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THE AIR EXCHANGE EFFICIENCY OF A LECTURE HALL

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ABSTRACT

The air flow pattern in a lecture hall ($V=690\ m^3$) designed for displacement ventilation was characterized by age analysis in the case of a non-occupied hall as well an occupied hall. The ventilation system was slightly (17%) unbalanced. For comparison the following three experimental signal-response tracer gas techniques were applied: "step-up", "decay" and pulse injection. The mean ages of air estimated by the "decay" technique were elevated (1-23%) compared to the results of the "step-up" method. Generally the pulse technique estimated the lowest mean ages. The estimated air exchange efficiency of the non-occupied hall was 50%, and for the occupied hall the efficiency was estimated to be 60%.

KEYWORDS

Displacement ventilation; air exchange efficiency; age analysis; tracer gas; lecture hall.

INTRODUCTION

A number of general 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 there is perfect mixing (Liddament, 1987). Systems using displacement flow are being installed at a growing rate, but very little is known about their efficiency. A field study of the air exchange efficency of displacement ventilation in a lecture hall has therefore been made. The flow field in rooms is usually very complex involving, for example, supplied airflow, extracted airflow and convective flow. Turbulence is a typical feature of airflows in rooms so that a detailed description of air movement is extremely difficult or even impossible (Niemela et al., 1987), and methods characterizing average behavior have to be used. A quantitative characterization of the ventilation process can be obtained by various tracer gas techniques. The technique on which the present study is based - age analysis and air exchange efficiency - is summarized first.

MATERIALS AND METHODS

Age analysis

Consider a mechanically ventilated room (volume $V\ m^3$) with one supply duct (supply flow rate Q_s, $m^3\ min^{-1}$) and one exhaust duct (exhaust flow rate, Q_e, $m^3\ min^{-1}$). Assuming a balanced ventilation system with a constant flow rate Q (i.e., $Q=Q_s=Q_e$), the nominal time constant of the system is τ_n, and

$$\tau_n = V/Q \tag{1}$$

Fluid elements of air entering the room, remain in it for some time and then leave. The age of a fluid element is defined to be the time that has passed since it entered the room. Three populations of fluid elements may be defined (Sandberg, 1981):

A) the population passing a point p within the room
B) the population of exhausted elements
C) the total internal population of all elements within the room

For each of the populations mentioned there is a cumulative age distribution $F(t)$, which is the fraction of the population with an age less than or equal to t. The corresponding age frequency distribution $f(t)$ is defined as the derivative of $F(t)$, i.e.

$$f(t) = dF(t)/dt, \text{ or } F(t) = \int_0^t f(t)\, dt \tag{2}$$

For the analysis of the mixing process within the room, some moments of the frequency distribution are of importance. The nth moment (n = 0, 1, 2, ..) of the frequency distribution is μ^n where

$$\mu^n = \int_0^\infty t^n f(t)\, dt = \int_0^\infty t^{(n-1)} [1-F(t)]\, dt \tag{3}$$

It is noted that the first moment, μ^1, is the centroid or the mean of the distribution. For convenience, μ^1 is denoted μ in the following.

Experimentally the age distribution may be determined by labelling the air using a signal-response tracer gas technique. The signal is the injection of tracer gas and the response is the measured tracer gas concentration. Three strategies of tracer gas injection are widely used, namely (Sandberg, 1981): decay ("step-down"), continuous injection at a constant rate ("step-up"), and pulse injection. The responses may be measured at given points within the room or at the flow exit, and a recorded curve of concentration against time represents an age distribution. The equation of the age distribution depends as follows on the tracer gas injection strategy used and on the population of fluid elements considered.

