TEST PROCEDURES FOR VENTILATION EFFECTIVENESS FIELD MEASUREMENTS

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SUMMARY

Substantial work on ventilation effectiveness is carried out, both in Norway and Sweden, using tracer gas technics based on fundamental physical and mathematical concepts. The state of the art at present is that we know the nature of, and how to characterize, by using tracer gas technics, the flow of ventilation air and contaminants through a ventilated room. Displacement flow is proved to be the best flow principle in ventilation in addition to that the ventilation air in general should be supplied to the zone of occupation. Results are reviewed from a field test of ventilation effectiveness, showing how the experimental tecnique can be applied for practical experiments.

1. INTRODUCTION

The main objects of ventilation for occupants in a building are to replace "old" and contaminated air in the zone of occupation with "new" fresh air as quick as possible and to remove generated contaminants as quick as possible. An additional requirement is that "new" air should reach the zone of occupation as "undiluted" (contaminants, "old" air etc.) as possible. The words "quick", "new" air and "old" air are related to time and can be quantified through the time parameter "age".

The air renewal process and the contaminant removal process are generally not identical. Consequently, these two processes have to be treated separately. The effectiveness of the air renewal process may be characterized through the "air exchange efficiency", and the effective- ness of the removal process of contaminants through the "ventilation effectiveness". To avoid ambiguities it is necessary to differ between average and local conditions. Research work in Norway and Sweden has proved that criteria for effective ventilation can be defined through the age concept (1,2).

2. THE PHYSICAL MEANING OF EFFECTIVENESS

2.1 Air Exchange Efficiency

The concept of and arguements for using age analyses, studying the ventilation process, are treated in (1,2,3). The age of the ventilation air is defined as the time elapsed since it entered the room. A unidirectional, parallell plug- or piston flow is taken as an example to explain the basic implications, fig 1. Local age of the air is the time it takes for the imaginary piston, starting at the left end, to reach a certain position. Generally, local age is defined as the time it takes for the air to reach a certain point in the room. It is obvious that the age of the exhaust air, $\bar{\tau}_e$, in fig.1 is:

$$\bar{\tau}_e = V/\dot{V} = \tau_n \qquad (1)$$

Where: V = room volume
$\dot{V}$ = ventilation air flow rate
Overbar is used to denote time mean values.

Other names for exit age are turnover time or holdback time for the ventilation air, flowing through the room.

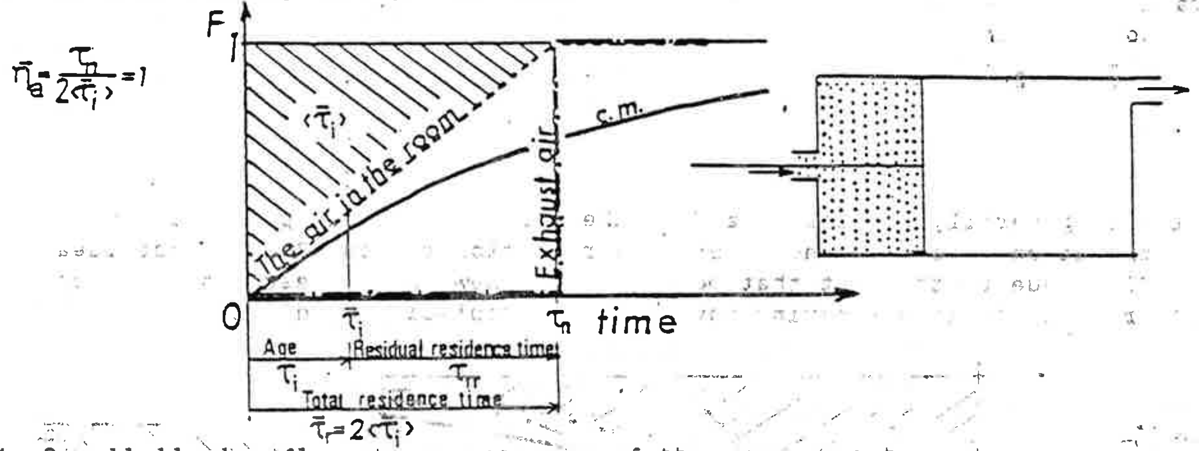


Fig. 1. Parallell plug-flow showing the use of the age concept.

