}(t) + \underline{q}(t) \tag{7}$$

$$\underline{c}(t) = \begin{vmatrix} c_1(t) \\ c_2(t) \end{vmatrix}, \quad \dot{\underline{c}}(t) = \begin{vmatrix} \dot{c}_1(t) \\ \dot{c}_2(t) \end{vmatrix} \tag{8a,b}$$

$$\underline{\underline{f}} = \begin{vmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{vmatrix}, \quad \underline{q}(t) = \begin{vmatrix} q_1(t) \\ q_2(t) \end{vmatrix} \tag{8c,d}$$

The problem is to estimate the elements of the flow matrix f from measurements of the tracer gas concentration. However, Equation (7) is not suitable for this purpose, since it requires also the knowledge of the derivative of the tracer gas concentration. In principle, it could be obtained from the measurement values of the concentration by numerical differentiation, but the result would be very sensitive to measurement errors. Instead, the elements of the flow matrix can be determined by an eigenvalue analysis. Another possibility is to remove the derivative of the concentration by integrating (7) over the time interval of the measurement, say for $t_0 < t < t_1$. One obtains

$$\underline{c}_\Delta = \underline{\underline{f}}\ \underline{c}_I + \underline{q}_I \tag{9}$$

with

$$\underline{c}_\Delta = \begin{vmatrix} c_1(t_1) - c_1(t_o) \\ c_2(t_1) - c_2(t_o) \end{vmatrix} \tag{10a}$$

$$\underline{c}_I = \begin{vmatrix} \int_{t_o}^{t_1} c_1(t)\,dt \\ \int_{t_o}^{t_1} c_2(t)\,dt \end{vmatrix}, \quad \underline{q}_I = \begin{vmatrix} \int_{t_o}^{t_1} q_1(t)\,dt \\ \int_{t_o}^{t_1} q_2(t)\,dt \end{vmatrix} \tag{10b,c}$$

Equations (7) and (9) are called the differential and the integral form of the tracer gas conservation law. Although the integral form does not contain any derivatives of the measurement values, it cannot be readily solved for the elements of the flow matrix, since the set of linear equations is underdetermined. Additional information in form of a second set of equations is necessary in order to invert the integral conservation law. Two different methods will be discussed here: The second set of equations can be obtained by integrating the concentration data over a second time interval or by using a second tracer gas and applying the conservation law to two tracer gases.

The above mentioned methods for the determination of the flow matrix differ by the form of the conservation law and the number of tracer gasses:

form of conservation law	number of tracers	injection strategy	name of method
differential	one	initial	eigenvalue analysis
integral	one	repeated	pulse decay
integral	two	initial	two tracer decay

The second method is called the pulse decay method, because a new pulse of tracer gas is injected before each integration interval. The names of the other methods are obvious. These methods and their injection strategies will now be described.

2.2 Eigenvalue Analysis

This method has been outlined in detail by Sinden [10]. A concise description using matrix notation can be found in [15]. Here, we will explain only the general idea.

We assume that the tracer gas has been injected into one or two of the zones at the beginning of the measurement and no more tracer gas is injected during the measurement. Then the tracer gas concentration curves $c_1(t)$ and $c_2(t)$ in each room are the sum of the same two exponential functions, but with different weights. It is the objective of this method, to extract information on the eigenvalues and the eigenvectors of the flow matrix f from these concentration curves. We consider the weighted difference of the two concentrations $h(t,a) = c_1(t) - a \cdot c_2(t)$, with variable weighting factor a. There are two distinct values for a where either one of the two exponentials cancels out. These values can be determined by attempting to fit a straight line to the log of $h(t,a)$ for varying a. A minimum of the squared residuals signals that the straight line model of log $h(t,a)$ is true. This indicates cancellation of one exponential term. This method yields two values for a and two time constants of the exponential function (i.e. the slopes of the straight line model). An eigenvalue analysis reveals that the time constants are the eigenvalues of the flow matrix, while the distinguished values for a determine the eigenvectors of the flow matrix. Thus the flow matrix can be calculated from this information.

This method was found to work well for uncorrupted data. But even a small amount of noise (2% and more) produced large errors in the estimated flows. A thorough analysis of this effect showed, that the presence of noise inhibits the determination of the right values for a from a goodness-of-fit condition ([14,15]). We will therefore exclude this method from further discussion.

2.3 Pulse Decay Method

The pulse decay method starts from the integral form of the tracer gas conservation law (9). It requires a suitable injection and measurement strategy that determines the vectors c_Δ, c_I and q_I in such a way, that the flow matrix f can be calculated with high accuracy. This strategy will be developed here. For a more general treatment of pulse injection tracer techniques see [12].

As already noted, the system of equations (9) is underdetermined and cannot be readily solved for the flow matrix. Sufficient information can be obtained by conducting two concentration measurements over different time intervals ΔT_1 and ΔT_2 with

$$\Delta T_k = [t_{ko},\ t_{k1}] \qquad ,\quad k = 1,\ 2 \tag{11}$$

First, we have to make some remarks concerning the choice of the time intervals relative to each other and with respect to the times of tracer gas injection. The intervals ΔT_1 and ΔT_2 should not overlap, because then their information content would not differ very much. On the other hand, they should not be spaced too far apart, because then the assumption of time independent flows becomes questionable. Furthermore, if ΔT_1 and ΔT_2 are chosen such that tracer gas injection and concentration measurement happen at disjunct time intervals, we can omit the source term q_I in (9). Figure 2 shows a time schedule for injection and measurement, that meets these requirements. The space between the intervals is just large enough to allow a quick release of tracer gas (pulse).

