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EFFICIENT VENTILATION IN OFFICE ROOMS

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Results from a two-box model for calculation of tracer gas concentrations in rooms are given and consequences of different definitions of "ventilation efficiency" are discussed. Results from three different series of experiments are presented. The first two series were dilution experiments; examples of the results are given and discussed. The third series of tests was performed with one person working at a desk in the test room. Above the person's head, a tracer gas (N_2O) was injected into the convection plume, with as low a momentum as possible. Starting with zero concentration, a test continued until steady-state conditions were established for the concentration levels in the different parts of the room. The tests included simulation of summer, autumn/spring, and winter daytime conditions. The results indicate a tendency towards lower tracer gas concentrations in the "breathing zone" when the supply air (typical flow rate equivalent to two air changes per hour) is brought into the room at a low level as compared to a high level close to the ceiling. The exhaust air terminal device in all tests was situated high in the "corridor" wall.

Introduction

In order to save energy there is now a tendency in Sweden to use lower ventilation air flow rates than previously used. This has caused an increased interest in the efficiency of ventilation, i.e., the ability of the ventilation arrangements in a room to keep the air in the occupied zone clean (see, for instance, Sandberg, 1981).

The starting point for this study was the problem of understanding results from measurements of the dilution of tracer gas in a room without artificial mixing of the room air. One of the first tests (Malmström and Öström, 1980) showed that large differences in tracer gas concentration within the room could occur (Fig. 1). (In all tests the exhaust air terminal device has been placed above the door, and in this particular test the supply was placed just above.) The room was 2.4 m wide × 4.2 m long × 2.7 m high (see Fig. 5). The nominal air change rate was 1.8 (room volumes per hour) and the test was for an extreme winter case. Windows were simulated by radiators which were cooled to 10°C below room air temperature. The "window" wall was also cooled to slightly below room air temperature. Supply air temperature was in this particular test 12°C above room air temperature. The electrical lighting was on, but no one was in the room or simulated. Under such circumstances thermal stratification is to be expected, causing stagnation in the main part of the room while the zone near the ceiling will be overventilated. This explains the differences in the measured decrease of tracer gas concentration.

Using a simple two-box model, equations have been derived for the case when the room air flow and the tracer gas emission are in steady states (see Appendix 1). Only the tracer gas concentrations vary with time; the initial tracer gas concentration is taken as even in the whole room. The plotted curves in Fig. 1 are transients calculated with the equations and fitted to the measurements. With increasing time, as can be seen, the curves (as do the measured values) tend to become parallel straight lines in the lin-log diagram. (The rather poor fit of the lowest line may be attributed to the fact that the plotted difference between measured concentration and the concentration in the supply air—the tracer gas was in this case CO_2—was small in comparison with the measured values.) The slope of the lines is $-n\epsilon_1$, where n is the total air change rate (room volumes/time). That the lines are parallel indicates that the boxes exchange air between each other and that the rate of concentration decrease is governed by the box with lowest ventilation.

Ventilation Efficiency

It can be shown (Malström and Öström, 1980) that ϵ_1 (also in multibox models) reflects the ratio of the transient parts of the tracer gas concentration in the exhaust

