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ADVANTAGES OF MICROCOMPUTER SUPPORT FOR AIR CHANGE
MEASUREMENTS

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SYNOPSIS

Air change rates are measured by an IR-gas-analyzer coupled with a microcomputer which is programmed to control measurements as well as data acquisition and -evaluation. The implemented programs provide an instant access to results. The experimental equipment is installed in compact form on mobile units.

Measurements have been taken in a university laboratory by using the decay- and constant-emission-method to examine air change rates under various conditions. Typical results are presented and show where each of the two methods is more appropriate. The advantages of microcomputer usage are discussed.

INTRODUCTION

The air change rate $Q = n \cdot V$ between an enclosure of effective volume V and its environment or the corresponding volumetric air change rate n are among the less understood aspects of building design and performance. They depend on building construction, meteorological parameters as well as on occupant's behaviour [1]. On the other hand, n -values are prerequisite to estimate the heating demand of buildings [2] and to predict indoor air quality and humidity [3]. Measurements of tracer gas concentrations can be used to calculate n -values according to three procedures [4]: A) concentration decay, B) constant emission and C) constant concentration of the gas. Two of them (A,B) have been implemented and investigated in detail.

The main objective of this work were improvements 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. They served only as illustrating examples showing the typical range of measuring values for the given situations. Special emphasis is given on data analysis and the estimation of errors as well as on the comparison of methods A and B.

THEORETICAL ANALYSIS OF MEASUREMENTS

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

$$V \frac{dc}{dt} = (c_A - c) \cdot V \cdot n + F \quad (1)$$

where $V(\text{m}^3)$ is the effective volume of the enclosed space, $n(\text{h}^{-1})$ air change rate, $F(\text{m}^3/\text{h})$ flow rate of tracer gas, c (e.g.: ppm) tracer concentration and $t(\text{h})$ time. Subscript A denotes ambient air. This first order differential eqn. (1) has to be solved for the initial condition:

$$c(t=0) = c_0 \quad (2)$$

Using a tracer gas which normally doesn't exist in the environment:

$$c_A = 0 \quad (3)$$

results in:

$$c(t) = c_\infty + (c_0 - c_\infty) \exp(-nt) \quad (4)$$

with the dimensionless tracer gas injection rate c_∞ :

$$c_\infty = F/(V \cdot n) \quad (5)$$

A suitable tracer gas has to meet a set of requirements [5] and leads to a restricted number of options. They have been compared with respect to accuracy [6]. Nitrous oxide (N_2O) emerges for a number of reasons as a favourable candidate and has been chosen as tracer in this case.

Method A - constant decay ($c_\infty = 0$) - results in:

$$c(t) = c_0 \cdot \exp(-nt) \quad (6)$$

whereas method B - constant emission ($c_\infty > 0$) - yields the more general solution of eqn. (4).

For method A the air change rate n is calculated in a straight-forward manner from eqn. (6):

$$n = \frac{1}{t} \ln \frac{c_0}{c(t)} \quad \text{or} \quad n = \frac{1}{\Delta t} \ln \frac{c(t)}{c(t+\Delta t)} \quad (7)$$

where t and Δt are any values of time and time increment during the measuring period. For method B the value of n can be determined from eqn. (4) only by numerical iteration or by differentiation of eqn. (4) with respect to time from:

$$n = - \frac{d^2c}{dt^2} \bigg/ \frac{dc}{dt} \quad (8)$$

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

$$x_1 = c(t), \quad x_2 = c_0 \quad \text{and} \quad x_3 = c_\infty \quad (9)$$

where we consider time t to be measured exactly. Then, the Gaussian law of error propagation results in:

$$(\delta n)^2 = \sum_1^3 \left| \frac{\partial n}{\partial x_i} \delta x_i \right|^2 \quad (10).$$

δ denotes deviation of a variable from its mean value. For method A which is independent on $x_3 = c_\infty$ we simply put $x_3 = \delta x_3 = 0$.