From each set of measurement values, we obtain the vectors (compare (10))

$$\underline{c}_{\Delta k} = \begin{vmatrix} c_1(t_{k1}) - c_1(t_{k0}) \\ c_2(t_{k1}) - c_2(t_{k0}) \end{vmatrix} \tag{12}$$

$$\underline{c}_{I,k} = \begin{vmatrix} \int_{t_{ko}}^{t_{k1}} c_1(t)\ dt \\ \int_{t_{ko}}^{t_{k1}} c_2(t)\ dt \end{vmatrix} \tag{13}$$

For each interval holds the conservation law (9). If we assume, that the air flows do not change between the begin of the first and the end of the second time interval (i.e. between t_{10} and t_{21}), then the flow matrices in both intervals are the same. Thus the conservation laws for both intervals can be combined into one matrix equation

$$\underline{\underline{c}}_{\Delta} = \underline{\underline{f}}\ \underline{\underline{c}}_I \tag{14}$$

with

$$\underline{\underline{c}}_{\Delta} = [\ \underline{c}_{\Delta 1}\ \underline{c}_{\Delta 2}\ ] \tag{15a}$$

$$\underline{\underline{c}}_I = [\ \underline{c}_{I,1}\ \underline{c}_{I,2}\ ] \tag{15b}$$

This set of equations is fully determined and can be solved for the flow matrix

$$f = \underline{\underline{c}}_I^{-1} \cdot \underline{\underline{c}}_{\Delta} \tag{16}$$

Although the basic procedure is rather simple, two problems might arise in the practical evaluation of (16). The first one concerns the accuracy with which the matrices c_Δ and c_I can be determined from noisy measurement data. The second problem is the inversion of the matrix c_I in case of (near) singularity. Both problems are discussed in some detail in [15]. Here we mention only briefly how they can be overcome.

The accuracy of the elements of c_Δ and c_I depends on the amount of noise with which the concentration decay curves are corrupted. While the integration in c_I tends to cancel out noise induced fluctuations, the accuracy of the elements of c_Δ is directly affected by the measurement noise. A better approach to the calculation of c_Δ is to fit the concentration decay curves with a parameter estimation algorithm. c_Δ follows then from the start and end points of the fitted curves. The advantage of this procedure is that all measurement values of each interval are used for the determination of c_Δ and not just the first one and the last one. Thus the error bounds for the elements of c_Δ are significantly reduced. c_I can be obtained in the same way, however the error reduction will be less pronounced.

Ill conditioning of the matrix c_I can be avoided by a suitable injection strategy. A good choice is (s. [12,15]):

1. prior to time interval ΔT_1:
   inject tracer gas only into zone 1, such that $c_1(t_{10}) > 0$, $c_2(t_{10}) = 0$.

2. prior to time interval ΔT_2:
   inject tracer gas only into zone 2, such that $c_2(t_{20}) \gg c_1(t_{20})$.

Additional protection from error amplification through near singular matrix inversion can be obtained by the use of a singular value decomposition algorithm for the inversion of c_I.

Figure 3 shows a typical measurement. The measurement values are denoted by markers, while the solid lines indicate the result of the parameter estimation. At first, we note that the parameter estimation determines the values at the beginning and the end of each interval with higher accuracy than the measurement values at these points. An inspection of the area under the concentration curves shows, that the diagonal elements of c_I are greater then the off-diagonal elements, which shows a good condition of c_I.

2.4 Two Tracer Method

The two tracer method is closely related to the pulse decay method. It is also based on the integral form of the tracer gas conservation law (9). Again, a second measurement has to provide the missing set of equations. Rather than performing the second measurement with the same tracer gas during a different time interval, two tracer gasses are used during the same time interval $\Delta T = [t_0, t_1]$. Thus, we obtain four sets of tracer gas concentrations $c_{k,i}(t)$, i.e. the concentration of tracer gas k in zone i for k, i = 1, 2. From these concentration values, we obtain the vectors (compare (12), (13))

$$\underline{c}_{\Delta k} = \begin{vmatrix} c_{k,1}(t_1) - c_{k,1}(t_0) \\ c_{k,2}(t_1) - c_{k,2}(t_0) \end{vmatrix} \tag{17}$$

$$\underline{c}_{I,k} = \begin{vmatrix} \int_{t_0}^{t_1} c_{k,1}(t)\,dt \\ \int_{t_0}^{t_1} c_{k,2}(t)\,dt \end{vmatrix} \tag{18}$$

Since the decay of both tracer gases is governed by the same air flow pattern, we can combine the tracer gas conservation for both tracers into matrix form as in Equation (14). We have a similar system of linear equations as in the pulse method. The matrices c_Δ and c_I are constructed from the corresponding vectors as in Equation (15). However, these vectors have a different meaning here, as can be seen by comparison of Equations (17), (18) with (12), (13). The flow matrix follows through solution of the system of linear equations according to (16).

Again some remarks concerning the accuracy of the matrices c_Δ and c_I are appropriate. Basically, the considerations of the pulse decay method apply here also. Especially the elements of the matrix c_Δ are obtained in the same way as before. Singularity of c_I can be avoided by a similar injection strategy:

prior to time interval ΔT:
- inject tracer gas 1 only into zone 1,
- inject tracer gas 2 only into zone 2,

such that $c_{1,1}(t_0) > 0,\ c_{2,2}(t_0) > 0$
and $c_{1,2}(t_0) = 0,\ c_{2,1}(t_0) = 0$.

Figure 4 presents an illustrative example. Again, measurement points are denoted by markers and solid lines stand for concentration profiles which are calculated from parameter estimations. Diagonal elements of matrix c_I are large in comparison with off-diagonal elements, as coinciding numbers of zone and gas yield higher concentrations than mixed combinations of these numbers do.

Although the mathematical description and numerical evaluation for the two tracer gas method and the pulse decay method are rather similar, there are considerable differences in the practical application.

The use of two tracer gases usually doubles the experimental expense for gas handling and analyzing. On the other hand, it allows to gather sufficient data for the air flow analysis of a two zone building during only one measurement interval. Thus, if the assumption of time independent flows is questionable (as is always the case), we can expect the most accurate results from the two tracer method.

3. NUMERICAL SIMULATION

In this section, we will analyze the pulse decay method and the two tracer method by means of numerical simulation. To this end, we assume a set of given flows F_{ij}, i,j = 1,2, volumes V_i, and initial concentrations $c_i(0)$, i = 1,2 and calculate the resulting concentration curves of the forward problem (7). Synthetic data sets are obtained by corrupting these curves with additive noise. The performance of the various methods can be analyzed, if they are used to estimate the airflows from the synthetic data. The comparison of the estimated flow values with the original ones allows quantitative statements on the accuracy of each method. Since the eigenvalue analysis has already shown to be very sensitive to measurement errors it will not be included here.

3.1 Numerical Model

It was intended to compare the performance of the above mentioned methods for different magnitudes of the interzonal air flows as well as for different measurement durations. Two combinations of airflows were chosen, and for each one measurements over three different time periods were simulated.

