VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER P2

A PORTABLE UNIT FOR MEASURING VENTILATION EFFICIENCY

N.O. BREUM AND J. SKOTTE

Danish National Institute of Occupational Health
Department of Industrial Hygiene
Baunegaardsvej 73
DK 2900 Hellerup
Denmark

SYNOPSIS

A computerized portable unit for measuring the ventilation efficiency by the tracer gas technique is described. The hardware of the unit is designed from readily available equipment. The software of the unit is menu-driven to be operated by computer non-experts. The software include several analytical models of ventilation processes and in the present study is discussed age analysis and the air exchange efficiency. In a field study the ventilation process of a non-occupied lecture hall was characterized by the portable unit, and in case of almost isothermal conditions the measured air exchange efficiency was 54% indicating a complete mixing. It is emphasized that the portable unit may also be used for characterizing the indoor air pollution.

SYMBOL LIST

		Units
A	mean age of air	h
C	generic symbol for concentration	ppm
$C(\infty)$	equilibrium concentration	ppm
$C(0)$	concentration at $\tau=0$	ppm
$C(\tau)$	concentration at time τ	ppm
MO	zeroth moment from origin of the concentration vs time	ppm h
M1	first moment from origin of the concentration vs time	ppm h^2

m	amount of tracer gas released as a pulse	m^3
NO	zeroth moment from origin of the complementary normalized concentration vs time	h
N1	first moment from origin of the complementary normalized concentration vs time	h^2
q	flow rate of tracer gas	m^3/s
Q	flow rate of air	m^3/s
V	volume of a room	m^3

Greek symbols

τ	time	h
τ_n	time constant of a ventilation system	h
τ_p	the "local time constant" of a point p	h
τ_o	given time interval	h
ϵ_a	air exchange efficiency	
β	off-set	

Subscribts and other symbols

e	refers to the exhaust air
p	refers to an arbitrary point p
< >	refers to the room average

1. INTRODUCTION

A common technique for ensuring an acceptable indoor air quality and thermal environment is mechanical ventilation. A number of ventilation system designs are in common use, and qualitatively the pattern of airflow can vary from one extreme (short circuiting) to the other extreme (displacement flow). Between these extremes is perfect mixing[1].
A proper air distribution in a room is essential, and the concept of age distribution is useful in the quantification of mixing and flow in a confined space. For this purpose the experimental impulse-response tracer gas technique is well established[2], and by the present study is reported details of a portable computerized unit[3] using this technique for measuring and modelling the ventilation process in a room. Some of the analytical models included in the software of the portable unit are the age distribution of the air in a room, the ventilation efficiency, the air exchange efficiency, the air change rate, and airflows of a two compartment model. In the present study, however, is included only details of modelling and estimating the age distribution of air and the air exchange efficiency. The unit is designed to allow an easy characterization of the ventilation process in a room, which finally is illustrated by an example.

2. THE PORTABLE MEASURING UNIT

For the purpose of documenting a ventilation process by the tracer gas approach a detailed experimental procedure is required, including a proper strategy for injecting the tracer gas, adequate hardware for measuring the tracer gas concentration vs time, and finally an analytical modell for the interpretation of the data obtained. As previously reported[2] common strategies for the injection of the tracer gas are constant release (step-up), decay (step-down) and the pulse injection mode. In the present study the equipment for the injection of the tracer (SF_6) is a release directly from a compressed gas cylinder and controlled by a needle valve and a calibrated rotameter to an accuracy[3] of +/-3%.

The hardware of the highly automated unit (fig. 1) is designed from readily available equipment[4]. By gas tight pumps air from up to 8 sample lines (25m length, 10mm i.d. tygon tubing) are continuously sucked through the sample lines and the manifold of 3-way solenoid valves, and air from each line is sequentially delivered to the gas analyzer at a flow of 33 l/min. The present gas analyzer is an IR-analyzer (MIRAN 80, Foxboro Analytical) with a time constant of 9.6 sec at a 33 l/min sampling rate. During an experiment the sequence of operations and the data acquisition is run by a portable IBM-compatible computer (COMPAQ 286). Continuously upgraded test results are displayed on location.