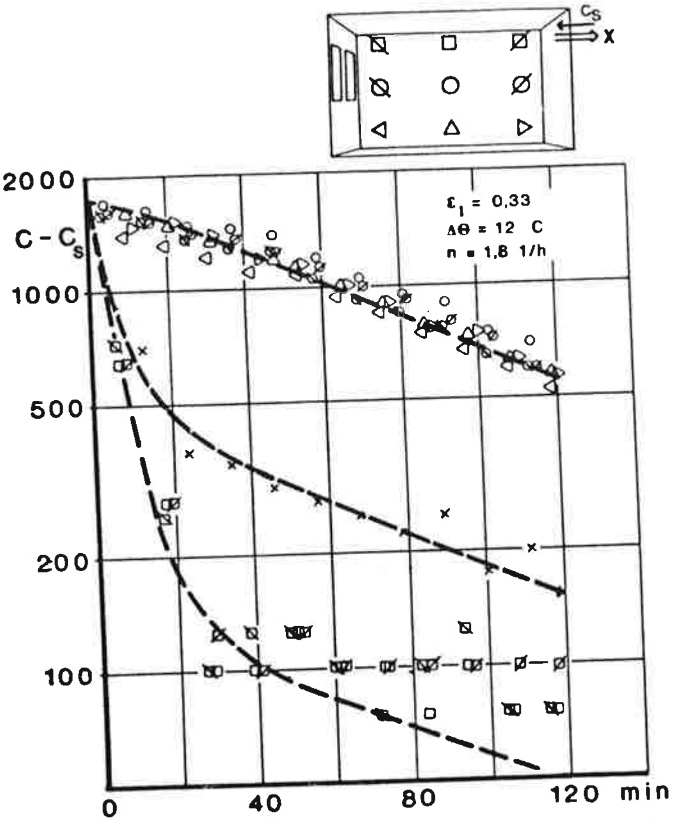


Fig. 1. Results from a dilution test (at time $t = 0$ the concentration was uniform in the room). A winter case with no person was simulated. Supply air temperature was 10 °C above ambient ($\Delta\theta = 10$ °C) and window surface temperature 10 °C below. The electrical lighting, hanging 0.3 m below the ceiling, was on. $n = 1.8$ ach. c is concentration of tracer gas. c_s is the concentration in the supply air. The result indicates severe stratification with its boundary located at about the upper level of the windows. (Because of this tendency, supply of warm air close to the ceiling is not considered good engineering practice.) The exhaust air terminal device was situated close to the boundary and has exhausted air brought to it from both zones. The concentration of tracer gas in the exhaust air therefore was very sensitive to minor changes in room air flow, which was showed by attempts to reproduce the test. A small change in the convection currents at the wall in which the terminal device was mounted thus resulted in a dramatic change of the rate of concentration decrease; compare the definition and discussion of ϵ_1.

air and the average concentration in the room (see Appendix 2). ϵ_1 is independent of the way in which the tracer gas is emitted—only the emission is constant in time—and depends only on the ventilation arrangements and the steady-state air flow in the room. This is not true for the ratio between the corresponding steady-state concentrations, the ratio of which is often used as a measure of ventilation efficiency.

If the lines become parallel at a time t_p after the start of the experiment, we can write

$$\epsilon_1 = \frac{c_E - c_e}{c_R - c_r} ;$$

for the case that there is emission of tracer gas (or a source of pollution) in the room,

$$\epsilon_{11} = \frac{c_E - c_S}{c_W - c_S} ,$$

and

$$\epsilon_{111} = \frac{c_E - c_S}{c_R - c_S} ,$$

where c_E = the steady-state concentration in the exhaust air;
c_e = the concentration in the exhaust air at a time $t > t_p$;
c_W = the steady-state concentration in the working zone;
c_S = the concentration in the supply air (constant);
c_R = the steady-state mean concentration in the room;
c_r = the mean concentration in the room at a time $t > t_p$.

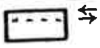
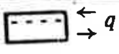
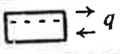
The terms ϵ_{11} and ϵ_{111} are conventionally used as measures of "ventilation efficiency." ϵ_{11} is preferred because it relates c_W, the concentration that is experienced by the persons working in the room, to c_E, the concentration that is calculated when designing the system.

Concentration c_E is determined by the amount of tracer gas brought to the room, since it must leave the room at the same rate. This means that for the four basic cases illustrated in Table 1, our two-box model will give us $\epsilon_{11} = 1$ for the two cases when the exhaust air is taken from the working zone (the lower zone in Table 1). Of the other two cases, the one with the supply air to the working zone will always give $\epsilon_{11} > 1$ and the other $\epsilon_{11} < 1$. The conclusion is that the supply air should be brought directly to the working zone and the exhaust air should be taken from the other (we are, of course, speaking of general ventilation, not local exhausts).

Even if the concentration level in the working zone is the same in two cases, we might prefer the case with lower concentration in the other zone. This information is not given by ϵ_{11} but by ϵ_{111}, which follows ϵ_1 in being >1 when supply and exhaust are connected to different boxes (see Table 1).

There are of course cases when arrangements giving $\epsilon_1 < 1$ give better ventilation of the working zone than arrangements giving $\epsilon_1 > 1$, for instance when the emis-

Table 1. Possible values of ϵ_1, ϵ_{11}, and ϵ_{111} calculated with the two-box model for the four basic ventilation schemes indicated. The values are valid for all possible locations of the sources of tracer gas.