In order to calculate the exact solution of the differential form of the homogeneous form of the tracer gas conservation law (7), the flow matrix f is expressed by its eigenvalues and eigenvectors:

$$\underline{\underline{f}} = \underline{\underline{M}}\ \underline{\underline{\Lambda}}\ \underline{\underline{M}}^{-1} \tag{19}$$

with

$$\underline{\underline{\Lambda}} = \begin{vmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{vmatrix}, \quad \underline{\underline{M}} = \begin{vmatrix} r_1 & r_2 \\ 1 & 1 \end{vmatrix}. \tag{20a,b}$$

λ_1 and λ_2 are the eigenvalues of f and the columns of M are the eigenvectors of f. The solution of (7) for q(t) =0 and a given initial concentration c(0) is then

$$\underline{c}(t) = \underline{\underline{M}}\ \exp(\underline{\underline{\Lambda}}t)\ \underline{\underline{M}}^{-1}\ \underline{c}(0) \tag{21}$$

with

$$\exp(\underline{\underline{\Lambda}}t) = \begin{vmatrix} e^{\lambda_1 t} & 0 \\ 0 & e^{\lambda_2 t} \end{vmatrix}. \tag{22}$$

The following numerical values were used for the simulation ($r = r_1 = -r_2$):

interzon. air exchange	F_{11} F_{22} F_{12} F_{12} in ℓ/h	f_{11} f_{22} f_{12} f_{12} in 1/h	λ_1 λ_2 in 1/h	r
low	-60 -60 20 45	-1/2 -1/2 1/6 3/8	-1/4 -3/4	2/3
high	-240 -240 80 180	-2 -2 2/3 3/2	-1 -3	2/3
	$V_1 = V_2 = 120$ ℓ			

The concentration decay is governed by the eigenvalue with the smallest magnitude (λ_1). The measurement time was therefore chosen in dependence on λ_1. Three different durations were simulated:

- short duration: $\tau_1 = 1/(2\lambda_1)$,
- medium duration: $\tau_2 = 1/\lambda_1$,
- long duration: $\tau_3 = 2/(\lambda_1)$.

The following measurement durations resulted for the two cases of low and high interzonal air exchange:

interzon. air exchange	duration of measurement in h		
	τ_1	τ_2	τ_3
low	2 h	4 h	
high	0.5 h	1 h	2 h

3.2 Generation of Synthetic Data Sets

This numerical model was used to simulate air exchange measurements for each method under investigation. Concentration values were calculated from these air flows every 20 s alternating for each zone. A second tracer gas injection in the middle of the measurement time was assumed for the case of the pulse decay method. Synthetic data sets were obtained from these concentration samples by adding Gaussian distributed white noise with a standard deviation of 10% of the initial concentration. About thousand data sets were generated

- for each measurement method (pulse decay and two tracer),
- for each system of interzonal airflows (low and high),
- for various measurement durations (τ_1, τ_2, τ_3).

3.3 Monte-Carlo-Simulation

The synthetic data sets were evaluated with the corresponding measurement methods in a Monte-Carlo fashion. Each run produced a slightly different result due to the different error signals. The frequency distribution of the estimated air flows was evaluated using histograms. The original values were determined correctly in most cases. From these histograms, we can calculate the relative standard deviation of each air flow value. Figure 5 shows the frequency distribution of F_{11}, F_{22}, F_{12}, F_{21} according to the system of high interzonal air flows obtained with the pulse decay method for a medium duration of the measurement (1 h). The relative standard deviations vary from 4.0% (F_{12}) to 10.6% (F_{21}). The influence of the measurement duration is shown in Figure 6 for F_{21} estimated with the pulse decay method for the measurement durations 0.5 h, 1 h and 2 h (high interzonal air exchange). The relative standard deviation drops from 20.3% to 4.8% with increasing duration.

3.4 Results

The results of the various simulation runs are compiled in Figures 7 and 8. Figure 7 compares the pulse decay method and the two tracer method for the system of high interzonal air flows.

The two tracer method performs well even for a short measurement duration of 0.5 h. An extended duration of 1 h decreases the relative standard deviation of the flows slightly to ca. 5 % and less. The pulse decay method achieves the same accuracy, if a measurement duration of 2 h is selected. Shorter durations produce unacceptable high errors.

Figure 8 shows the performance of the pulse decay method for high and for low air flows. (The curves for the high air flow case correspond to fig. 7.) The pulse decay method achieves an accuracy of 5 % and less for both cases, provided that the duration of the measurement is sufficiently long (2 h for the high, 4 h for the low air flow case).

4. EXPERIMENTAL EQUIPMENT AND MEASUREMENT RESULTS

Numerical simulation showed, that the pulse decay method and the two tracer method are both capable of delivering accurate results for the air flows in two zone buildings. It was therefore desirable to test these methods more thoroughly also under field like conditions.

To this end, a two zone test box and a flow generator were built. The test box consists of two air-tight chambers and a tubing system that provides air exchange paths between the chambers according to Figure 1. The flow generator consists of air pumps, flow meters and adjustable valves. It is connected to the tubing system of the test box and allows to establish arbitrary air flows between the chambers with high precision. The combination of the test box and the flow generator serves as a laboratory-scale two zone building model with well determined air flows.

These air flows were measured with the tracer gas system MULTI-CAT [16]. Beneath various types of single zone measurements it is also able to perform the above described three two-zone measurement methods.

This equipment was used to carry out measurements on the laboratory-scale model. The air flow systems produced by the flow generator were somewhat different than those reported here. However, the tracer gas measurements results were accompanied by the corresponding Monte-Carlo-Simulations. (See [14,15] for more details.) The results indicate, that in practical situations the total measurement time is critical. If it is chosen sufficiently long, then the pulse decay method delivers satisfactory results with one tracer gas only.

5. CONCLUSIONS

In conclusion, we can sum up with the following points:

- The eigenvalue analysis method is not suitable for field measurements with any sizeable scattering in the concentration profiles. It is of theoretical value only.

- For short-time measurements the two/multiple tracer method promises to yield better accuracy than the pulse decay method. This is confirmed by evaluation results of both simulations and measurements. In this context the term "short-time" means a time interval in which typically half of the chamber volume is exchanged by the air flows.

- If, however, the pulse decay technique is applied for a longer period of time (e.g. corresponding to a two times exchange of the volume) it performs equally well as the short-time two tracer method. Again, this follows from MC-simulations as well as from laboratory measurements.