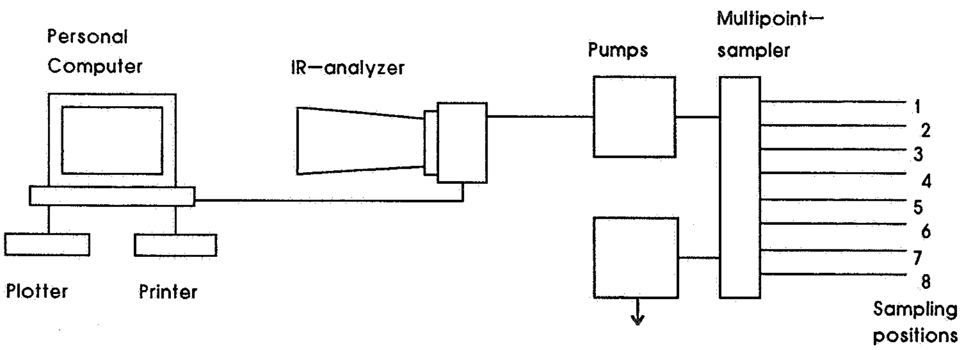

Fig. 1. The multipoint tracer measurement equipment.

The software running the outlined hardware is designed to be menu-driven and to be operated by computer non-experts. The two main menues of the software are entitled setting up the system and modelling, respectively. Some major points in setting up the system include preselecting of

- the tracer gas to be used: the software may contain the calibration curves of up to 9 different gases. In the present study SF_6 is used, the calibration ranging 0.2-50 ppm with an accuracy[3] of +/-2.5%.
- the gas analyzer to be used: a digital or an analog output is accepted, and one sample line may, if needed, contain a span gas for an automatic correction of a possible drift in the baseline of the analyzer.
- the measurement cycle: usually a 45 sec step period of the sequential sample line scanning is used ensuring a 1% maximum bias in data due to an insufficient purging of the present gas analyzer.
- the number of sample lines to be used: each line may be described by a 40 character free text.

When the system has been set up measurements are running until a manual stopping procedure is applied. All data obtained are stored on a disk for the subsequent modelling.

3. THE ANALYTICAL MODEL

The modelling software menu include several analytical models, but in the present study is only discussed the mean age of air and the air exchange efficiency. By definition[6] the air exchange efficiency $\langle \epsilon_a \rangle$ is computed by the equation

$$\langle \epsilon_a \rangle = \tau_n / 2 \langle A \rangle \qquad (1)$$

where τ_n is the nominal time constant of the ventilation system and <A> is the mean age of air.

The analytical model of the mean age of air depend as outlined below on the applied strategy for the tracer gas injection.

3.1 Tracer decay technique

Using the tracer decay technique the mean age of air (<A>) within the room and the local mean age of air (A_p) at a point p can be computed using the equations[2]:

$$\langle A \rangle = Q/V \int_0^\infty \tau \; C_e(\tau)/C_e(0) d\tau, \text{ and} \tag{2}$$

$$A_p = \int_0^\infty C_p(\tau)/C_p(0) d\tau \tag{3}$$

where $C(\tau)$ is the tracer gas concentration at time τ, and $C(0)$ is the concentration at $\tau=0$. Subscript e refers to the exhaust air, and subscript p to a point p. V is the indoor volume, and Q is the exhausted airflow. For convenience the zeroth moment of the measured concentration vs time about the origin is denoted MO, where[2]

$$MO = \int_0^\infty C(\tau) d\tau \tag{4}$$

Likewise the first moment is denoted M1, where[2]