As mentioned above, the function $n(x_1, x_2, x_3)$ is not generally available as an explicit analytic expression. We use eqns. (9), (4) and (5) and define an implicit function f of n, x_1, x_2 and x_3 :

$$f(n, x_1, x_2, x_3) = x_1(t) - x_3 - (x_2 - x_3) \exp(-n \cdot t) = 0 \quad (11)$$

Thus, partial derivatives $\partial n / \partial x_i$ in (10) can be substituted by:

$$\frac{\partial n}{\partial x_i} = - \frac{\partial f}{\partial x_i} / \frac{\partial f}{\partial n}, \quad i = 1, 2, 3 \quad (12)$$

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

$$(\delta n)^2 = \left(\frac{1}{\partial f / \partial n} \right)^2 \cdot \sum_1^3 \left| \frac{\partial f}{\partial x_i} \cdot \delta x_i \right|^2 \quad (13)$$

This relationship has been evaluated for the general case. For the asymptotic value of the squared error we find finally:

$$\left(\frac{\delta n}{n} \right)^2 = \left(\frac{\delta c}{c_\infty} \right)^2 + \left(\frac{\delta V}{V} \right)^2 + \left(\frac{\delta F}{F} \right)^2 \quad (14).$$

If we restrict our attention to method A error estimation for $(\delta n)^2$ is immediately obtained by differentiation of n in eqn. (7):

$$(\delta n)^2 = \frac{1}{t^2} \left[\left(\frac{\delta c}{c} \right)^2 + \left(\frac{\delta c_0}{c_0} \right)^2 \right] \quad (15)$$

$c_0, \delta c_0$ and δc are assumed as constant values. The error δn then decreases rapidly with increasing time t . However, as soon as $c(t)$ becomes small itself, the error δn increases again. The optimum measuring time τ is in the proximity of $1/n$. Because method A 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.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental equipment consists of three main components:

- gas analyzer with RS 232 interface
- microcomputer with printer-plotter

- gas injection apparatus
as well as a bottle with compressed calibrated gas.
They are installed in compact form on mobile test
units (Fig. 1).

A key-component of the measuring system is the commercially available nondispersive one-beam IR gas analyzer UNOR 6N, which detects low concentrations (1 ppm to 100 ppm) of the tracer gas nitrous oxide (N_2O). Its physical principles and main features are described in detail elsewhere [7,8].

A specially designed RS 232 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 (5 1/4 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 interface.

The gas injection apparatus is very simple (Fig. 2): It consists of a storage bottle of compressed gas with throttling valve followed by a pressure vessel of known volume and a flexible tube connected with a mixing fan which can be moved freely.

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.

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

- 1) calibration of the analyzer
- 2) definition and/or preparation of measuring conditions
- 3) measurement control and data handling.

Microcomputer programs have been developed to support and to facilitate these points [7]. 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 second.

The second point is of special importance for method B 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 A only c_0 and t_M have to be selected.

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 $c(t)$.

DATA EVALUATION

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:

$$c(t) = A_0 + A_1 \cdot \exp(-A_2 \cdot t) \quad (16)$$

A_0, A_1 and A_2 are numerical parameters fitting eqn. (16) to measured data by means of the Gaussian least squares method. Comparison of eqns. (16), (4) and (5) yields:

$$A_0 = c_\infty = F/(nV) \quad (17)$$

$$A_1 = c_0 - c_\infty \quad (18)$$

$$A_2 = n \quad (19)$$

The asymptotic value A_0 is zero for method A and the air change rate n is determined unequivocally from eqn. (19) or A_2 , respectively. For method B, however, n can be independently derived at least from eqns. (17) and (19). This duality in determining n provides a good test for credibility of results.

Air change rates have been numerously measured in a somewhat leaky university laboratory ($V = 42 \pm 2 \text{ m}^3$) for winter conditions and three different cases [7]:

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

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

DISCUSSION OF TEST RESULTS

Figures 3 and 4 show illustrative examples for case (1) and present concentration profiles measured according to method A and method B. Recorded concentration decay follows extremely well the approximation function resulting in a rather small error of the air change rate ($n = 1.30 \pm 0.03 \text{ h}^{-1}$). If under similar conditions a constant flow rate $F = 8.2 \cdot 10^{-3} \text{ m}^3 \text{ h}^{-1}$ is applied, concentrations increase with time and follow also fairly well a corresponding approximation function (figure 4). Air change rate is determined from eqn. (19) and yields a somewhat larger error: $n = 1.15 \pm 0.13 \text{ h}^{-1}$. If determined independently from eqn. (17) the resulting n -value is in good agreement with the preceding figure: $n = 1.22 \text{ h}^{-1}$.

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 figure 5 for conditions of rapid air renewal: $n = 12.7 \pm 0.3 \text{ h}^{-1}$. Concentration fluctuations around the approximation 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 B is recommended for such conditions instead of concentration decay method A which was used here.