Decay ("Step-Down"). Let tracer gas be artificially mixed in the room, and at t=0 the gas injection and the mixing process is terminated and the homogeneous concentration is denoted C(0). Let at a position p within the room the concentration at time t be denoted $C_p(t)$. Then the cumulative age distribution $F_p(t)$ of the fluid elements at this position is (Niemela, 1986)

$$F_p(t) = 1-C_p(t)/C(0) \tag{4}$$

The mean age μ_p of the fluid elements passing this position p is

$$\mu_p = \int_0^\infty t\, f_p(t)\, dt = \int_0^\infty [1-F_p(t)]\, dt = \int_0^\infty C_p(t)/C(0)\, dt \tag{5}$$

If p is at the exhaust duct the population of fluid elements leaving the room is also described by Equation (5), and in that case it is noted that Equation (5) also provides an estimate of τ_n (Skaaret and Mathisen, 1985). The concentration at the exhaust is $C_e(t)$ and the age frequency distribution <f(t)> of all the fluid elements within the room is (Niemela, 1986)

$$\langle f(t)\rangle = C_e(t) \Big/ \int_0^\infty C_e(t)\, dt \tag{6}$$

and the room mean age <μ> of the fluid elements is

$$\langle \mu \rangle = \int_0^\infty t \langle f(t)\rangle\, dt = \int_0^\infty t\, C_e(t)\, dt \Big/ \int_0^\infty C_e(t)\, dt \tag{7}$$

Continuous injection ("Step-Up"). Let, from t=0, tracer gas be injected at a constant rate into the supply duct and mixed homogenously with the supply air before entering the room. At steady state the gas concentration at a position p in the room is denoted $C_p(\infty)$, and the cumulative age distribution of fluid elements passing this position is (Breum and Skotte, 1987)

$$F_p(t) = C_p(t)/C_p(\infty) \tag{8}$$

The mean age of fluid elements passing this position is

$$\mu_p = \int_0^\infty t\, f_p(t)\, dt = \int_0^\infty [1-F_p(t)]\, dt \tag{9a}$$

$$= \int_0^\infty [1-C_p(t)/C_p(\infty)]\, dt \tag{9b}$$

If p is at the exhaust duct, the population of fluid elements leaving the room is also described by Equations (8) and (9), and in that case it is noted that Equations (9a) and (9b) also provide estimates of τ_n (Skaaret and Mathisen, 1985). The concentration at the exhaust is denoted $C_e(t)$ and the age frequency distribution <f(t)> of all fluid elements within the room is

$$<f(t)> = [1-C_e(t)/C_e(\infty)]\ dt \Big/ \int_0^\infty [1-C_e(t)/C_e(\infty)]\ dt \tag{10}$$

The mean age $<\mu>$ of all the fluid elements within the room is

$$<\mu> = \int_0^\infty t <f(t)>\ dt \tag{11a}$$

$$= \int_0^\infty t\ [1-C_e(t)/C_e(\infty)]\ dt \Big/ \int_0^\infty [1-C_e(t)/C_e(\infty)]\ dt \tag{11b}$$

Pulse injection. Let at $t=0$ a pulse of tracer be injected into the supply duct and mixed homogenously with the supply air before entering the room. It is noted that the tracer should be released over a time period δt which is very short compared to τ_n. The age frequency distribution of fluid elements passing a position p in the room is (Breum and Skotte, 1987)

$$f_p(t) = C_p(t) \Big/ \int_0^\infty C_p(t)\ dt \tag{12}$$

The mean age of fluid elements passing the position p is

$$\mu_p = \int_0^\infty t\ f_p(t)\ dt = \int_0^\infty t\ C_p(t)\ dt \Big/ \int_0^\infty C_p(t)\ dt \tag{13}$$

If p is at the exhaust duct the fluid elements leaving the room is also described by Equations (12) and (13), and in that case Equation (13) provides an estimate of τ_n (Skaaret and Mathisen, 1985). The concentration at the exhaust is $C_e(t)$ and the age frequency distribution $<f(t)>$ of all the fluid elements in the room is (Lefevre and Muller, 1987)

$$<f(t)> = t\ C_e(t) \Big/ \left[2\ \tau_n \int_0^\infty C_e(t)\ dt\right] \tag{14}$$