$$M1 = \int_0^\infty \tau \; C(\tau) d\tau \tag{5}$$

Assuming a complete mixing at $\tau = 0$, it is noted that

$$MO_e = (V/Q) \; C_e(0) \tag{6}$$

Substituting equation 4,5 and 6 into equation 2 and 3 the mean ages may be expressed as follows[3]:

$$\langle A\rangle = M1_e/M0_e, \text{ and} \tag{7}$$

$$A_p = M0_p/C_p(0) \tag{8}$$

3.2 Tracer pulse technique

Using the technique of delivering a tracer pulse by the supply air the mean ages may be computed using the equations[3]:

$$\langle A\rangle = \int_0^\infty \tau\, C_e(\tau)d\tau / \int_0^\infty C_e(\tau)d\tau = M1_e/M0_e, \text{ and} \tag{9}$$

$$A_p = \int_0^\infty \tau\, C_p(\tau)d\tau / \int_0^\infty C_p(\tau)d\tau = M1_p/M0_p \tag{10}$$

If m is the amount of tracer gas released as a pulse it is noted that $m = Q\, M0_e$.

3.3 Tracer step-up technique

Delivering the tracer by the supply air and using the step-up technique the mean ages of air can be computed using the equations[5]

$$\langle A\rangle = Q/V \int_0^\infty \tau\, (1-C_e(\tau)/C_e(\infty))d\tau, \text{ and} \tag{11}$$

$$A_p = \int_0^\infty (1-C_p(\tau)/C_p(\infty))d\tau \tag{12}$$

where $C(\infty)$ is the equilibrium concentration, and $C_e(\infty) = q/Q$ where q is the flow rate of the tracer gas. Two quantities NO and N1 are defined for convience as follows:

$$NO = \int_o^\infty (1-C(\tau)/C(\infty))d\tau, \text{ and} \qquad (13)$$

$$N1 = \int_o^\infty \tau\ (1-C(\tau)/C(\infty))d\tau \qquad (14)$$

Normalizing the measured concentration to $C(\infty)$ it is noted that the quantities NO and N1 are the zeroth and the first moment about the origin of the complementary normalized concentration vs time, respectively. It is noted[4] that the nominal time constant τ_n of the ventilation system may be obtained by

$$t_n = V/Q = NO_e \qquad (15)$$

By substituting equation 13,14 and 15 into equation 11 and 12 the ages may be computed as follows:

$$\langle A\rangle = N1_e/NO_e, \text{ and} \qquad (16)$$

$$A_p = NO_p, \qquad (17)$$

4. ESTIMATING THE PARAMETERS

In the field the sampling period of an experiment may often be restricted so the measured concentration vs time is obtained only for a given time interval τ_o. Theoretically, however, an integration of the concentration vs time is needed for $\tau \to \infty$. By the menu-driven software of the present study this integration over the interval $0<\tau<\infty$ may be approximated firstly by curvefitting, secondly by integrating the extrapolated fitted curve. When using the tracer decay or the tracer pulse technique the fitting of the data obtained from a point p is by the function $C_p(\tau) = C \exp(-\tau/\tau_p)$, where τ_p is a "local time constant". When using the tracer step-up technique the fitting is by the function

$$C_p(\tau) = C_p(\infty)(1-\exp(-(\tau+\beta_p\tau_p)/\tau_p)) \quad (18)$$

where β_p is a possible off-set. In case of no off-set it may benoted that $\tau_p = NO_p$, otherwise $\beta_p\tau_p$ indicate a delay in the stimulus-response relationship of the experiment. As an option of the software the moments mentioned may also be estimated on only a preselected time interval within τ_o in case of an unacceptable low coefficient of regression of the fitted function.