	 $\leftrightarrows q$	 $\leftrightarrows q$	 $\overset{\leftarrow}{\rightarrow} q$	 $\overset{\rightarrow}{\leftarrow} q$
ϵ_1	<1	<1	>1	>1
ϵ_{11}	≤1	1	1	≥1
ϵ_{111}	≤1	≤1	≥1	≥1

sion is terminated before a steady state is reached. $\epsilon_l \cong 1$ is not necessarily an indication of perfect mixing. Even in cases of severe stratification, ϵ_l can be 1 because exhaust air is taken from the boxes in proportion to their volumes. For instance, in dilution experiments—with no supply of tracer gas—the concentration level can, in addition, be uniform in the entire space in spite of stagnation. Then the supply air flow is proportional to the volumes of the boxes.

This discussion has been based on the two-box model. It indicates, however, that also for actual rooms important information about the performance of the ventilation system may be achieved if a tracer gas measurement with artificial mixing of room air (in order to establish the total air exchange rate n) is followed by a test without artificial mixing. The result is, however, valid only for the room air flow during the experiment. Realizing the difficulty of achieving a stable air flow in an office room, this fact implies that attempts to attribute a certain value of "ventilation efficiency" to an installation or a ventilation system may prove to be of doubtful practical value. But the test will tell an experienced ventilation engineer a great deal about the tendencies for the air flows in the room and how well the type and location of air terminal devices have been chosen. For a further discussion of different definitions of ventilation efficiency and "local air exchange," see Sandberg (1981).

Example

Figures 2–4 show examples of the concentration increase of a pollutant (gas) for two different emission patterns and for the four basic ventilation schemes from Table 1. They are computed using the two-box model for the smallest possible exchange (for one of the cases) from the lower to the upper box, an air flow equal to the ventilation rate ($n = 1.8$). The sizes of the "boxes" are taken from the case discussed above (Fig. 1). Figure 2 shows the concentration increase in the working zone when the pollutant is emitted and distributed directly into the working zone. The ventilation arrangement with both the outlet and the inlet in the upper zone gives the highest concentration of pollutant in the working zone. The other three arrangements all have the same steady-state concentration. During the transient stage the arrangement with both the outlet and inlet in the working zone gives the lowest concentration in the working zone, reflecting the fact that it has $\epsilon_l < 1$ (see Table 1) and a slow response to the step change.

Figure 3 gives results from calculations with 50% of the pollutant emitted and mixed into the upper zone. The source may be in the working zone but 50% of the pollutant, such as, for instance, tobacco smoke, is directly transported to the upper zone without mixing into the working zone. The arrangement with both the outlet and the inlet in the upper zone still gives the highest concentrations in the working zone, but now the arrangement with supply air to the working zone and exhaust air from the upper zone gives much smaller concentrations in the working zone than the other arrangements. The large differences are a consequence of the small air exchange between the zones. This is illustrated in Fig. 4, which shows the concentration curves for the two ventilation arrangements discussed above when the air exchange is larger.