Method B has been applied to case (3) and results are presented in figure 6. A constant flow rate $F = 7.7 \cdot 10^{-3} \text{ m}^3 \text{ h}^{-1}$ 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 $n = 1.10 \pm 0.14 \text{ h}^{-1}$ during the first 600 s to $n = 17.4 \pm 1.3 \text{ h}^{-1}$ after 900 s, a process which is accompanied by a sudden decay of concentration. Because theoretical analysis is based on constant n -values the transient range $600 \text{ s} \leq t \leq 900 \text{ s}$ cannot be evaluated. Determination of n for the domain $900 \text{ s} \leq t \leq 1800 \text{ s}$ from eqn. (17) instead of eqn. (19) results in $n = 18.3 \text{ h}^{-1}$, a value which is situated within the expected limits of error.

A very interesting result is presented in figure 7 which shows the tracer gas profile for a method B measurement in the case of varying window positions in an adjacent room. The alterations of the concentration profile are retarded in time with respect to changing window positions but the interdependence is quite obvious. This shows the importance of interzonal air exchange rates which cannot be treated with the simple 1-node-model discussed in this paper.

SUMMARY AND CONCLUSION

A moveable 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 minutes and measuring periods between 15 and 30 minutes. Evaluation and output of results takes less than 5 minutes.

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

The main advantage for the two measuring methods A and B comes due to the capabilities of microcomputers. They help to perform thoroughly and quickly the following tasks:

- Preparation of measurements: Calibration. Choice of initial concentration, measuring time, injection rate (if required).
- Control of measurement: Time steps, interrupts, conditions for ending.
- Automatic display, graphic presentation, recording of measuring parameters and values.
- Immediate and fast evaluation of measurements with complete presentations from initial conditions up to the results.
- Theoretical error analysis as well as statistical evaluation procedures for measured data.
- Evaluation of a reduced data set only if so required by failings of instruments or other obviously erroneous effects.

Moreover, a microcomputer is able to perform even more complicated measuring and evaluation procedures as they are required for constant concentration measurements

or for a determination of interzonal air change rates between different rooms of a building. In addition, correlation analysis of air change rate and other relevant meteorological or user-specific parameters can be done easily and without much effort in time. We conclude finally that the capabilities of traditional measuring methods are enhanced by the usage of micro-computers and that they are even mandatory for any more sophisticated measuring and evaluation method to obtain air change rates.

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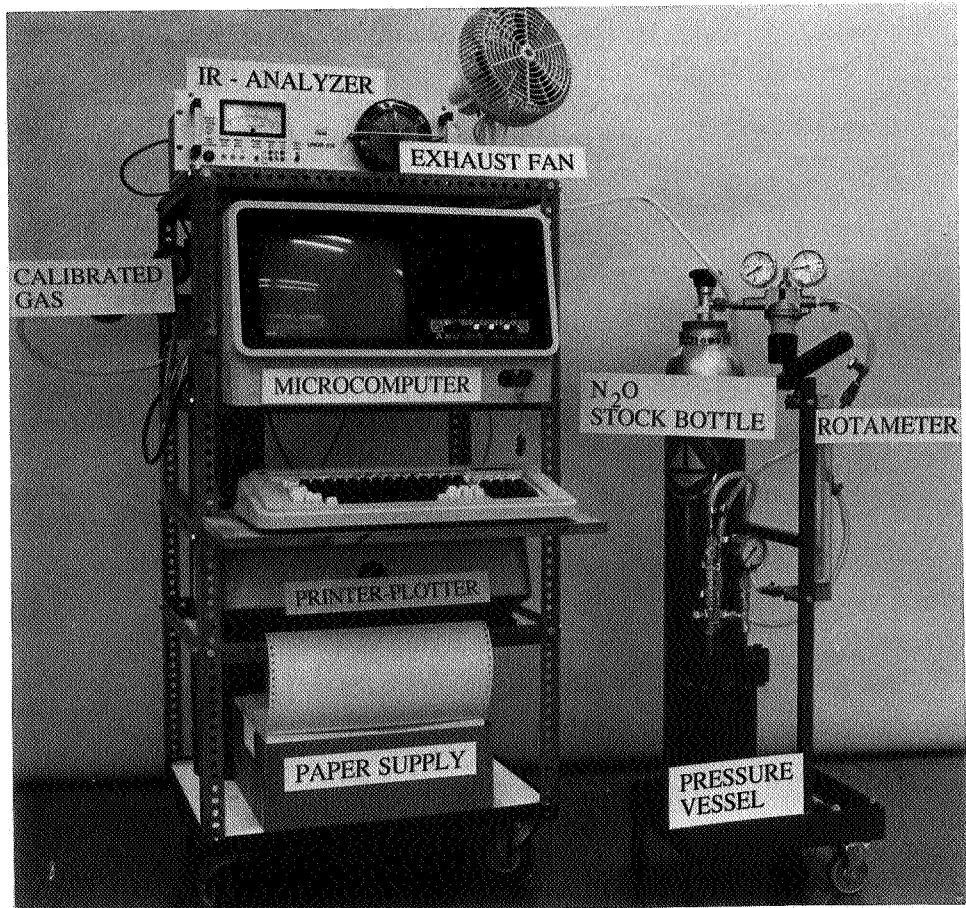