The average total residence time for all the air in the room is defined as the average total residence time for all air molecules in the room. From fig.1 it is easy to see that the residence time in the case shown is the sum of the local age, τ_i, and the residual residence time, τ_{rr}. In the case of piston flow, the total residence time is τ_n. The room average age, however, for the air in the room is the average age for all positions and is for piston flow:

$$\langle\bar{\tau}_i\rangle = \tau_n/2 \qquad (2)$$

Consequently, the total average residence time, $\bar{\tau}_r$, for all the air in the room is two times its space average age:

$$\bar{\tau}_r = 2\langle\bar{\tau}_i\rangle \qquad (3)$$

Where: < > is the symbol for space average.

F(t) is defined as the cumulative fraction of air having age less than or equal to t. The derivative of F(t) is the frequency distribution function of the age, giving the mean age as:

$$\bar{\tau} = \int_0^\infty F'(t)t\,dt = \int_0^\infty (1 - F(t))\,dt \qquad (4)$$

Above expression means that the mean age is the area between F=1 and the F(t)-curve, called the "area above" the curve. Turning to fig.1, $F_e(t)$ is zero between t = 0 (piston in left position) and $t = \tau_n$ (piston in right position) and 1 for greater times, giving for the exit age, $\bar{\tau}_e$:

$$\bar{\tau}_e = \tau_n \qquad (5)$$

The fraction of new air in the room, $F_i(t)$, is linearly increasing from zero to one as time increases from zero to τ_n. Generally, $\langle F_i(t)\rangle$ is constructed from the $F_e(t)$-curve in the following way:

$$\langle F_i(t)\rangle = S(t)/S(\infty) \qquad (6)$$

$$S(t) = \int_0^t (1 - F_e(t))\,dt$$

Subscript i = internal
Subscript e = exhaust

According to eq.4, $\langle\bar{\tau}_i\rangle$ is the "area above" the $\langle F_i\rangle$- curve.

Generally, in a continuous flow system, like a ventilating system, all above rules apply, giving:

$$\langle\bar{\tau}_r\rangle = 2\langle\bar{\tau}_i\rangle \qquad (7)$$

$$\bar{\tau}_e = \tau_n = V/\dot{V}$$

The flow is generally turbulent causing the air at a certain point to have an age distribution. The air-renewal process runs slower, fig. 2, than for ideal piston flow, due to the fact that more or less "new" air is escaping the room (shortcircuiting) without having any effect on replacing "old" air.

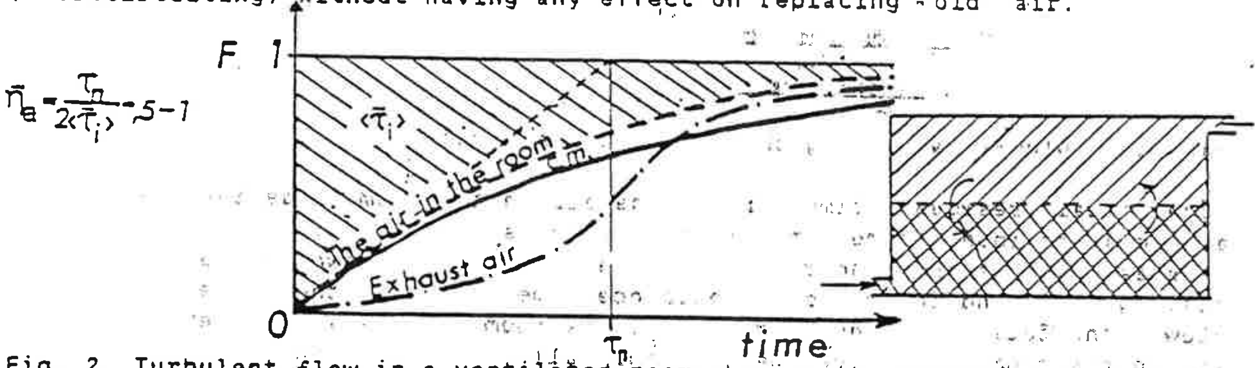


Fig. 2. Turbulent flow in a ventilated room showing the general use of the age concept.

Defining the air exchange efficiency, it was found appropriate to com- pare the actual air exchange speed, $1/\tau_r$, for the system with the nominal exchange speed, $1/\tau_n$. Doing so, the average air excange efficiency, $\langle\eta_a\rangle$, becomes a unique system parameter:

$$\langle\eta_a\rangle = \frac{1/2\langle\bar{\tau}_i\rangle}{1/\tau_n} = \frac{\tau_n}{2\langle\bar{\tau}_i\rangle}\;100\;(\%) \qquad (8)$$

The maximum efficiency, 100%, is achieved only for ideal piston flow. Ideal mixing results in only 50%, while stagnant flow gives less than 50%.