The mean age $<\mu>$ of all fluid elements in the room is

$$<\mu> = \int_0^\infty t^2\ C_e(t)\ dt \Big/ \left[2\ \tau_n \int_0^\infty C_e(t)\ dt\right] \tag{15}$$

Air exchange efficiency

By definition (Skaaret and Mathisen, 1985), the displacement flow pattern (plug-flow) is considered the most efficient for the renewal of the air within a room. If the flow pattern of the room investigated were like plug-flow, the mean age of the air within the room would be "low". Let this mean age be denoted $<\mu_d>$. Then

$$<\mu_d> = \tau_n/2 \tag{16}$$

The actual flow pattern of the room investigated may, however, deviate from the defined ideal, and the mean age of the air in the room would be "high". Let this actual mean age be denoted $<\mu>$. The air exchange efficiency, ε, is by definition (Skaaret and Mathisen, 1985)

$$\varepsilon = <\mu_d> / <\mu> = \tau_n/2 <\mu> \tag{17}$$

It is noted that $0 < \varepsilon < 1.0$. An efficiency of $\varepsilon = 1.0$ is achieved for ideal displacement flow. Complete mixing is characterized by an efficiency of 0.5, while stagnant flow yields $\varepsilon < 0.5$.

Description of the lecture hall

The layout and a cross-section of the lecture hall ($V=690\ m^3$) investigated are shown in Fig. 1. At the beginning of the period of investigation the hall was non-occupied (test period A), and during a subsequent shorter period (test period B) the hall was occupied by 30 mainly seated adults. As indicated in Fig. 1 fresh (no recirculation) cool air was introduced at a low air velocity in the zone of occupancy through diffusors located at the walls. The air was exhausted through outlets in the ceiling. The ventilation process was designed for a basically-balanced displacement system with a nominal air supply rate of 98 $m^3\ min^{-1}$ and an exhausted flow rate of 106 $m^3\ min^{-1}$.

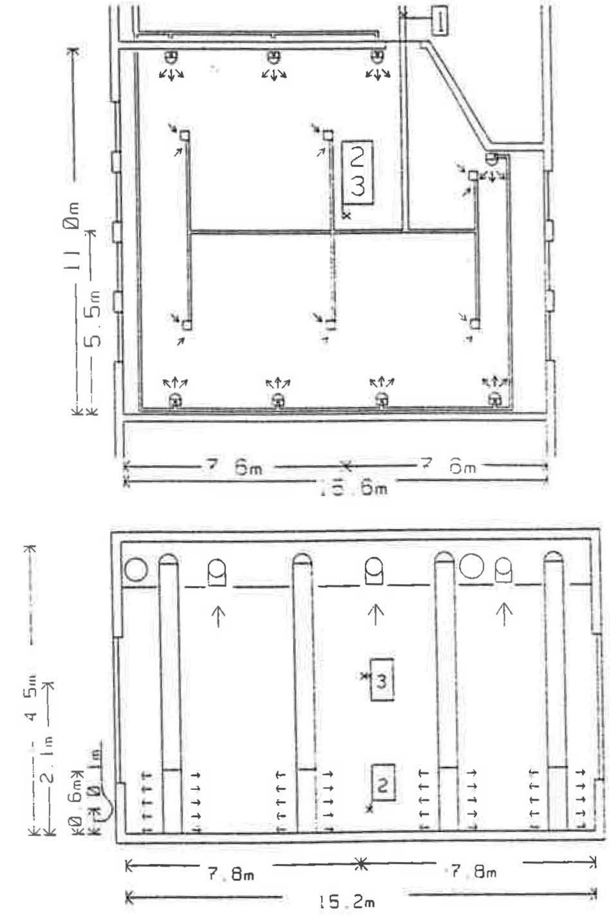

Fig. 1. The layout and a cross section of the lecture hall (not drawn to scale).

