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Microcomputer-aided Measurement of Air Change Rates

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SUMMARY

Air change rates are measured by a non-dispersive one-beam IR gas analyzer using the decay and constant-emission methods with nitrous oxide as tracer gas. Disturbing influences due to H_2O and CO_2 are low. The analyzer is coupled via a RS-232-C interface to a microcomputer, which is programmed to service the following functions: (1) calibration, (2) preparation and control of measurements, (3) recording, displaying and storing of data, (4) evaluation of results, and (5) error analysis. The implemented programs provide an instant access to results. The whole equipment is installed in compact form on a mobile rack.

Measurements have been taken in a university laboratory to examine air change rates with (1) closed door and window, (2) open door only, and (3) tilted window only. Typical results are given and show where the decay method or the constant-emission method is more appropriate.

INTRODUCTION

The rate of air exchange $Q(\mathrm{m}^3/\mathrm{h}) = V\lambda$ between an enclosure of effective volume V and its environment or the corresponding volumetric air change rate $\lambda(\mathrm{h}^{-1})$ are among the least understood aspects of building design and performance. They depend on building construction (e.g., crack length and pressure characteristics), meteorological parameters (e.g., thermally and wind-induced pressure field) as well as on occupant's behaviour (e.g., type of activity, early-learned attitudes).

On the other hand, λ-values are a prerequisite to estimate the thermal performance of buildings — with increasing importance if the thermal transmittance of the building's envelope is further reduced [1] — and to predict indoor air quality. The last point is highly relevant if moisture control [2] and detrimental indoor gas emissions (e.g., radon, formaldehyde) are considered [3]. Measurements of λ are also required to characterize airtightness of a room or building under natural conditions, that means without mechanically induced pressure difference between room and ambient air.

Measurements of tracer gas concentrations can be used to calculate λ-values according to three procedures [4]: I — concentration decay, II — constant emission, and III — constant concentration of the gas. There are specific problems with all of the three methods; however, these techniques offer the only way to observe naturally occurring air change rates. Procedures I and II have been implemented and investigated in detail, and these results are the main subject of this paper. The third method III requires considerably more sophisticated equipment and funds and, therefore, is omitted here. Method III would generally enable long-term and automatic measurements [5]. However, the quicker and cheaper sampling methods I and II have a comparable accuracy (because mixing and effective-volume problems are essentially the same for all methods) and may be equivalent or even more appropriate to practice.

The main objective of this work was the improvement of experimental procedures, and especially, of data acquisition and evaluation techniques by combining tracer gas measurements with a microcomputer. Measurements of air change rates have been conducted in a university laboratory under different conditions. They served only as illustrating examples showing the typical range of measuring

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values for the given situations. There have been no investigations of the correlation between various relevant parameters and measured results, but special emphasis is given to the comparison of methods I and II as well as on the estimation of errors.

PRINCIPLE OF MEASUREMENTS AND THEORETICAL ANALYSIS

A small amount of an inert tracer gas is well mixed with room air and its concentration values are recorded as a time series.

Then, conservation of mass (continuity equation) requires

$$V\frac{dC}{dt} = (C_A - C)V\lambda + F \tag{1}$$

The meanings of symbols are given in the List of Symbols, and subscript A denotes ambient air.

This first order differential eqn. (1) has to be solved for the initial condition

$$C(t = 0) = C_0 \tag{2}$$

and yields

$$C(t) = C_A + C_\infty + (C_0 - C_A - C_\infty)\exp(-\lambda t) \tag{3}$$

with the dimensionless tracer gas injection rate, C_∞

$$C_\infty = F/(V\lambda) \tag{4}$$

An illustration of eqn. (3) is presented in Fig. 1, showing the typical time-dependent behaviour of tracer concentrations which is determined by the ratio r of $(C_A + C_\infty)$ and C_0:

$$r = (C_A + C_\infty)/C_0 \tag{5}$$

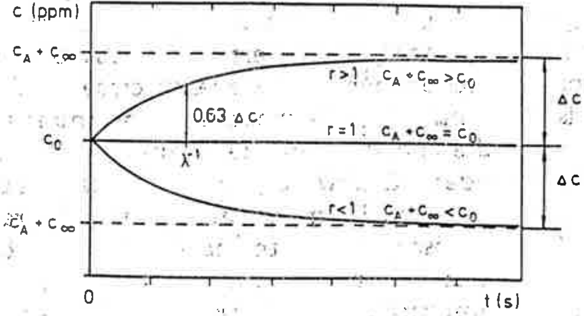

Fig. 1. Typical graphs of tracer concentration vs. time depending on parameter $r = (C_A + C_\infty)/C_0$.

$C(t)$ increases with time if $r > 1$, remains constant for $r = 1$ and decreases for $r < 1$, where a typical time scale τ is given by $\tau = \lambda^{-1}$(h). A suitable tracer gas has to meet a set of requirements [6] and leads to a restricted number of options. They have been compared with respect to accuracy [7]. Nitrous oxide (N_2O) emerged for a number of reasons as a favourable candidate and has been chosen as tracer in this case. Normally, N_2O is not contained in the environment. That means for single cell measurements

$$C_A = 0 \tag{6}$$

Method I (constant decay, $C_\infty = 0$) results in

$$C(t) = C_0 \exp(-\lambda t) \tag{7}$$

whereas method II (constant emission, $C_\infty > 0$) yields

$$C(t) = C_\infty + (C_0 - C_\infty)\exp(-\lambda t) \tag{8}$$

The constant concentration method III would require a probably time-dependent tracer gas flow rate:

$$F = C_0 V\lambda \tag{9}$$

Because λ is not known a priori and may be a varying parameter, F would have to be determined from concentration measurements and by emission control — a method which is not further outlined here due to its additionally required, rather sophisticated experimental efforts.

For method I the air change rate λ is calculated in a straightforward manner from eqn. (7):

$$\lambda = \frac{1}{t}\ln\frac{C_0}{C(t)} \quad \text{or} \quad \lambda = \frac{1}{\Delta t}\ln\frac{C(t)}{C(t+\Delta t)} \tag{10}$$

where t and Δt are any values of time and time increment during the measuring period. For method II the value of λ can be determined from eqn. (8) only by numerical iteration or by differentiation with respect to time from

$$\lambda = -\frac{d^2C}{dt^2}\Big/\frac{dC}{dt} \tag{11}$$

A reasonably large gap ΔC between final and initial concentrations can be produced by suitable choice of flow rate F:

$$|\Delta C| = |C_\infty - C_0| = |F/(V\lambda) - C_0| \qquad (12)$$

In this way a sufficiently large variation of concentration values $C(t)$ to ensure good measuring resolution is obtained.

The accuracy in determining λ depends for both methods on the observation errors of the parameters:

$$x_1 = C(t), \qquad x_2 = C_0 \qquad \text{and} \qquad x_3 = C_\infty \qquad (13)$$

where time t is considered to be measured exactly. Then, the Gaussian law of error propagation results in

$$(\delta\lambda)^2 = \sum_1^3 \left| \frac{\partial\lambda}{\partial x_i} \, \delta x_i \right|^2 \qquad (14)$$

δ denotes deviation of a variable from its mean value. For method I which is independent of x_3 one simply puts $x_3 = \delta x_3 = 0$.

As mentioned above, the function $\lambda(x_1, x_2, x_3)$ is not generally available as an explicit analytic expression.

Equations (8) and (13) are used to define an implicit function f of λ, x_1, x_2 and x_3:

$$f(\lambda, x_1, x_2, x_3) = x_1(t) - x_3 - (x_2 - x_3) \times \exp(-\lambda t) = 0 \qquad (15)$$

Thus, partial derivatives $\partial\lambda/\partial x_i$ in eqn. (14) can be replaced by

$$\frac{\partial\lambda}{\partial x_i} = -\frac{\partial f}{\partial x_i} \bigg/ \frac{\partial f}{\partial \lambda} \qquad i = 1, 2, 3 \qquad (16)$$

and the squared error $(\delta\lambda)^2$ becomes:

$$(\delta\lambda)^2 = \left(\frac{1}{\partial f/\partial\lambda}\right)^2 \sum_1^3 \left| \frac{\partial f}{\partial x_i} \, \delta x_i \right|^2 \qquad (17)$$