Rule no. 1 for designing effective ventilating systems is from now on defined to design for air exchange efficiencies above 50%. This definition of effective ventilation is of no practical value however, if the efficiency cannot be measured. Fortunately this is not too difficult. For practical measurement procedures the air may be labelled with tracergas, either well mixed with the supply air (labelling the "new air") or initially well mixed with the room air (labelling the "old air). The first method involves a step-up procedure, the second one a step-down procedure. The step-up procedure involves constant supply of tracergas, stepping up from zero at time zero:

$$F(t) = C(t)/C(\infty) \qquad (9)$$

The step-down procedure involves a decay from a uniform concentration of tracergas in the room at time zero and no supply of tracergas after that time.

$$F(t) = 1 - C(t)/C(0) \qquad (10)$$

C(t) is the concentration of tracergas as a function of time.

Local conditions is characterized by measuring local age. If this age is lower than the average age the "fresh" air potential is better than the average. Local age is used for defining a local air exchange indicator, ε_a:

$$\varepsilon_a = \frac{\langle \bar{\tau}_i \rangle}{\bar{\tau}_i} \qquad (11)$$

Rule no. 2 for effective ventilation is consequently defined to design for local age (in the breathing zone) lower than the room-average, i.e: $\varepsilon_A < 1$.

2.2 Ventilation Effectiveness

The contaminants live their own life in the room so to speak, fig.3 . Surplus heat is also treated as a contaminant. The ventilation effectiveness is determined by the turn-over time, i.e. the exit age of the contaminant flow through the room. The average concentrations of contaminants in the room is

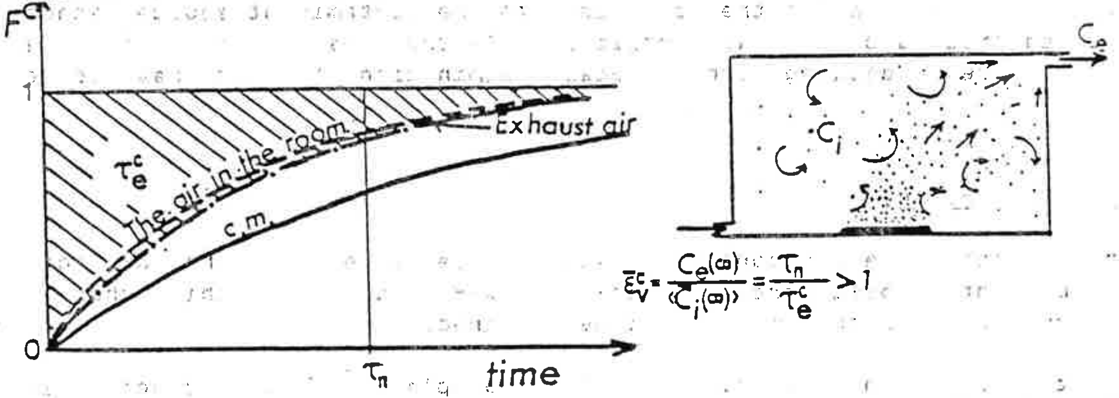


Fig. 3. Flow-pattern of contaminants in a ventilated room showing the use of the age concept.

consequently determined by the exit age. The space average and local mean ages are, contrary to the situation for the ventilation air flow, ambiguous parameters. The meaning of age and the evaluation principles are identical to what is said for the ventilation air flow. F- curves may be determined either from measureing the real contaminant concentrations or by labelling the contaminants with tracergas. The following relation apply:

$$\langle\bar{C}_i(\infty)\rangle\ \dot{V} = \tau_e^c\ \dot{V}_c \qquad (12)$$

Where: $\dot{V}_c$ = contaminant production rate (nm^3/s) ; $\langle\bar{C}_i(\infty)\rangle$ = space ave.

Dividing eq.11 with V, bearing in mind that $\dot{V}_c/V = C_e(\infty)$, gives:

$$\frac{\tau_n}{\bar{\tau}_e^c} = \frac{C_e(\infty)}{\langle\bar{C}_i(\infty)\rangle} \qquad (13)$$

The above expression is a unique system parameter, describing the contaminant flow and consequently the expression is taken to be the definition of the average ventilation effectiveness, $\langle\varepsilon_v^c\rangle$:

$$\langle\varepsilon_v^c\rangle = \tau_n^c/\bar{\tau}_e^c \qquad (14)$$

This definition of ventilation effectiveness is in agreement with Rydbergs old definition.

The shorter the turnovertime, $\bar{\tau}_e^c$, the higher the ventilation effectiveness is. Short turnover time is obtained when the contaminants flow more or less directly to the exhaust, fig. 3. If the conditions become stagnant, i.e. the contaminants are trapped in a stagnant zone, the turnovertime may become very long.