Since smaller and short-term fluctuations of the air change rate during a longer measuring period result in added noise superposed to the concentration profiles, this possible effect is already included to some extent in our MC-simulations with 10% noise. From their results one can draw the conclusion that such fluctuations should not be critical.

Therefore, the pulse decay method has to be considered as a very interesting and competitive technique, with similar accuracy as the two tracer method when properly used. It avoids higher equipment cost -as it is required for the two tracer method due to multiple or flexible analysers - and needs only one tracer gas.

Further investigations are planned in real buildings, under conditions which are not as steady as in a laboratory, in order to attempt a verification of the predicted well performance of pulse decay methods.

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FIGURE CAPTIONS

Fig. 1: Nomenclature and air flow scheme in a two zone building model.

Fig. 2: Time schedule for injection and measurement for pulse decay measurement method.

Fig. 3: Concentration curves for pulse decay method.

Markers: + measured concentration in zone 1,
Δ measured concentration in zone 2.

Solid lines: Calculated concentrations from parameter estimations.

Fig. 4: Concentration curves for two tracer method.

Markers: + measured concentration in zone 1,
Δ measured concentration in zone 2.

Solid lines: Calculated concentrations from parameter estimations.

Fig. 5: Frequency distributions of results from Monte-Carlo-simulations (pulse decay method, case of high interzonal air flows, medium measurement duration): flows F_{11}, F_{22}, F_{12}, F_{21} and corresponding relative standard deviation.

Fig. 6: Frequency distributions of results from Monte-Carlo-simulations (pulse decay method, case of high interzonal air flows, flow F_{21}): short, medium, long measurement duration (top down) and corresponding relative standard deviation.

Fig. 7: Comparison of the pulse decay method (solid lines) and the two tracer method (dashed lines): relative standard deviations for the case of high interzonal air flows and different measurement durations.

Fig. 8: Pulse decay method: comparison of the cases of high and low interzonal air flow. Relative standard deviations for different measurement durations.