This relationship has been evaluated for the general case — method II — by using eqns. (8), (15) and (16). The procedure is elementary but somewhat tedious and details are omitted. The asymptotic value of the squared error (i.e., after a long measuring period) yields finally

$$\left(\frac{\delta\lambda}{\lambda}\right)^2 = \left(\frac{\delta C}{C_\infty}\right)^2 + \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta F}{F}\right)^2 \qquad (18)$$

Restricting the attention to method I only, an error estimation for $(\delta\lambda)^2$ is immediately obtained by differentiation of λ in eqn. (10):

$$(\delta\lambda)^2 = \frac{1}{t^2}\left[\left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta C_0}{C_0}\right)^2\right] \qquad (19)$$

C_0, δC_0 and δC are assumed as constant values. The error $\delta\lambda$ then decreases rapidly with increasing time t. However, as soon as $C(t)$ becomes small itself, the error $\delta\lambda$ increases again. The optimum measuring time t_{opt} is in the proximity of $1/\lambda$. Because method I is normally used only for medium-to-low air change rates the available measuring time is always large enough to avoid a time domain with increasing error.

MEASURING EQUIPMENT

The experimental equipment consists of four main components:
- gas analyzer
- RS-232-C interface
- microcomputer with printer-plotter
- gas injection apparatus

as well as a bottle of compressed calibrated gas. They are installed in compact form on a mobile test unit (Fig. 2).

A key component of the measuring system is the commercially available non-dispersive one-beam IR gas analyzer UNOR 6N, which detects low concentrations (1 - 100 ppm) of the tracer gas nitrous oxide (N_2O). Its physical principles and main features are described in detail elsewhere [9, 10]. Figure 3 illustrates schematically the optical construction of the analyzer. An important point is that IR radiation is absorbed within the apparatus by three successively allocated volumes: cuvette, primary and secondary absorption chamber. Chambers are filled with N_2O and designed so as to produce special absorption characteristics (Fig. 4). Without IR-active gas in the measuring cuvette the absorbed energy is equally distributed among primary and secondary chambers. The first one absorbs predominantly the energy close to the band centre whereas the second one absorbs mainly the energy from the flanks (Fig. 4, left-hand side). If, however, the active gas is also contained in the measuring chamber, IR radiation is absorbed near the band centre already here, thus lowering almost exclusively the energy absorption of the primary chamber (Fig. 4, right-hand side). This leads to low disturbing influences of overlapping IR-active gas