Local concentrations may be lower or higher than the room average. A local ventilation index is defined as the following concentration ratio:

$$\varepsilon_v = C_e(\infty)/\bar{C}_i(\infty) \qquad (15)$$

$C_i(\infty)$ = local concentration of contaminants at steady state

Rule no. 3 for designing for effective ventilation is consequently defined to design for $\langle\varepsilon_v^c\rangle$ greater than 1 and for lower concentrations of contaminants in the zone of occupation than the room average, fig. 3,

i.e.: $(\varepsilon_v/\langle\varepsilon_v^c\rangle) > 1$

Generally, the conditions in the zone close to the contaminant source cannot be properly controlled by general ventilation. If the near zone cannot be kept out of the breathing zone, local elimination technics have to be applied.

3. THE TWO-ZONE MODEL

In the next chapter the two-zone model will be used to explain the influence on the measurement of efficiency from in- and ex-filtration. In this chapter the basic equations for this model will be examined.

However, it should also be mentioned that the displacement flow principle is the most efficient design principle (4,5,6) for ventilating system for two main reasons:

1. It improves the air renewal and contaminant removal speed.

2. It assists in maintaining favourable concentration gradients of the contaminants generated in the room.

Piston flow. There are several ways of accomplishing displacement ventilation in a ventilated room. The most obvious one is to supply air through one surface and to extract it at the opposite (parallell flow). This principle requires that disturbances like bouyancy forces and momentum fluxes from contaminant sources have to be overcome by the piston flow.

Thermal stratification. Practical design principles for displacement ventilating systems for normal use is, rather than to overcome natural forces, to utilize buoyancy, momentum fluxes from contaminant sources etc. The displacement direction can either be vertical-up or vertical-down. Vertical-up flow direction is accomplished by supplying ventilation air to the zone of occupation with a lower temperature than the temperature in this zone, and to extract it at ceiling level. Vertical-down flow direction is accomplished in the opposite way, i.e. by supplying ventilation air under the ceiling heated to a temperature above the temperature in the zone of occupation and extract it at floor level.

In applying vertical up displacement the air is filling the room from below due to gravity and "older" air is displaced upwards. Any heat source in the zone of occupation creates convective currents and contributes to carrying the air to the upper zone. In this way a temperature stratification will be formed, creating two more or less distinct flow regions. The "new" air should spread through the zone of occupation before being carried to the upper zone.

3.1 Calculation procedures

It has been justified, (7), to base calculations for designing displacement ventilating systems on a two-zone flow model, fig. 4. An important prerequisit for the calculations is that it is assumed that the air and contaminants are well mixed within each zone. Between the zones the air recirculation is characterized through the air exchange parameter β_{12}. This parameter quantyfies the relative air flow from zone 1 to zone 2. The absolute value of the air flow is $\beta_{12}\dot{V}$. The numerical values of the effectivenesses thus calculated are generally conservative, i.e. they are lower than in the practical case.

The basic equations and formulas for calculating concentrations and effectivenesses, given in fig. 4, are based on the following mass balance equations:

$$\begin{aligned} d\bar{C}_1/dt &= a_{10} + a_{11}\bar{C}_1 + a_{12}\bar{C}_2 \\ d\bar{C}_2/dt &= a_{20} + a_{21}\bar{C}_1 + a_{22}\bar{C}_2 \end{aligned} \qquad (16)$$

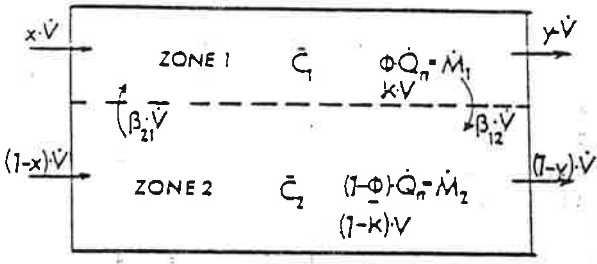
$$a_{10} = \frac{\phi\, Q_n}{\kappa V} \; ; \quad a_{11} = -\frac{y+\beta_{12}}{\kappa}\, n \; ; \quad a_{12} = \frac{y-x+\beta_{12}}{\kappa}\, n$$

$$a_{20} = \frac{(1-\phi)Q_n}{(1-\kappa)V} \; ; \quad a_{21} = \frac{\beta_{12}}{1-\kappa}\, n \; ; \quad a_{22} = -\frac{1-x+\beta_{12}}{1-\kappa}\, n$$

Where: Q_n = Net load to the room of either chemical contaminants or surplus heat.