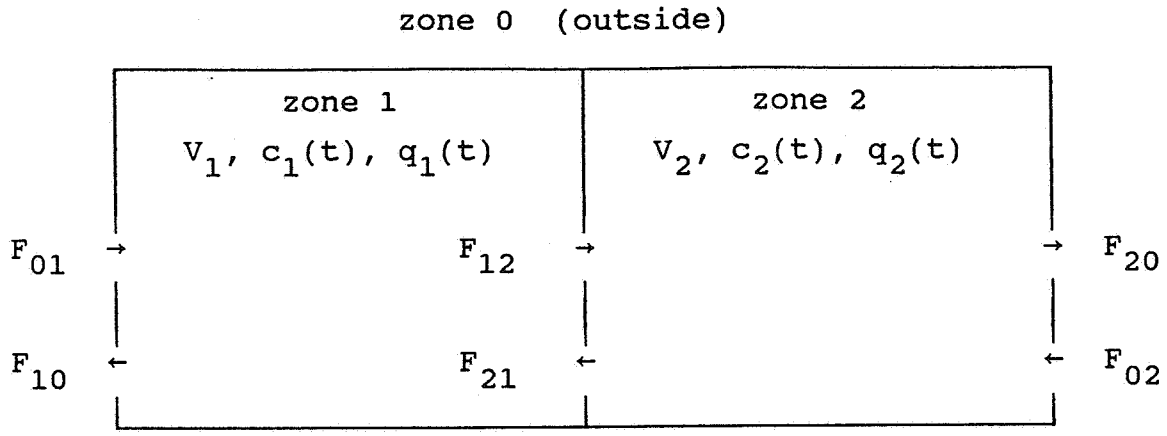

Figure 1

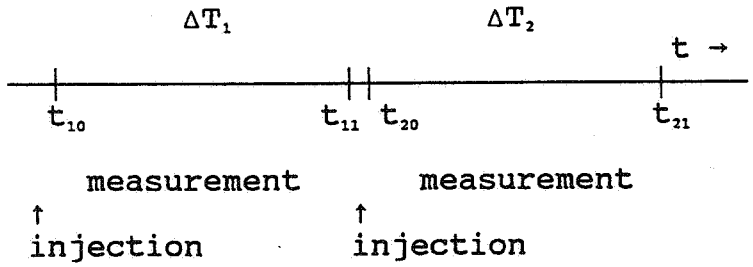

Figure 2

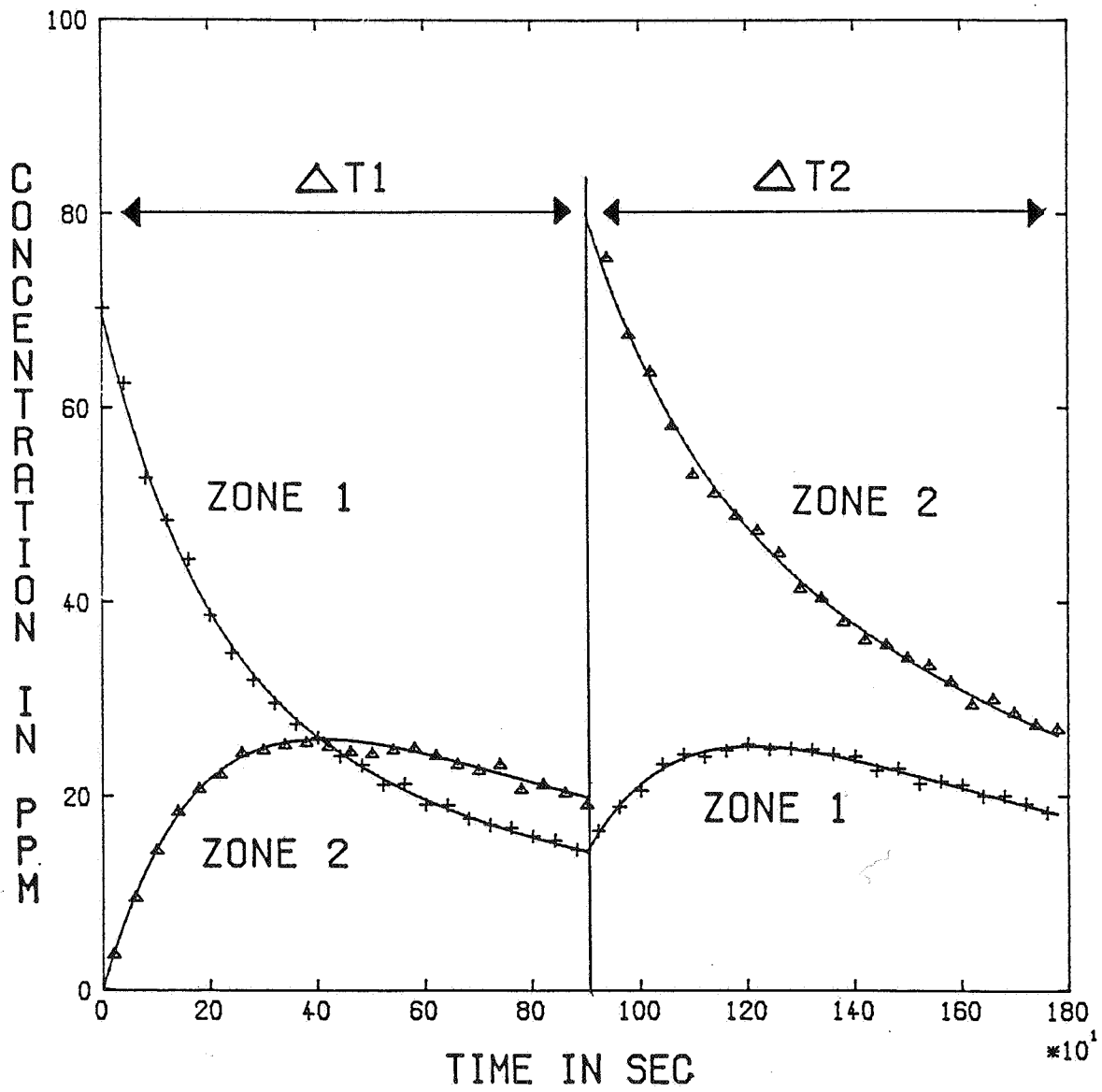
100
80
60
40
20
0
CONCENTRATION IN PPM
△T1
△T2
ZONE 1
ZONE 2
ZONE 2
ZONE 1
0
20
40
60
80
100
120
140
160
180
*10¹
TIME IN SEC

Figure 3

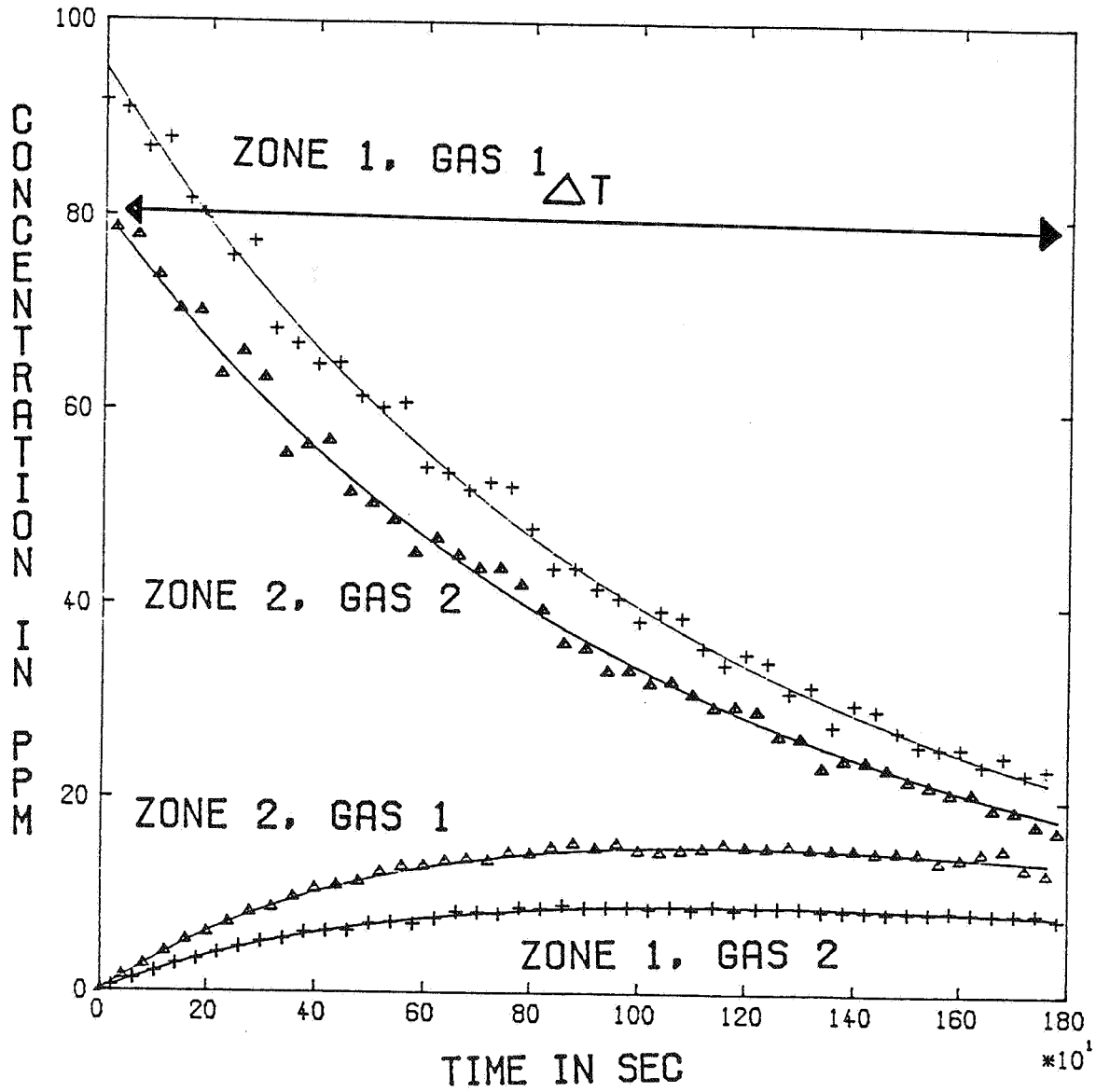
CONCENTRATION IN PPM
100
80
60
40
20
0
ZONE 1, GAS 1
ΔT
ZONE 2, GAS 2
ZONE 2, GAS 1
ZONE 1, GAS 2
0
20
40
60
80
100
120
140
160
180
TIME IN SEC
*10¹