5. TEST RESULTS

In a field study the ventilation process of the non-occupied lecture hall ($V = 400m^3$) shown in fig. 2 was characterized by the tracer step-up method. The nominal flow rate of the balanced mechanical ventilation system (supply/exhaust) was $Q = 0.22m^3/s$ and the air temperature of the supply air was 20.0° C. The tracer gas was delivered ($q = 5.3\ 10^{-6} m^3/s$) in the supply duct, and the concentration vs time was sequentially (45 sec step period) measured at 5 different points (No. 2-6) in the room, and at a point (No. 1) in the exhaust duct. Additionally the air temperature was measured at some of the points.

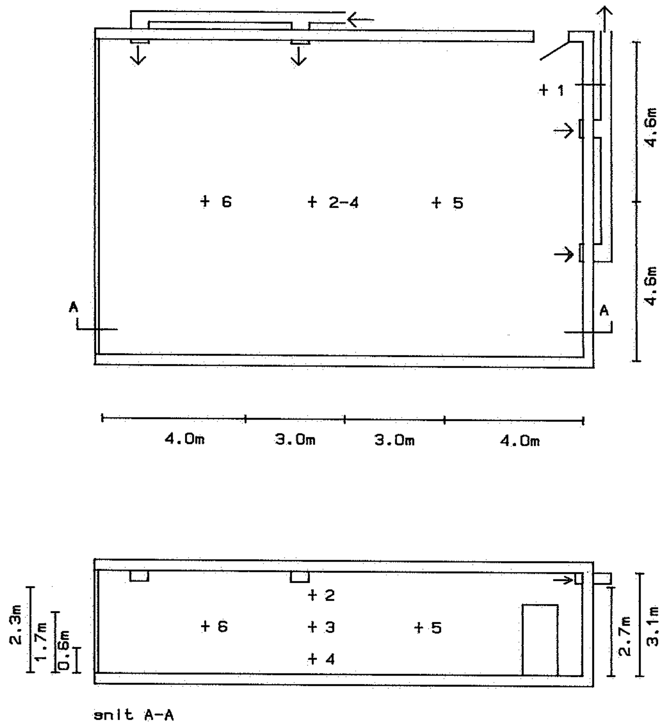

Fig. 2. The lecture hall where the test was carried out.

As an example the measured concentration vs time at point No.3 is plotted in fig 3. In the plot is also shown the function fitted to the data. For each of the points measured the estimated parameters of the fitted function are listed in table 1 as well as the estimated moments N0 and N1.

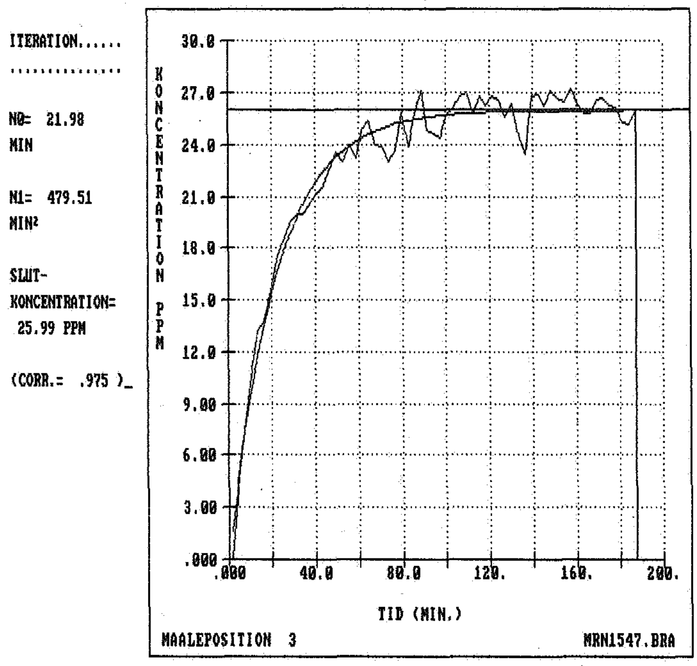

Fig. 3 Step-up test in point No. 3.