ϕ = Fraction of the load that is released in zone 1.
κ = Fraction of the room volume belonging to zone 1
Superscript s = Steady-state (stationary)

The parameters that determine the air exchange efficiency are β_{12} and κ. The concentrations and the ventilation effectiveness are, in addition to above parameters, determined by ϕ and Q. The air exchange efficiency η and the ratio between average age and local age are shown in fig.5 as a function of β_{12} for different values of κ.



$$\bar{c}_1 = K_1 e^{n\sigma_1 t} + K_2 e^{n\sigma_2 t} + \bar{c}_1^{s} \qquad \bar{c}_1^{s} = \frac{a_{10}a_{22} - a_{20}a_{12}}{a_{12}a_{21} - a_{11}a_{22}}$$

$$\bar{c}_2 = K_1\,{}^{1}k_2 e^{n\sigma_1 t} + K_2\,{}^{2}k_2 e^{n\sigma_2 t} + \bar{c}_2^{s} \qquad \bar{c}_2^{s} = \frac{a_{20}a_{11} - a_{10}a_{21}}{a_{12}a_{21} - a_{11}a_{22}}$$

$$\sigma_1 = \frac{1}{2n}\left[(a_{11} + a_{22}) + \sqrt{(a_{11} - a_{22})^2 + 4a_{12}a_{21}}\right] \qquad {}^{1}k_2 = \frac{n\sigma_1 - a_{11}}{a_{12}}$$

$$\sigma_2 = \frac{1}{2n}\left[(a_{11} + a_{22}) - \sqrt{(a_{11} - a_{22})^2 + 4a_{12}a_{21}}\right] \qquad {}^{2}k_2 = \frac{n\sigma_2 - a_{11}}{a_{12}}$$

$$K_1 = \Delta\bar{c}_1 \frac{{}^{2}k_2 - \frac{\Delta\bar{c}_2}{\Delta\bar{c}_1}}{{}^{2}k_2 - {}^{1}k_2} \qquad K_2 = \Delta\bar{c}_1 \frac{\frac{\Delta\bar{c}_2}{\Delta\bar{c}_1} - {}^{1}k_2}{{}^{2}k_2 - {}^{1}k_2} \qquad \begin{aligned}\Delta\bar{c}_1 &= \bar{c}_1^{0} - \bar{c}_1^{s}\\ \Delta\bar{c}_2 &= \bar{c}_2^{0} - \bar{c}_2^{s}\end{aligned}$$

Fig. 4. The two-zone flow and diffusion model showing the mathematics.

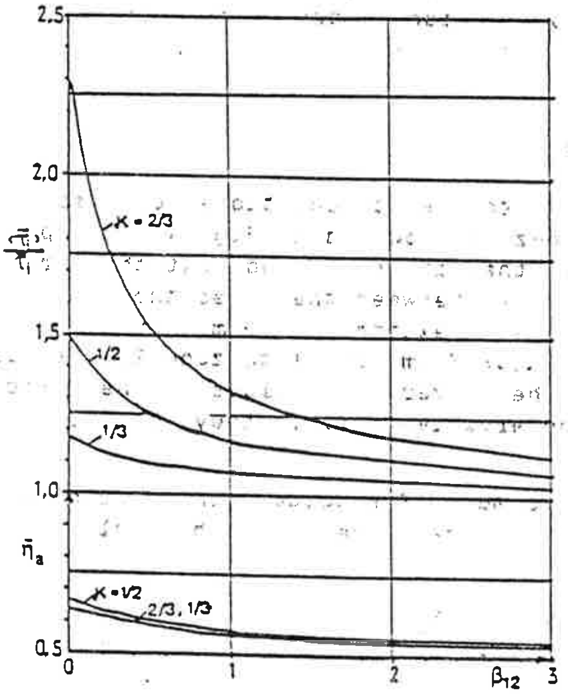
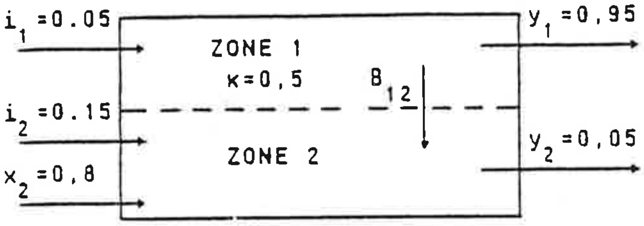
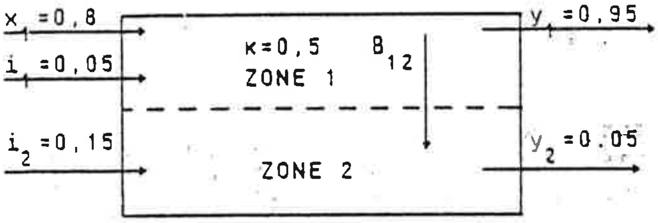