Figure 4

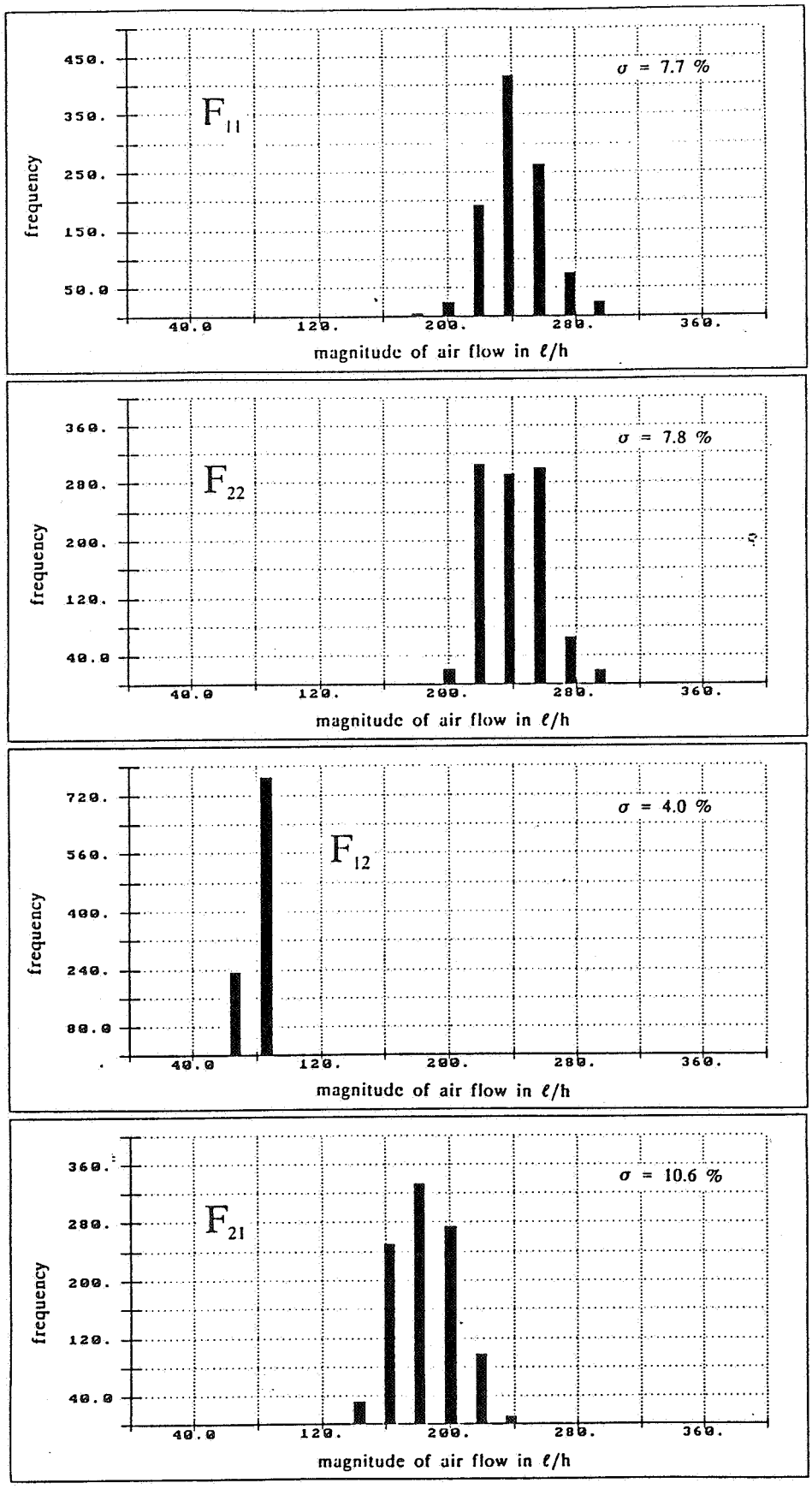
F11
σ = 7.7 %
frequency
450.
350.
250.
150.
50.0
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h
F22
σ = 7.8 %
frequency
360.
280.
200.
120.
40.0
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h
F12
σ = 4.0 %
frequency
720.
560.
400.
240.
80.0
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h
F21
σ = 10.6 %
frequency
360.
280.
200.
120.
40.0
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h