Fig. 1: Measuring unit's configuration. Left-hand side: IR-analyzer with RS 232 interface, gas exhaust fan, calibrated gas, microcomputer and related equipment. Right-hand side: gas injection apparatus consisting of stock bottle, pressure vessel, rotameter and related armatures.

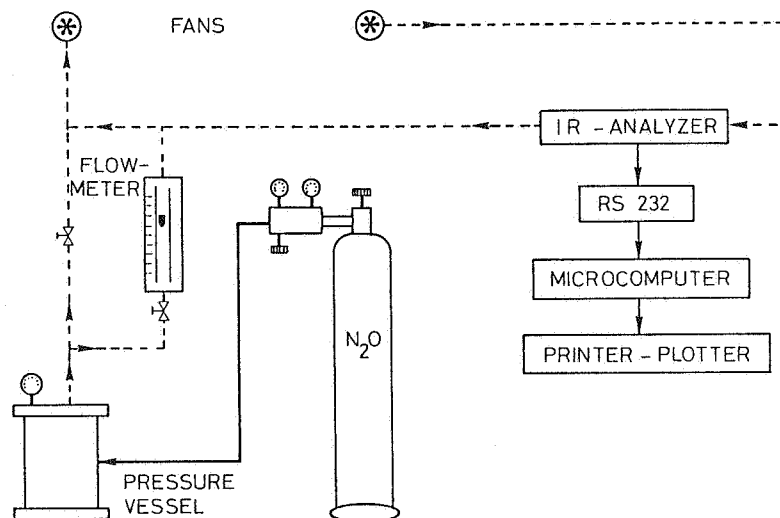


Fig. 2: Schematical illustration of measuring system and gas injection apparatus.

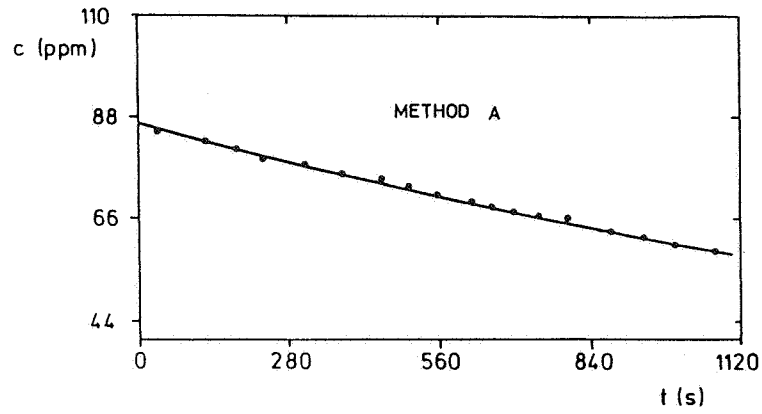


Fig. 3: Tracer gas concentration decay for case (1) - measurements: closed door and window: $n = 1.30 \pm 0.03 \text{ h}$ (measurements: points, approximation: line).

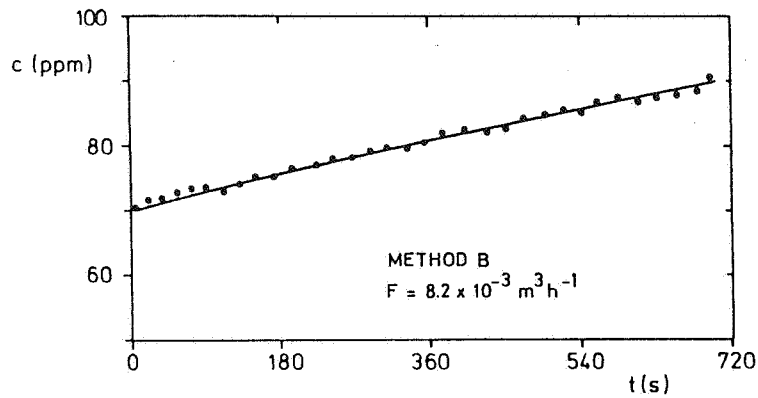


Fig. 4: Increasing tracer gas concentrations for case (1) - measurements: closed door and window: $n = 1.15 \pm 0.13 \text{ h}^{-1}$ (measurements: points, approximation: line).