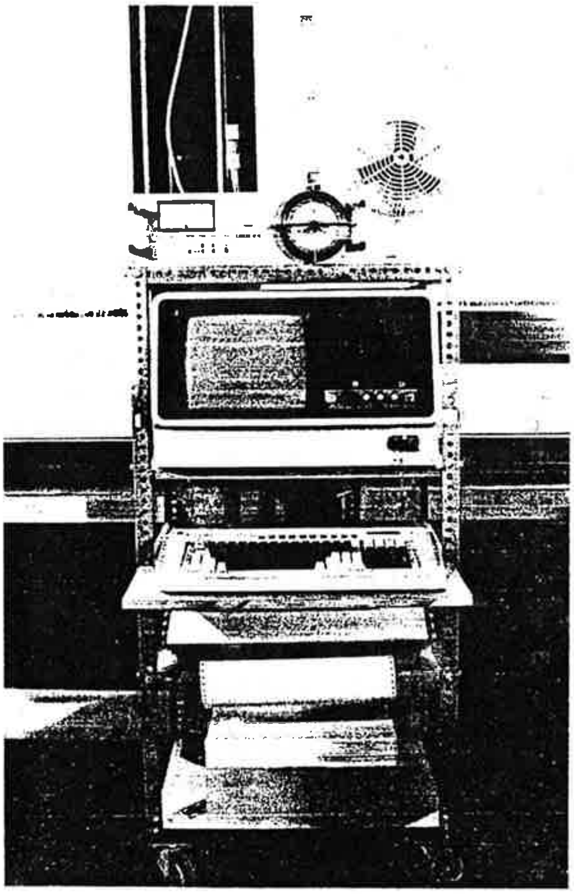

Fig. 2. Measuring unit's configuration. Top level: analyzer, interface, rotameter, mixing fan. Middle level: microcomputer, keyboard, printer-plotter. Bottom level: paper supply. Rear side: compressed tracer gas bottles — mixing and injection, calibration.

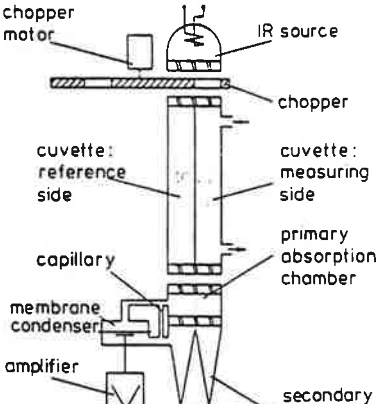

Fig. 3. Construction scheme of the IR gas analyzer (adapted from ref. 10).

components such as H_2O and CO_2. Analyzer measurements were compared for dry and completely humidified calibration gas and showed concentration differences of only 2%.

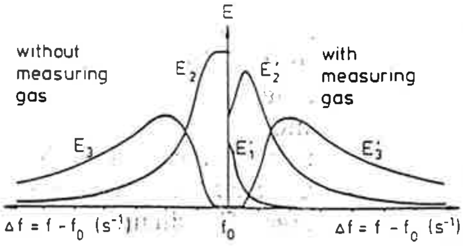

Fig. 4. Spectral distribution of absorbed energy E for three successive absorption volumina (adapted from ref. 9). E_1 — measuring side of cuvette; E_2 — primary absorption chamber; E_3 — secondary absorption chamber.

A specially designed RS-232-C interface unit enables coupling of a microcomputer with the N_2O analyzer which is normally equipped with an analog data output.

The microcomputer is an ABC 24 of AI Electronics Corporation, Tokyo, Japan. It is based on a Z-80-A microprocessor with 64 kB RAM, two floppy disk drives (5¼-inch, double-side, double-density) and a 12-inch-high resolution screen. The ABC 24 is connected with a printer-plotter which is controlled via another RS-232-C interface.

The gas injection apparatus is very simple: It consists of a bottle of compressed gas, a throttling valve and a flexible tube connected with a mixing fan which can be moved freely. Also, the location of gas sampling can be chosen arbitrarily within the measuring room by means of another flexible tube. Another small mixing fan is used in order to reduce concentration fluctuations at the gas intake.

For constant emission measurements the tracer gas streams through a rotameter and its flow rate is manually controlled by means of an adjustable quenching element at the tube. Calibration gas flows directly from the stock bottle to the gas intake of the analyzer. For concentration decay measurements as well as for constant emission measurements, the analyzer's exhaust gas is recirculated indoors, whereas for calibrations, the gas is transferred to the outside of the room under consideration.

EXPERIMENTAL PROCEDURE

Running an experiment is essentially simple and consists of the following sequence of operations:

(1) calibration of the analyzer (typically once a week is sufficient);

(2) definition and/or preparation of measuring conditions (measuring time t_M, time step Δt, C_0, V, F);

(3) measurement control and data handling.

Microcomputer programs have been developed to support and to facilitate these points [8]. The first one can be executed by using the program SIOINT which activates the serial input-output interface between analyzer and microcomputer. Measured values are displayed on screen every 0.2 or 2.0 seconds. They enable a careful adjustment of zero-point and sensitivity potentiometers of the analyzer when measuring calibrated gas.