Fig. 5. Two-zone model. Curves showing the air exchange efficiency.
x = 0 ; y = 1



B_{12}	0,2	0,5	1,0	2,0
${}^{d}\bar{\tau}_2/{}^{s}\tau_2$	1,007	1,009	1,009	1,007
${}^{s}\bar{\tau}^{1}_{e}/\tau_n$	1,043	1,04	1,025	1,016
${}^{s}\langle\bar{\tau}^{1}_{i}\rangle/\langle\bar{\tau}_i\rangle$	1,055	1,041	1,029	1,018
${}^{d}\bar{\tau}^{1}_{e}/\tau_n$	1,02	1,016	1,01	1,01



B_{12}	0,2	0,5	1,0	2,0
$\bar{\tau}^{d}_2/{}^{s}\bar{\tau}_2$	0,9	0,929	0,95	0,971
${}^{s}\bar{\tau}^{1}_{e}/\tau_n$	0,76	0,87	0,92	0,96
${}^{s}\langle\bar{\tau}^{1}_{i}\rangle/\langle\bar{\tau}_i\rangle$	0,64	0,83	0,91	0,95
${}^{d}\bar{\tau}^{1}_{e}/\tau_n$	o,95	0,97	0,98	0,99

Fig. 6. Comparision of calculated ages for the ventilation air using a two-zone model.

Notations used in fig. 6.:

i = infiltration
e = exfiltration
x = mechanically supplied ventilation air
y = mechanically exhausted air
Subscript 2 = belonging to zone 2
Subscript e = exhaust air
Subscript i = internal air (total air volume for the room)
< > = room average
Overbar - = time mean
Subscript 12 = from zone one to zone 2
Superscript 1= measured in exhaust air from zone 1
Superscript d= decay from an initially well-mixed room (step-down)
Superscript s= measurements during step-up, tracergas injected to mechanically supplied ventilation air.

$$x_1 + x_2 + i_1 + i_2 = 1$$
$$y_1 + y_2 + e_1 + e_2 = 1$$

Constants used in equation 14:

$$a_{10} = \frac{x_1 C_s}{\kappa} v \quad ; \quad a_{11} = -\frac{y_1 + e_1 + B_{12}}{\kappa} v \quad ; \quad a_{12} = \frac{x_1 + x_2 - (y_2 + e_2) + B_{12}}{\kappa} n$$

$$a_{20} = \frac{x_2 C_s}{1-\kappa} n \quad ; \quad a_{21} = \frac{B_{12}}{1-\kappa} n \quad ; \quad a_{22} = -\frac{x_2 + i_2 + B_{12}}{1-\kappa} n$$

C_s = tracer-gas concentration in supply-air during step-up

4. MEASUREMENT OF AIREXCHANGE EFFICIENCY.

There are three procedures using tracer gas to determine the air exchange efficiency:

- o Continuous supply of tracer gas to the supply-air (step-up).
- o A pulse injection of tracer gas to the supply-air.
- o Decay from an initially well mixed space (step-down)

Two types of problems have to be overcome. The first is the measurement of low tracergas concentrations. The other one is the influence from in- and exfiltration. The significance of measureing low concentrations is most pronaunced using the step up and pulse procedures. In-/exfiltration play a role in all procedures, but in different ways. In the step up and pulse procedures all air cannot be labelled with tracergas in addition to that all exhaust air cannot be measured. This will influence on both average and local performance assessment. Using step down procedures, evaluations from exhaust air measurements only are influenced.

The two-zone model is used to illustrate how various conditions may influence on the results from practical measurements and evaluation procedures. Calculations are based on equation 16, but in- and ex- filtration are introduced , see fig. 6.

From the calculations one can conclude as follows:

1. The step-down procedure is most relieable.

2. The step-up procedure can be used if infiltration and mechanical air supply are mainly to the same zone. The most accurate results are obtained if exfiltration and mechanical exhaust are mainly from the same zone.

3. Local performance are less sensitive than average performance to the choice of procedures.

5. MEASUREMENTS OF VENTILATION EFFECTIVENESS AND VENTILATION INDEX

The same considerations as to instrumentation, choice of procedures and evaluation of results as for measureing air exchange efficiency are to be made when measuring ventilation performance.