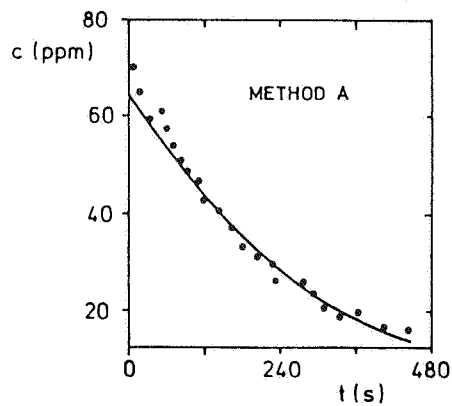


Fig. 5: Rapid concentration decay for case (2) - measurements: open door and closed window: $n = 12.7 \pm 0.3 \text{ h}^{-1}$ (measurements: points, approximation: line).

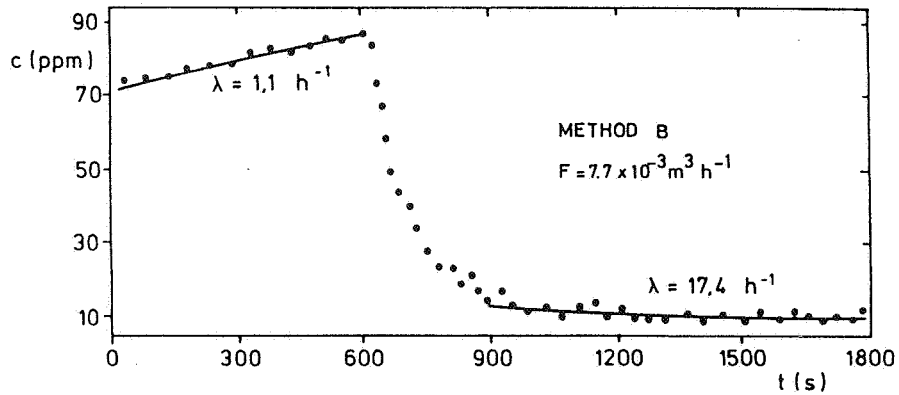


Fig. 6: Concentration profile for case (1)/case (3)-measurements: closed door and window/closed door and tilted window. During the time interval [600 s, 900 s] the air change rate increases from $n = 1.1 \text{ h}^{-1}$ to $n = 17.4 \text{ h}^{-1}$ (measurements: points, approximation: lines).

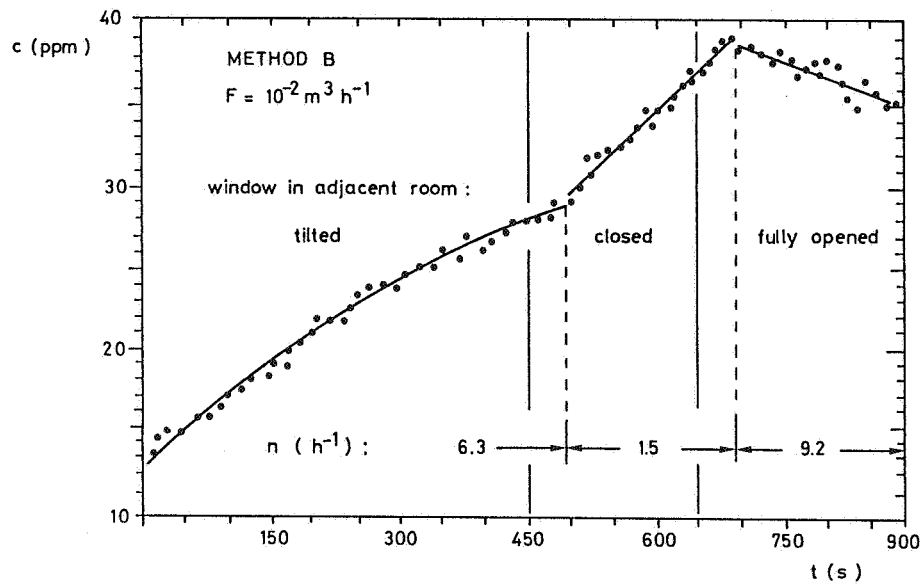


Fig. 7: Concentration profile for case (1)-measurements: closed door and window. A window in the adjacent room is tilted, closed or fully opened at the indicated moments of time. With some time lag the air change rate is significantly altered by these changed window positions (measurements: points, approximation: lines).