Experimental procedure

For comparison the three above-mentioned tracer gas injection strategies were used during the two test periods A and B. In the short test period B, however, the pulse technique was not applied due to lack of time allowed for the testing. For each of the two test periods considered, tracer gas (SF_6) was initially introduced into the fresh air supply at a constant flowrate of 2100 $cm^3\ min^{-1}$ controlled by a calibrated rotameter at an estimated accuracy of ± 3%. The tracer was injected in the supply duct at a distance from the inlet more than 80 times the duct diameter, and when it enters the hall the tracer may be considered homogenously mixed with the supply air (Presser and Becker, 1988). When a steady state tracer gas concentration in the hall was achieved the injection was stopped, and a decay experiment was performed. Finally the pulse injection strategy was applied by injecting tracer (14.2 l in $\delta t=38$ s) in the supply duct.

At positions 1-3 (Fig. 1) tracer gas concentration was recorded sequentially (45 s step period) using the multipoint measuring unit (Breum and Skotte, 1987) shown in Fig. 2. This unit sucked air continuously through the sample lines (10 mm i.d. tubing) and the sampling manifold of 3-way solenoid valves using gas-tight pumps. Air from each line was delivered sequentially to the gas analyser at a flow rate of 33 $l\ min^{-1}$. The gas was analysed by an ir-analyser with a time constant of 9.6 sec at a 33 $l\ min^{-1}$ sampling rate. The accuracy of the tracer gas analysis was estimated to be ± 5%. During an experiment the sequence of operations and the data acquisition was run by menu-driven software (Breum and Skotte, 1987) using a portable IBM-compatible computer.

The exhausted air flow rate (Q_e) was estimated by injecting the tracer gas at a constant flow rate (q=2100 cm^3 min^{-1}) in an outlet (100% capture efficiency). With no tracer gas in the hall and assuming homogenous mixing in the duct, the steady state concentration was measured at position No. 1. The rate of supply air (Q_s) was estimated by measuring the steady state concentration at an inlet when tracer was injected (q=2100 cm^3 min^{-1}) in the supply duct. In addition to the tracer gas measurements, the air temperatures and air velocities were recorded at selected positions (Nos. 2-3) using a low velocity flow analyser with technical characteristics meeting accepted standards (ISO, 1982).

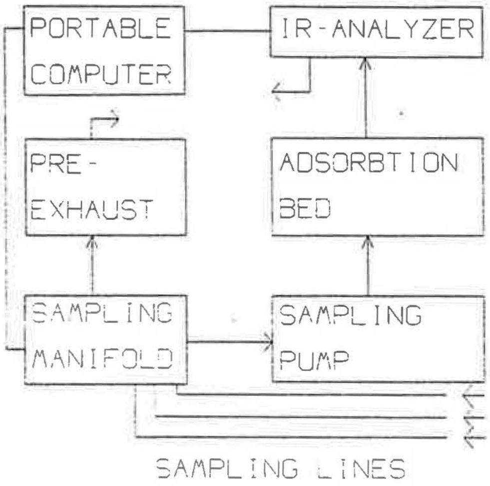

Fig. 2. The tracer gas measuring equipment (the adsorption bed was bypassed in the present study).

RESULTS

All the tracer gas test results were collected on the hard disk of the portable computer for subsequent analysis. As an example of the results obtained the measured concentration at position No. 1 plotted against time is shown in Fig. 3 (Fig. 3A: "step-up" test, Fig. 3B: "decay" test, Fig. 3C: "pulse" test). In Fig. 3A is included the measured supply air tracer concentration. For each of the positions measured the estimated mean age of air is listed in Table 1. Table 1 also lists the estimated mean age of all the air within the room, the estimated air exchange efficiencies and the recorded air temperatures. During test period A the estimated fresh air supply rate was Q_s=93 m^3 min^{-1} (supply air temperature 22.8°C) and the estimated exhausted air flow was Q_e=80 m^3 min^{-1}. During test period B the supply air temperature was 23.1°C, and Q_s was estimated to be 95 m^3 min^{-1} and Q_e was estimated to be 82 m^3 min^{-1}. All recorded air velocities were below 0.10 m s^{-1}.