The second point is of special importance for method II where a suitable value of initial concentration C_0 and gas flow rate F has to be selected in order to achieve a favourable resolution for a given measuring range within a desired time period t_M. For method I only C_0 and t_M have to be selected. The program CONCAL calculates tracer concentrations as a function of time according to eqn. (3) for every given set of parameters and guess-value of air change per hour. A program ERROR estimates the time-dependent error of λ as a function of standard deviations of each of the influencing parameters following the procedure of eqns. (13) and (15) - (17). This provides the ability of quickly defining the experimental parameters and gives a fairly precise prediction of the expected concentration values if the anticipated value for λ is not too far from reality. An approximate value of the desired initial concentration C_0 is set up by mixing all at once a certain mass of N_2O with room air. The result is monitored by the analyzer which has a typical delay time of about 10 seconds. Flow rate F is regulated manually and indicated by the swimmer level in the rotameter.

Point 3 is supported by a program MEASMT which defines all variables and operation parameters of measuring procedure and data management. The program establishes data files on the floppy disk where all variables, parameters and measuring values are stored. Basically, two measuring modes have been realized: time-dependent and value-dependent mode (TDM, VDM). TDM means that measured values are taken and stored every given time step. VDM means that the decision whether measured data are stored or not depends on their relative difference to the preceding values. This reduces the required capacity for data storage without omission of significant information.

All programs are intended to be user-friendly by an interactive part for the input of required variables and program control parameters from keyboard. After the input has been completed, programs run automatically and the output of results appears on the screen and/or printer–plotter according to the choice of a specific control parameter. Results include tabular listings and graphic presentations of $C(t)$. If not otherwise stated, mixing fans run continuously during the preparation phase as well as the measuring period of an experiment to ensure a smooth spatial distribution of the tracer.

DATA ANALYSIS

Data analysis is performed either immediately after measurements or any time later by calling and evaluating the appropriate data file. The first case is executed by the program MEASMT if a special control parameter is set. The second case requires an own program EVALTN which includes the evaluation procedures of MEASMT. Additionally, EVALTN is able to restrict the evaluation procedure to definable subsets of the whole data file. In this way, measuring periods with obviously erroneous values or strong transient conditions as they occur in occupied houses, e.g., by opening of windows (see e.g., Fig. 8) can be excluded from evaluations.

The principle of data analysis is the approximation of measured concentrations $C_k(t_k)$ (the index k varies from 1 to N, where N is the total number of measurements) by an exponential expression:

$$C(t) = A_0 + A_1 \exp(-A_2 t) \tag{20}$$

A_0, A_1 and A_2 are numerical parameters fitting eqn. (20) to measured data by means of the Gaussian least squares method. Comparison of eqn. (20), (8) and (4) yields

$$A_0 = F/(\lambda V) \tag{21}$$

$$A_1 = C_0 - F/(\lambda V) \tag{22}$$

$$A_2 = \lambda \tag{23}$$

The asymptotic value A_0 is zero for method I and the air change rate λ is determined unequivocally from eqn. (23) or A_2, respectively. For method II, however, λ can be independently derived at least from eqns. (21) and (23). Equation (22) or A_1, respectively, is not much suited for that purpose because C_0 itself has to be treated as the fitting parameter. The duality in determining λ provides a good test for credibility of results.

Mean deviations of measured values $C_h(t_k)$ from the approximation function, eqn. (20), are calculated and compared with results of error analysis according to eqn. (17). The observed deviations from the approximation function are usually smaller than these calculated errors.

PRELIMINARY TEST RESULTS

Air changes rates have been numerously measured in a somewhat leaky university laboratory ($V = 42 \pm 2$ m^3) for winter conditions and three different cases [8]:

(1) closed door, closed window
$(0.5 \leqslant \lambda(\mathrm{h}^{-1}) \leqslant 1.4)$
(2) open door, closed window
$(2.4 \leqslant \lambda(\mathrm{h}^{-1}) \leqslant 18.0)$
(3) closed door, tilted window
$(6.2 \leqslant \lambda(\mathrm{h}^{-1}) \leqslant 23.2)$

The numbers in brackets above on the right-hand side give the range of observed values for each case. Large scattering of λ-values is attributed to varying meteorological parameters such as wind- and temperature-induced pressure differences between the considered room and its environment. These parameters have not been investigated further within the context of this work.