6. FIELD-MEASUREMENTS OF EFFECTIVENESS

Several laboratory and field measurements of air exchange efficiency have been carried out. We will here show some experimental results from a large room in Royal Garden Hotel, Trondheim, see fig. 7. This room has a vertical-up displacement ventilation system.

Room and ventilation construction data:

- Floor area: $400\ m^2$
- Maximum heat load: 400 persons, 25 kW of electric light, 170 m^2 of windows in eastward direction
- Air supply: 1 m high filter clothing along three of the walls, see fig. 7.
- Room air temperature control: Variable air volum system (VAV)
- Supply air temperature: $20^0 C$
- Maximum air flow rate: $20.000\ m^3/h$

Only the air exchange efficiency is examined in this paper. It was measured by a step-up test with constant supply of N_2O to the supply air fan inlet. The step down test was not executed because it was difficult to get an initially well mixed room. The test probe for local age measurement was located in the middle of the room, 1.7 m above the floor.

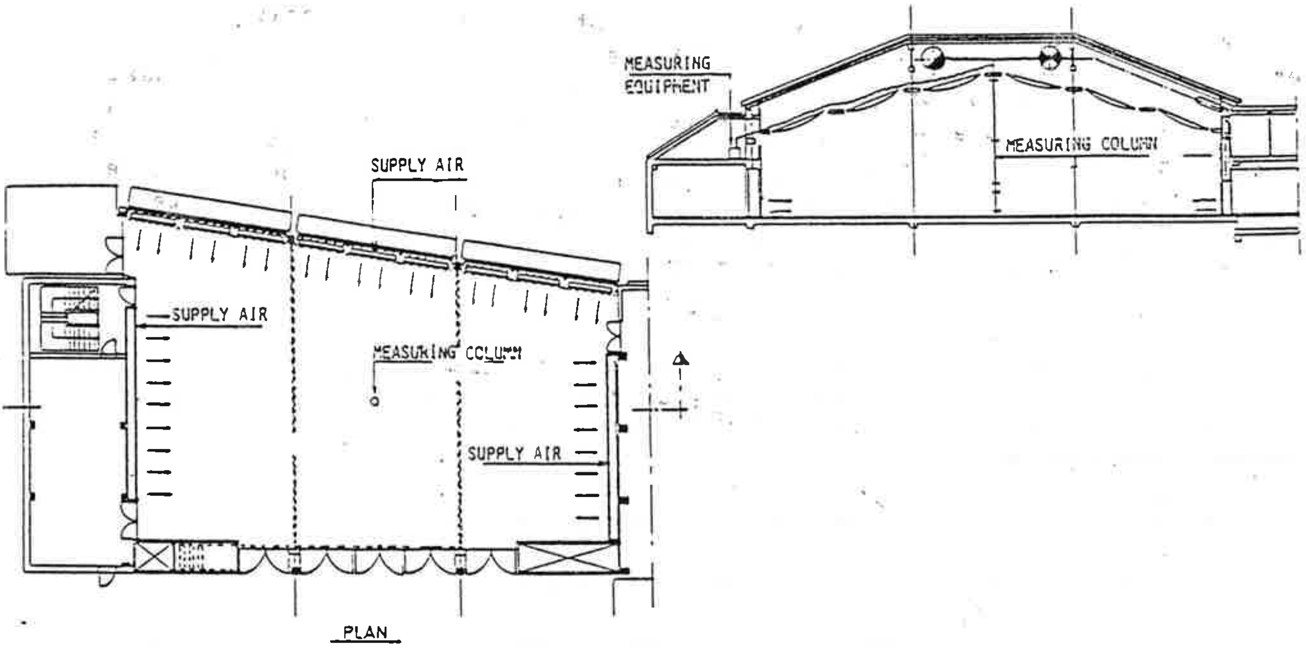


Fig. 7. The room where the test was carried out.

The first evening the measurements were carried out with 200 people present in the room. The second evening 5-600 people were present. During the tests there were no ceiling lights on, nor was there any sun shine outdoors.

Results:

	200 people present	5-600 people present
Mean air exchange efficiency	0.59	0.58
(Local age)/(Room average age)	0.87	1.24

Table 1 Results from tests in Royal Garden Hotel.

From the table above it is clearly seen that the room has a displacement ventilation system. However, there were some problems due to air leaks. This can be seen from fig. 8., where the room air concentration never reaches the level of the supply air concentration. The situation was probably not unlike the conditions shown in the upper part of fig. 6 exept for that the infiltration is about half the amount. The curves in fig. 5 indicate a β_{12} of about 0.5. The ratio $\langle\tau_i^{s-1}\rangle/\langle\tau_i\rangle = 1.041$ if the infiltration is 20 % of the total air supply.This indicates that the true internal room mean age is about 2% lower than the measured one.