Figure 5

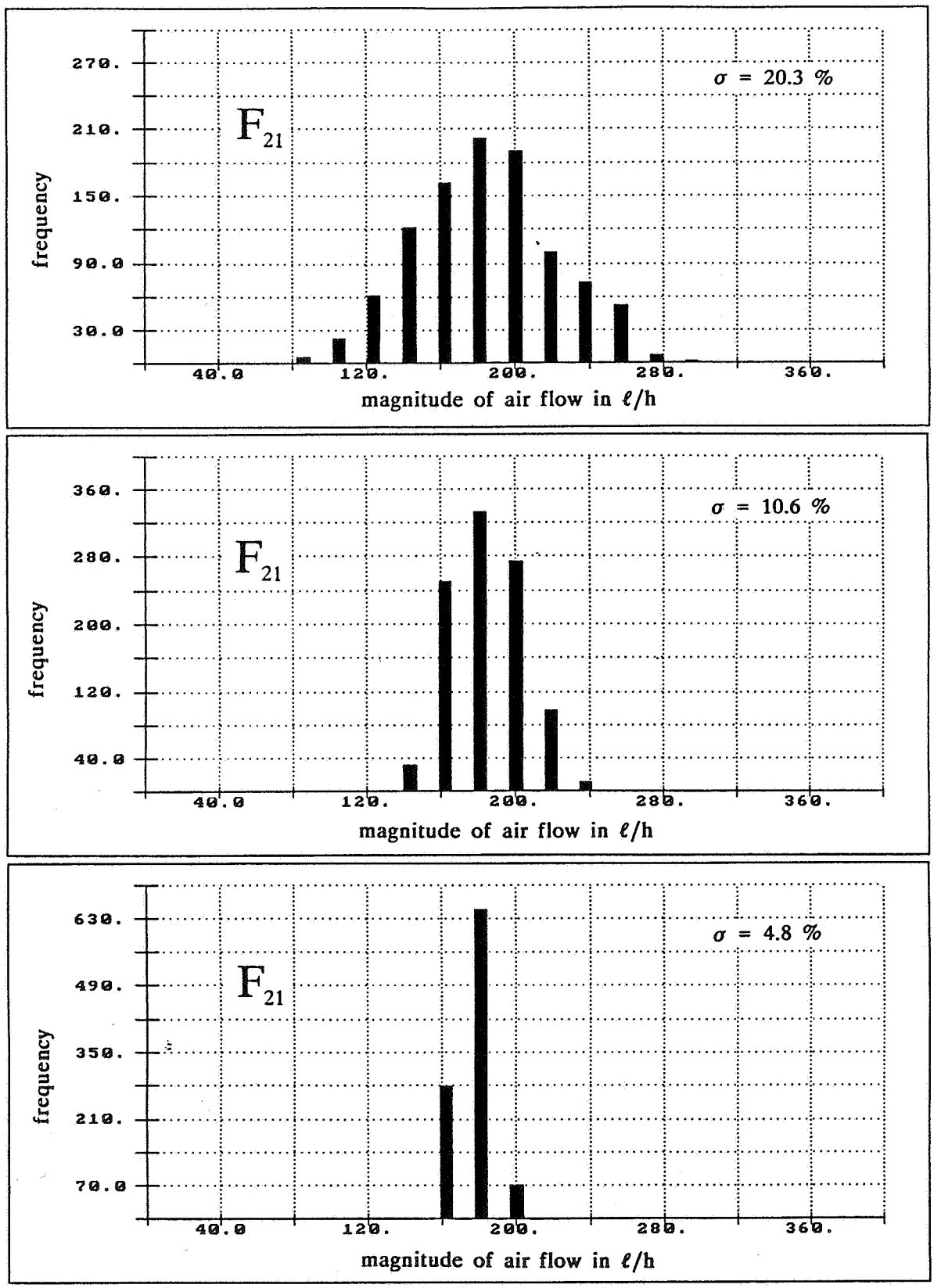
270.
210.
150.
90.0
30.0
frequency
F_{21}
σ = 20.3 %
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h
360.
280.
200.
120.
40.0
frequency
F_{21}
σ = 10.6 %
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h
630.
490.
350.
210.
70.0
frequency
F_{21}
σ = 4.8 %
40.0
120.
200.
280.
360.
magnitude of air flow in ℓ/h

Figure 6

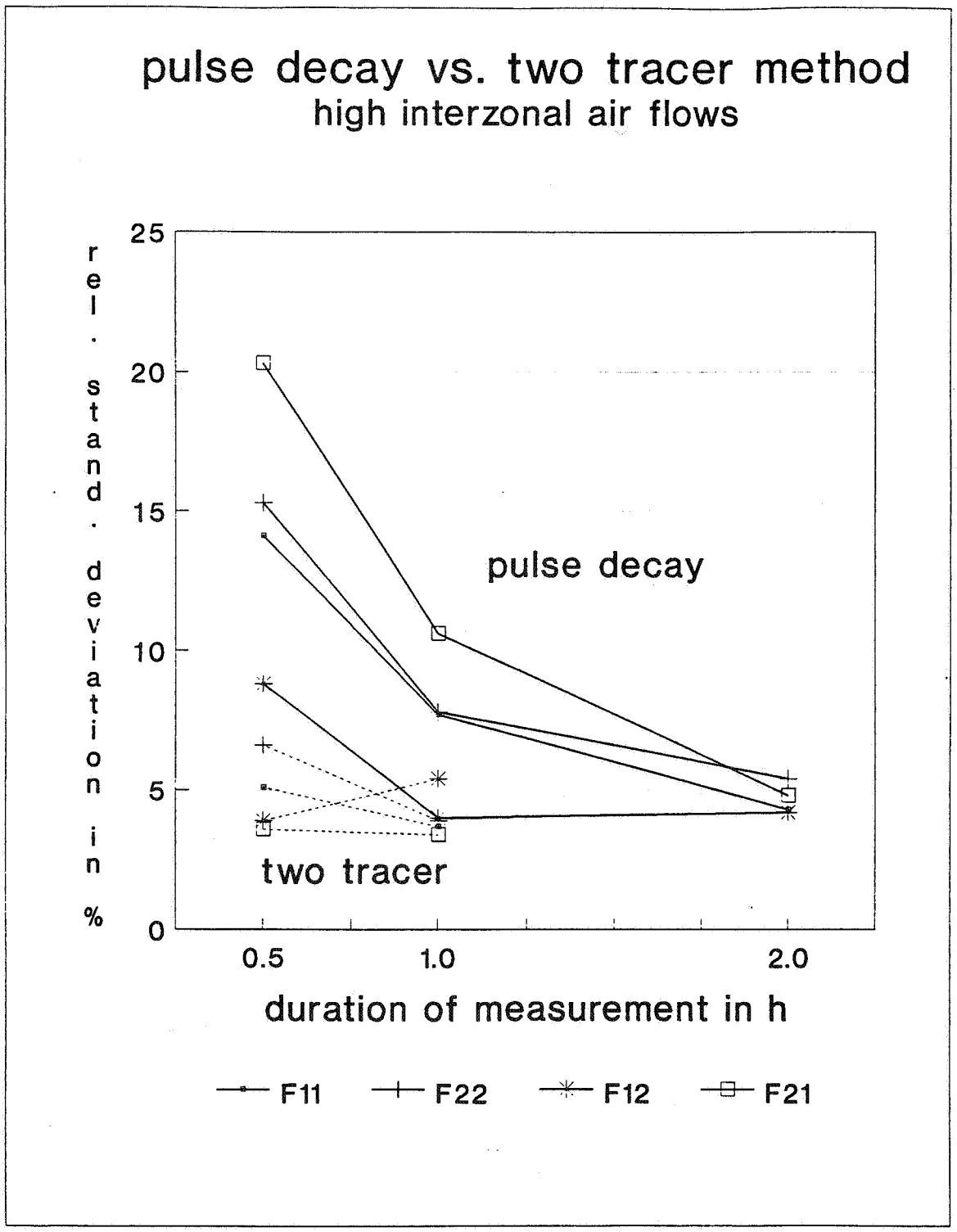
pulse decay vs. two tracer method
high interzonal air flows
rel. stand. deviation in %
25
20
15
10
5
0
pulse decay
two tracer
0.5
1.0
2.0
duration of measurement in h
F11
F22
F12
F21