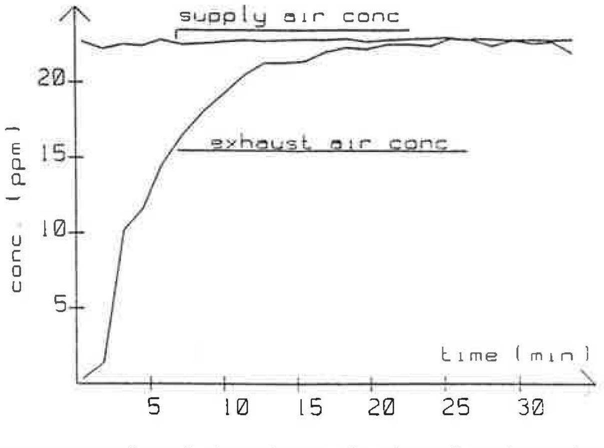

Fig. 3A. Tracer gas concentration of the exhaust air plotted against time ("step-up" test).

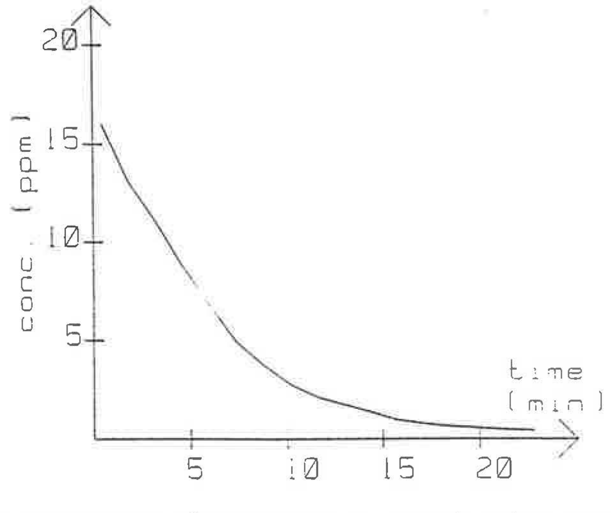

Fig. 3B. Tracer gas concentration of the exhaust air plotted against time ("decay" test).

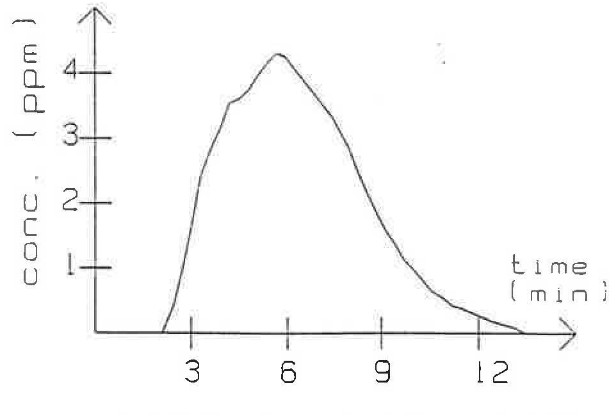

Fig. 3C. Tracer gas concentration of the exhaust air plotted against time ("pulse" test).

Table 1. Estimated parameters of a tracer gas field study of displacement ventilation.