The low local age with 200 people present might be due to the location of the test probe. The public, which was the only heat source in the room, was sitting in the front of the room. The fresh air was probably sweeping beneath the test point, causing this to be located outside the supply zone. If the test point had been located in the middle of the crowd, the result would have been more like that with 5-600 people present. It should also be mentioned that measurements of CO_2 and temperature profiles confirm the statement above.

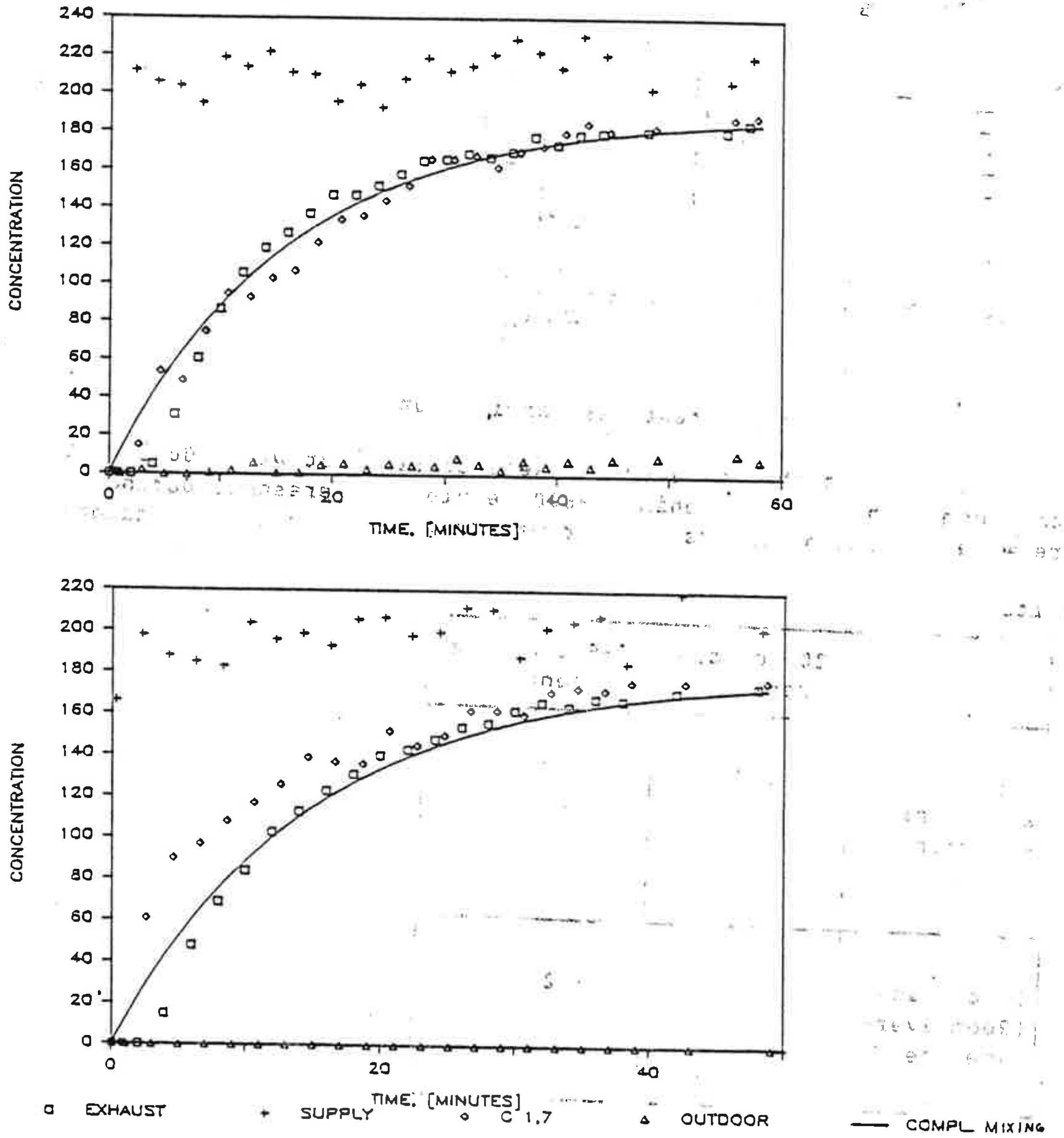


Fig. 8. Step-up tests are shown with 200 people present at the upper figure. 5-600 are present at the lower.

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