Figures 5 and 6 show illustrative examples for case (1) and present concentration profiles measured according to method I (Fig. 5) and method II (Fig. 6). Recorded concentration decay follows extremely well the approximation function resulting in a rather small error of the air change rate ($\lambda = 1.30 \pm 0.03$ h^{-1}). If under similar conditions a constant flow rate $F = 8.2 \times 10^{-3}$ m^3 h^{-1} is applied, concentrations increase with time and follow also fairly well a corresponding approximation function (Fig. 6). Air change rate is determined from eqn. (23) and yields a somewhat larger error: $\lambda = 1.15 \pm 0.13$ h^{-1}. If determined independently from eqn. (21) the resulting λ-value is in good agreement with the preceding figure: $\lambda = 1.22$ h^{-1}.

In case (2), at first a uniform tracer gas concentration is established in the measuring room. Then the door is opened and concentration decreases. The latter situation is illustrated in Fig. 7 for conditions of rapid air renewal: $\lambda = 12.71 \pm 0.28$ h^{-1}. Concentration fluctuations around the approximation

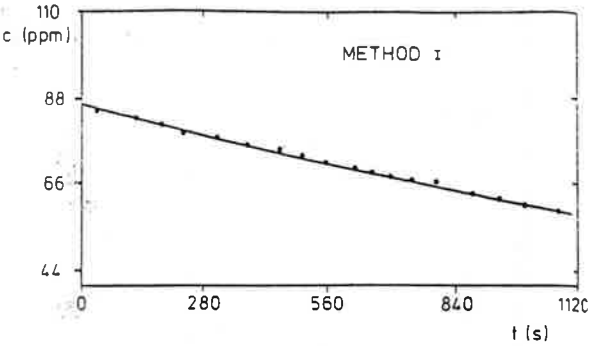

Fig. 5. Tracer gas concentration decay in a case (1) experiment; $\lambda = 1.30 \pm 0.03$ h^{-1} (room with closed door and window; measurements indicated by points, approximation given by line).

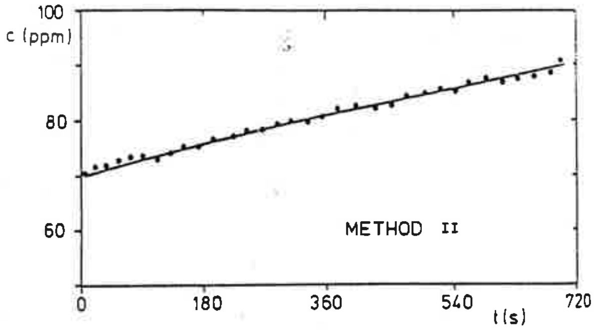

Fig. 6. Increasing tracer gas concentration in a case (1) experiment; $\lambda = 1.15 \pm 0.13$ h^{-1} (room with closed door and window; measurements indicated by points, approximation given by line).

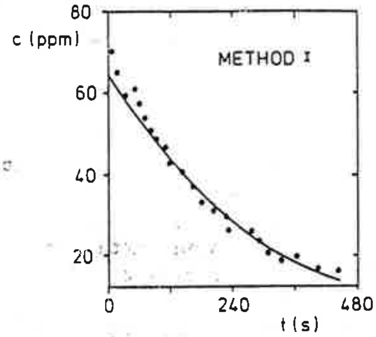

Fig. 7. Rapid decay of tracer gas concentration in a case (2) experiment; $\lambda = 12.71 \pm 0.28$ h^{-1} (room with open door and closed window; measurements indicated by points; approximation given by line).

function are quite sizeable. They show that at the beginning of the experiment the composition of fresh air and room air is not perfectly mixed but consists of large eddies with slightly different concentrations. Due to the rapid air change, very low concentrations are reached a few minutes after the beginning of the experiment. This lowers the accuracy of data evaluation and, therefore, constant emission method II is recommended for such conditions instead of concentration decay method I which was used here. Method II would be most useful in a building with an HVAC system bringing in large amounts of fresh air.