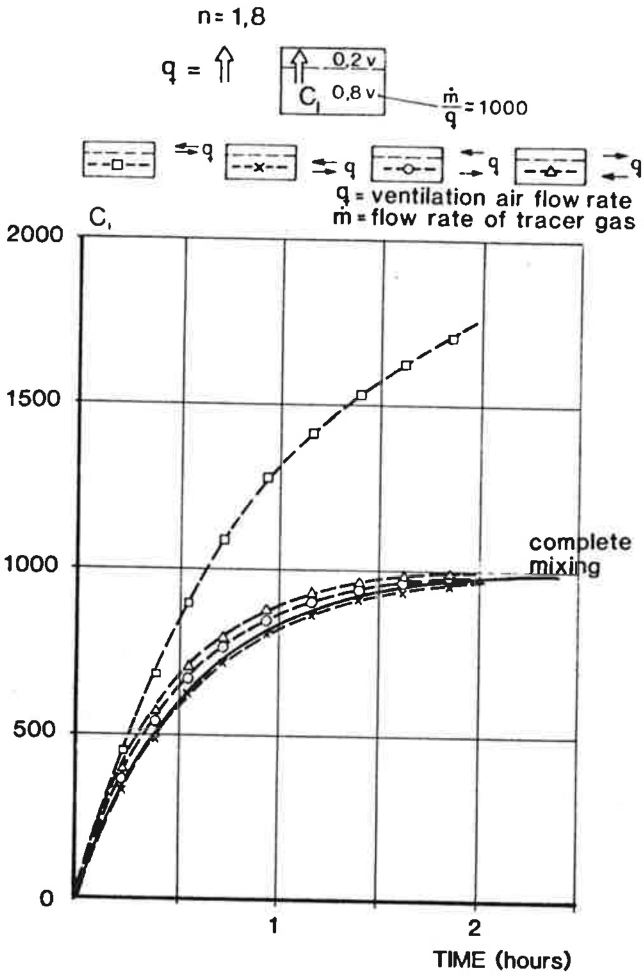


Fig. 2. The computed concentration increases of tracer gas (or a pollutant) in the working zone of a room. The exchange of air from zone 1 (the working zone) to zone 2 (the upper zone) is equal to the ventilation flow rate (q). Shown here are the concentrations in the working zone when all tracer gas is emitted into that zone.

Table 2 shows steady-state concentrations and values of ϵ_l for the ventilation cases of Figs. 2 and 3. (For the fourth case ϵ_l is not defined because there is no return air flow from the upper box to the lower.)

Experiments

When trying to apply the conclusions of the discussion above, it must be realized that a two-box model is a rough model of an actual case. Also, which "box" the supply air mixes into depends not only on the location of the terminal device but also on the air flow in the room. For the exhaust air, the corresponding case was

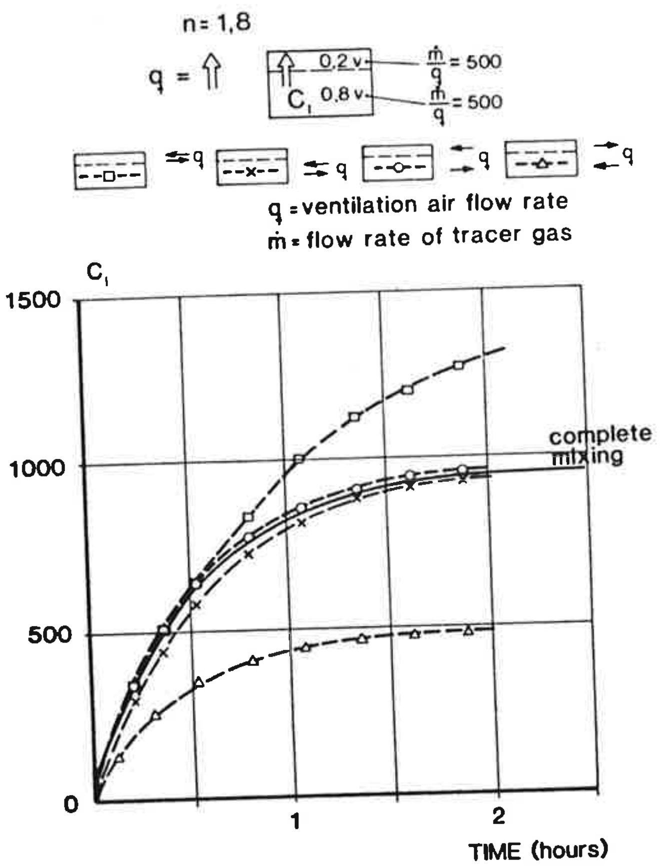


Fig. 3. Computerized concentration increases of tracer gas in the working zone when 50% of the tracer gas is emitted into the upper zone. Exchange of air as in Fig. 2.