TEST PERIOD		A	A	A	A	B	B	B
Tracer injection stategy		step-up	decay	pulse		step-up	decay	
Posi-tion No.	Height above the floor m	μ min	μ min	μ min	T °C	μ min	μ min	T °C
1	-	5.8	5.9	6.3	-	8.0	8.1	-
2	0.1	2.6	3.2	2.0	23.4	3.6	4.2	23.5
3	2.1	3.5	4.1	2.9	23.4	5.5	5.7	24.2
Room mean age $\langle\mu\rangle$		5.2	5.9	3.5	-	6.8	6.9	-
Air exchange efficiency ε		56%	50%	90%	-	59%	59%	-

DISCUSSION

In chemical reactor engineering mixing processes are characterized by age distribution theory (Levenspiel, 1963). The concepts of this theory may be applied for characterizing air flow pattern of ventilation processes (Sandberg, 1981), and test results are available from experiments in the laboratory (Sandberg and Sjoberg, 1983) and from field studies including large spaces (Skaarest and Mathisen, 1985, Lefevre and Muller, 1987, Breum, 1988). A recent field study (Majanen et. al., 1987) of office buildings reported air exchange efficiencies ranging from 0.36 to 0.57.

Balanced air flow (i.e. $Q=Q_S=Q_e$) is an assumption of the theoretical model of the mean age of all fluid elements within a room (Sandberg, 1981). This assumption also applies to the model of air exchange efficiency (Skaaret and Mathisen, 1985). There is no obvious way in which the sensitivity of the two models to leakage of air, inwards and outwards, can be quantified (Persily, 1985). Using the "step-up" or the "pulse" procedure all fresh air delivered by the supply duct is labelled with the tracer, and air delivered by infiltration is not labelled. Using the "step-down" procedure all fresh air delivered to the room (by the duct and by infiltration) dilutes the tracer concentration. For all three procedures considered only the exhausted tracer concentration is measured, i.e. tracer leaving the room by exfiltration is not measured. When using the "step-up" procedure infiltrated air prevents, at steady state, a spatial homogenous tracer concentration in a room (Malmström and Noguchi, 1987), unless mixing is good. Considering the estimation of the mean age the "step-down" procedure may, from fluid mechanical reasons, in general be considered the most reliable due to the ideal starting point. Experimentally the "step-down" procedure is attractive as the initial tracer gas concentration may be selected high compared to the detection limit of a gas analyser, and when the concentration by decay has reached a low level analytical extrapolation may be applied beyond the detection limit. The performance of the "step-down" procedure for the estimation of the mean age has been (Skaaret and Mathisen, 1985) compared to that of the "step-up" procedure by simulating air flows in a two compartment computer model, and the results may be summarized as follows: 1) the "step-down" procedure is the most reliable, 2) the "step-up" procedure can be used if infiltration and mechanical air supply are mainly to the same zone, 3) local performance are less sensitive than average performance to the choice of procedure. It is noted, however, that the assumptions of a two compartment model may be unrealistic in practice.

In the present field study the ventilation system was slighly unbalanced ($Q_S/Q_e=1.17$). The estimated mean ages by the "decay" procedure were elevated compared to the results of the "step-up" procedure, and the difference ranged 1-23%. Generally the "pulse" procedure estimated the lowest mean ages, but it is emphasized that the time period δt of the pulse injection was not very short compared to τ_n. The test results listed in Table 1 indicate a displacement flow pattern. Neglecting the test result of the "pulse" procedure and considering the test result of the "step-down" procedure as the most reliable, the estimated air exchange efficiency of the non-occupied hall was 50%. The estimated air exchange efficiency of the occupied hall was 60%.

CONCLUSION

For comparison three different tracer gas stimulus-response techniques were applied for characterizing the air flow pattern of a lecture hall designed for displacement ventilation. For the unbalanced (17%) ventilation system investigated the mean ages of air estimated by the "decay" technique were elevated (1-23%) compared to the results of the "step-up" method. Generally the pulse technique estimated the lowest mean ages, but it is emphasized that the time period δt of the pulse injection was not very short compared to τ_n. The "step-down" technique may in general be considered the most reliable of the three tracer gas techniques. The estimated air exchange efficiency of the non-occupied hall was 50%, and for the occupied hall the efficiency was estimated to be 60%.

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