Point No.	$C_p(\infty)$ ppm	τ_p h	β_p	$\tau_p\beta_p$ h	R^2 a)	$N0_p$ h	$N1_p$	Air temp°C
1	26.4	0.51	0.094	0.047	0.982	0.56	0.29	21.0
2	24.0	0.34	0.004	0.002	0.854	0.34	0.11	20.8
3	26.0	0.36	0.004	0.002	0.975	0.37	0.13	-
4	25.7	0.48	0.054	0.025	0.957	0.50	0.24	21.3
5	26.6	0.44	0.048	0.021	0.985	0.46	0.20	-
6	27.4	0.42	-0.114	-0.048	0.954	0.38	0.16	-

Table 1. Estimated parameters of a tracer gas step-up field study. a: coeff. of regression.

From table 1 the mean age of the air in the room is calculated (point No. 1) as $\langle A \rangle = N1_e/N0_e = 0.51$ h, and the exhausted flow rate of air is estimated to be $Q = q/C_e(\infty) = 0.20\ m^3/s$. The time constant of the room is estimated to be $\tau_n = N0_e = 0.56$ h. The air exchange efficiency is estimated to be $\langle \epsilon_a \rangle = N0_e^2/2\ N1_e = 0.54$.

6. DISCUSSION

The approach of age analysis in characterizing the ventilation process has mainly[4] been used in small spaces with relatively simple geometry and ventilation arrangement. Test results are available from experiments in the laboratory[2], and as recently reported[6] the approach may also be useful in field studies, including large spaces. The results of the pre- sent field study were obtained in a non-occupied room at near isothermal conditions with a temperature difference between supply and room of less than 1.3° C. The time constant of the room was estimated to be 0.56 h. At positions within the room the estimated "local time constant" ranged 0.34-0.51 h. As listed in table 1 the estimated delay of the stimulus-response relationship of the experiment ranged (-0.048;0.047 h) causing a difference ranging 0-0.05 h between τ_p and $N0_p$. Within the room the estimated local mean age of air ranged 0.34-0.50 h, and the mean age of the exit air was 0.56 h. On the average the ventilation process of the non-occupied room may be characterized as almost complete mixing, the estimated air exchange efficiency being 54%. This conclusion, however, may not be valid for the occupied room due to convective currents from people. Finally it is emphasized that the portable unit may also be useful in documenting the indoor air pollution.

7. CONCLUSION

A portable computerized unit is described for documenting the ventilation process by the approach of age analysis. The software of the unit is menu-driven, designed to be operated by computer non-experts. By the portable unit the air exchange efficiency of a non-occupied mechanically ventilated lecture hall was estimated to be 54%.

ACKNOWLEDGEMENT

The study was supported by the Danish Work Environment Fund (grant No. 1985-10).

REFERENCES

1. Fisk, W.J. et al
"A Multi-Tracer System for Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically Ventilated Buildings." Paper presented at 6th AIC Conference, Sept 16-19 1985, The Netherlands.

2. Sandberg, M. and Sjöberg, M.
"The Use of Moments for Assessing Air Quality in Ventilated Buildings." Build Env 18 (4): 181-197, 1983.

3. Breum, N.O. and Skotte, J.
"How to Measure the Ventilation Efficiency." (In Danish with English summary). The Danish Work Environment Fund, Copenhagen, 1987.

4. Niemelä, R.
"Characterization of the Performance of Industrial Ventilation Systems by a Tracer Gas Technique." Ph.D. thesis, University of Helsinki, Helsinki, Finland, 1986.

5. Persily, A.K.
"Ventilation Effectiveness in Mechanically Ventilated Office Buildings." Gaithersburg, USA: Dept Commerce, NBS 1985, NBSIR 85-3208.

6. Skåret, E. and Mathisen, H.M.
"Test Procedures for Ventilation Effectiveness Field Measurements." Proc Int Symp on Recent Advances in Control and Operation of Building HVAC Systems, Trondheim, Norway, 1985.