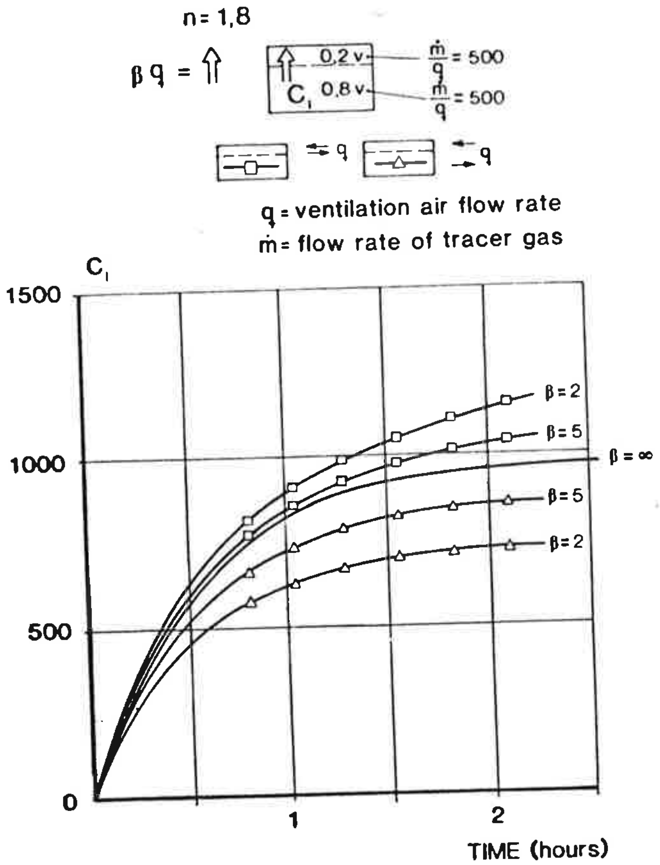


Fig. 4. Computations for the two extreme cases from Fig. 3; also valid for larger exchange rates between the zones.

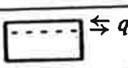
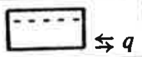
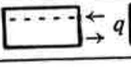
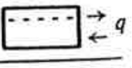
illustrated in Fig. 1. However, this project deals with a small office room. Earlier studies (see, for instance, Honma, 1979) indicate that there is often a tendency for higher concentrations of pollutants from persons, for instance CO_2, close to the ceiling. These gases are at least partly transported by the convection flows from human beings. A ventilation scheme trying to take advantage of the tendencies to stratification could then be favourable; Table 1 indicates that it also works properly for other types of gaseous pollutants, for instance from building material. For other pollutants, such as particulates, neither the discussion nor the experiments are generally applicable.

In experiments studying air flows in ventilated rooms it has been customary in Sweden to use a 100 W electric lamp as a simulator of a person. Figures 5A and B show results from dilution experiments for (A) a winter case with a lamp simulator and (B) a person sitting at the desk working. The supply air was introduced high in the "corridor wall" (n = 1.8) and the exhaust was also high in the corridor wall, as in all tests presented in this paper.

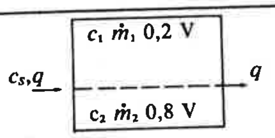
The differences between measured concentrations of tracer gas (N_2O) within the room were much smaller than those reported in Fig. 1, because the supply air now had the same temperature as the room air. The main reason for thermal stratification was therefore eliminated. Figure 5A shows, however, that in this case the differences were also rather large. The highest concentrations were about 50% higher than the lowest concentrations in the room. ϵ_1 was 0.75.

The presence of a person increased mixing considerably. The difference between measured concentrations, Fig. 5B, was about 20% and ϵ_1 was 0.85. How-

Table 2. Steady-state concentrations and values of ϵ_1 for the ventilation arrangements from Figs. 2–3. The values are computed for an air exchange from box 1 (working zone) to box 2 (upper zone) equal to the ventilation flow rate.

				
$c_1 - c_s$	$\frac{2\dot{m}_1 + \dot{m}_2}{q}$	$\frac{\dot{m}_1 + \dot{m}_2}{q}$	$\frac{\dot{m}_1 + \dot{m}_2}{q}$	$\frac{\dot{m}_1}{q}$
$c_2 - c_s$	$\frac{\dot{m}_1 + \dot{m}_2}{q}$	$\frac{\dot{m}_1 + \dot{m}_2}{q}$	$\frac{0.5\dot{m}_1 + \dot{m}_2}{q}$	$\frac{\dot{m}_1 + \dot{m}_2}{q}$
ϵ_1	0.6	0.95	1.1	

q = ventilation air flow rate;
$\dot{m}$ = flow rate of tracer gas;
n = 1.8.