Figure 7

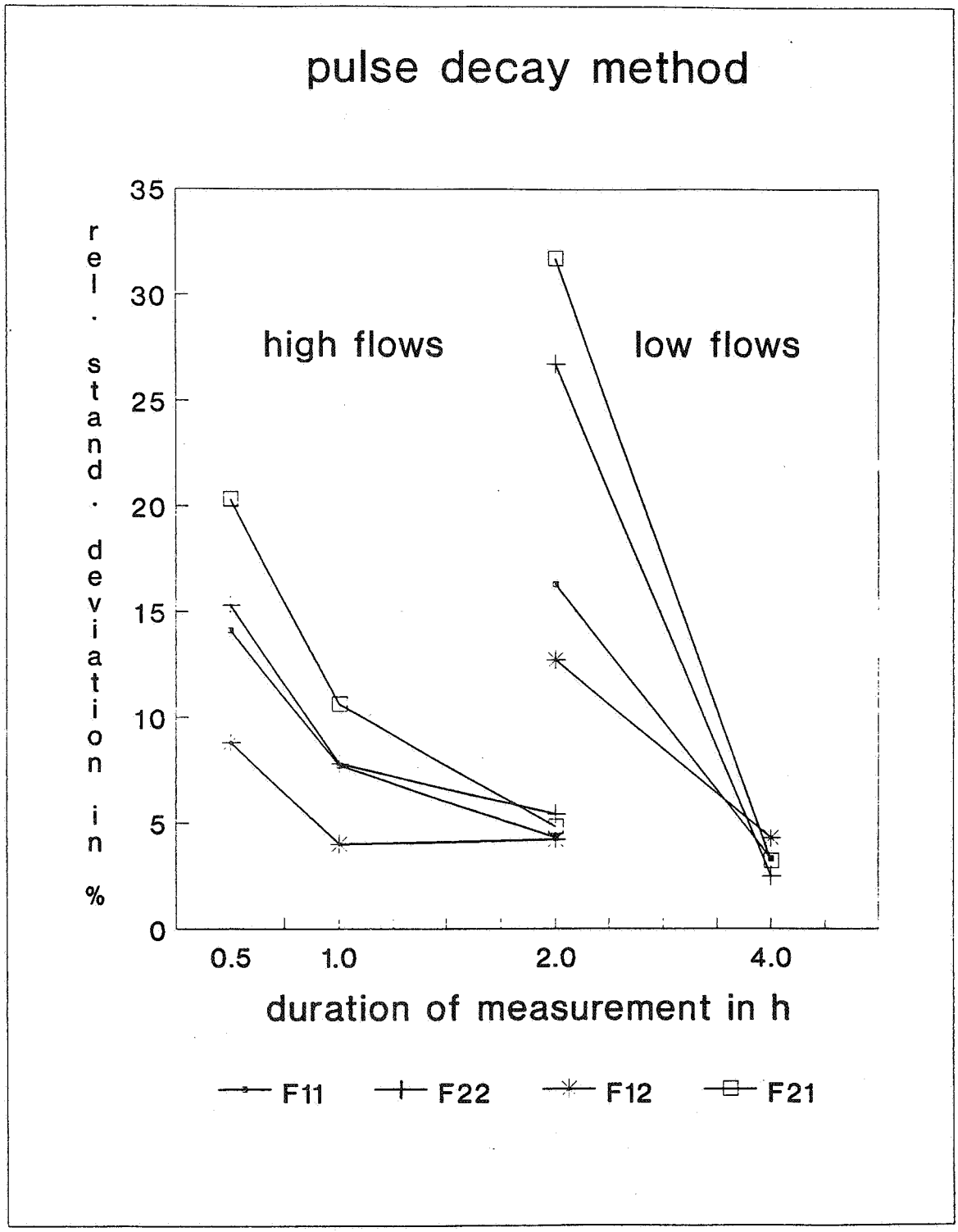
pulse decay method
rel. stand. deviation in %
35
30
25
20
15
10
5
0
high flows
low flows
0.5
1.0
2.0
4.0
duration of measurement in h
F11
F22
F12
F21

Figure 8

Discussion

Paper 10

M.Liddament (AIVC, UK)

Your comparison represents a special case of the general multizone tracer measurement problem which was presented by Sherman at the 10th AIVC conference. Could you compare your findings with those?

R.Rabenstein, F.D. Heidt (Univ.of Siegen, Germany)

I am sorry that I don't remember the results of the paper by Sherman last year. But I would like to emphasise that our special case of comparison comprises very detailed investigations with numerical simulations and laboratory scale measurements as well. And the interesting outcome so far is that the accuracy of the wo tracer method and the pulse decay method become comparably good provided that the measurement time is sufficiently long.

Earle Perera (BRE, UK)

Would it be realistic to use the pulse-technique in a real building given that sufficient tracer (for measuring purposes) may not have moved to all zones (other than the one in which it was initially distributed) within the measuring period.

R.Rabenstein, F.D. Heidt (Univ.of Siegen, Germany)

The answer to this question can come only from field experience. We mentioned that point at the end of our conclusions. It may be helpful for measuring under field conditions that we can select the integration borders according to the performance of measured concentration profiles. This could be a possibility to avoid the above-mentioned problem.

J.Axley (MIT, USA)

Several issues must be kept in mind: For multizone air flow determination we presently have; 1) Two injection strategies (constant and pulse injection); 2) Two mass balance formulations to form the inverse problems and; 3) The possibility of using single or multiple tracers. Pulse injection offers the advantages of requiring less gas and allowing relatively rapid completion of a test that both saves time and tends to avoid error induced by flow variation, but pulse injection must be more sensitive to imperfect mixing within the zone. Constant injection tests demand larger quantities of tracer gas and tend to take more time but constant injection tends to drive zones at more uniform concentrations (whether well-mixed or not) and thus tend to be less sensitive to imperfect mixing. Finally, if the resources are in hand one should prefer to use multiple tracers rather than single tracers, because the test procedure may be completed in less time and thus errors induced by unsteady flows will be avoided or minimized.

R. Rabenstein, F.D. Heidt (Univ.of Siegen, Germany)

This is a useful comment concerning the general classification of multizone air flow measuring techniques. But it reaches beyond the scope of our paper, in which we confined ourselves to two-zone-models with initial and or intermediate pulse decay and with one or two tracer gases.