Method II has been applied to case (3) and results are presented in Fig. 8. A constant flow rate $F = 7.7 \times 10^{-3}\ \mathrm{m^3\,h^{-1}}$ of tracer gas is mixed with air of the measuring room (closed door and window) and concentration increases. Then, the window is tilted and air change rate rises rapidly from $\lambda = 1.10 \pm 0.14\ \mathrm{h^{-1}}$ during the first 600 s to $\lambda = 17.41 \pm 1.25\ \mathrm{h^{-1}}$ after 900 s, a process which is accompanied by a sudden decay of concentration. Because theoretical analysis is based on constant λ-values the transient range, $600\ \mathrm{s} \leqslant t \leqslant 900\ \mathrm{s}$, cannot be evaluated. Determination of λ for the domain $900\ \mathrm{s} \leqslant t \leqslant 1800\ \mathrm{s}$ from eqn. (21) instead of eqn. (23) results in $\lambda = 18.28\ \mathrm{h^{-1}}$, a value which is situated within the expected limits of error.

IN CONCLUSION

A movable measuring station for air change rates has been constructed and tested in a university laboratory under various conditions. The measuring procedure provides a quick access to results with a preparation phase of typically 15 min and measuring periods between 15 and 30 min. Evaluation and output of results takes less than 5 min. The measuring equipment is not intended to record long-term average air change rates but is designed for short-duration measurements.

Two methods are examined: concentration decay (I) and constant flow rate (II). Method I is very well suited for small λ-values (typically $\leqslant 6\ \mathrm{h^{-1}}$), whereas method II seems to be more appropriate for larger λ-values, because too rapid concentration decays and corresponding short measuring periods are avoided by suitably dimensioned injections of tracer gas. As an additional advantage of this method, λ-values can be determined by two different ways, and thus offer the opportunity to compare and to test credibility of results.

Error analysis is theoretically outlined and programmed in detail. For method I, measuring time is restricted and its optimum value is approximately given by λ^{-1}. Method II allows an unlimited measuring period. Here, time-dependent errors are difficult to take in at a glance generally, but asymptotic values are easily determined from eqn. (18). Errors are usually larger than those for method I due to additional inaccuracies of flow rate and effective volume.

Limits of applicability are reached for both methods if tracer gas concentration or injection are not homogeneously distributed in space and if probe sampling does not include the whole gas volume.

Mixing fans can be used to reduce concentrations differences, but an artificial pressure difference between indoors and outdoors must be avoided. Tracer injection and probe sampling equipment may be installed at multiple

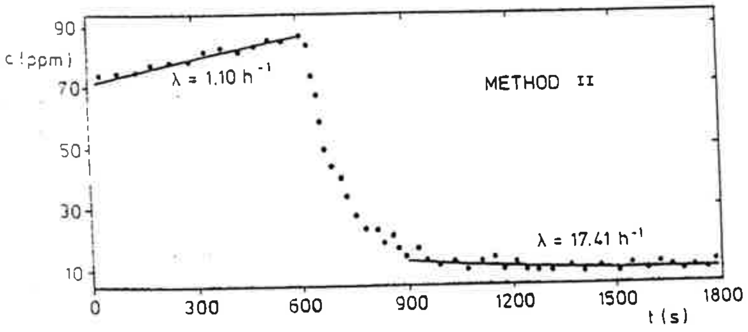

Fig. 8. Concentration profile for a case (1)/case (3) experiment (initially: closed door and closed window, afterwards: closed door and tilted window; measurements indicated by points, approximation given by line). For $600\ \mathrm{s} \leqslant t \leqslant 900\ \mathrm{s}$, air change rate varies between $1.10\ \mathrm{h^{-1}} \leqslant \lambda \leqslant 17.14\ \mathrm{h^{-1}}$.

and various locations within the room in order to establish and to record a well-mixed situation. Due to the variety of possible improvements, absolute values of upper limits for volume and air change rate are hard to estimate.

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