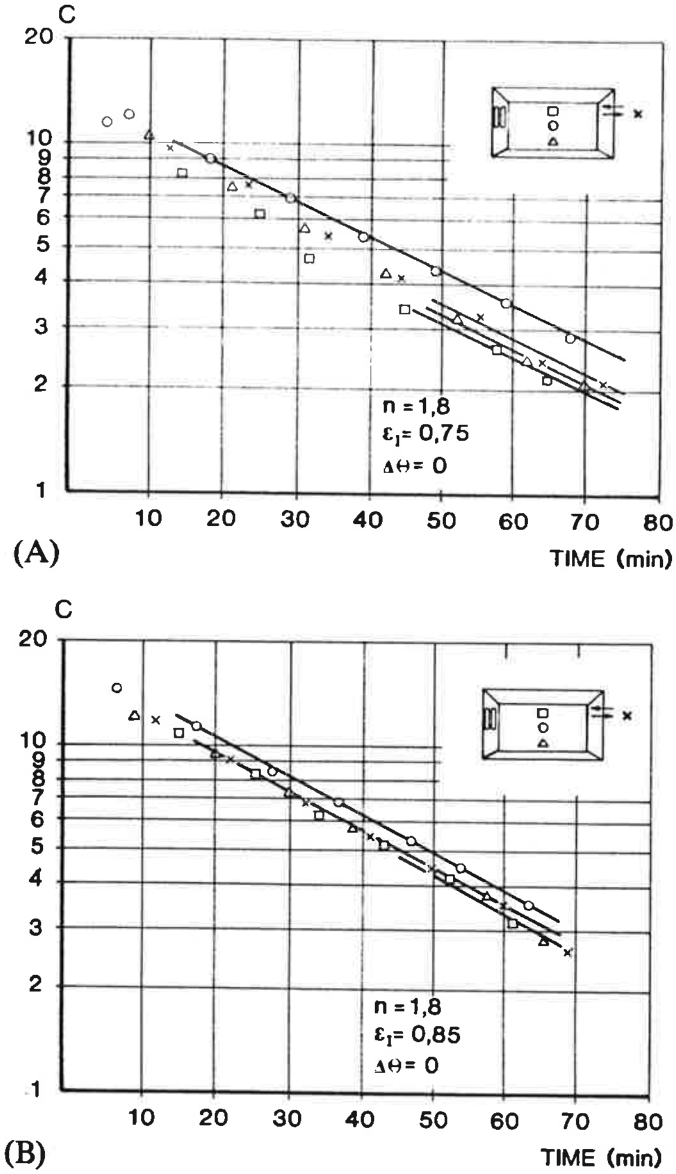


Fig. 5. Results of dilution measurements (A) with a person simulated by a 100 W lamp and (B) with a person in the room, working at the desk. The supply air outlet is high in the back wall. A winter case is simulated, the window surfaces having a temperature 9 °C below room air temperature. Supply air has the same temperature as the room air ($\Delta\theta = 0$). Ventilation flow rate is equal to $n = 1.8$ ach.

ever, the room air evidently was still far from being completely mixed.

As mentioned earlier, the local concentrations in the room depend upon how and where tracer gas is emitted. In order to explore what differences might be expected when the person in the room also happens to be the source of pollution, some tests have been performed in which tracer gas (N_2O) was supplied with low momentum above the head of the person working at a desk in the test room. (The reason for not measuring the natural increase of, for example, CO_2 exhaled by the person was primarily the limitations of the measuring device.) As breathing air leaves the nose with relatively high velocity and a direction downwards, the "natural" increase of

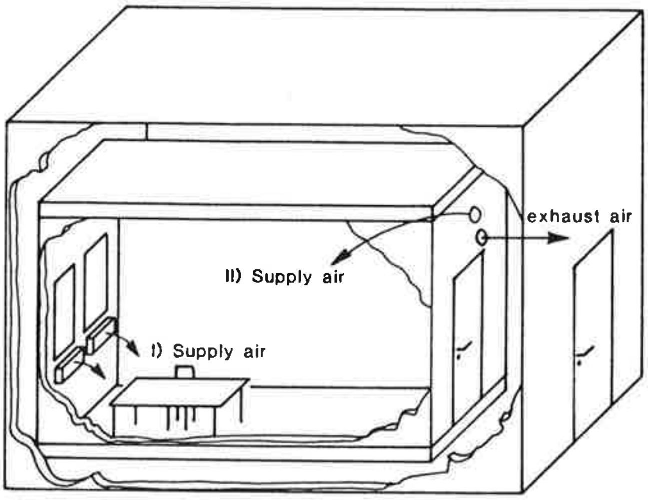


Fig. 6. Sketch of test room.

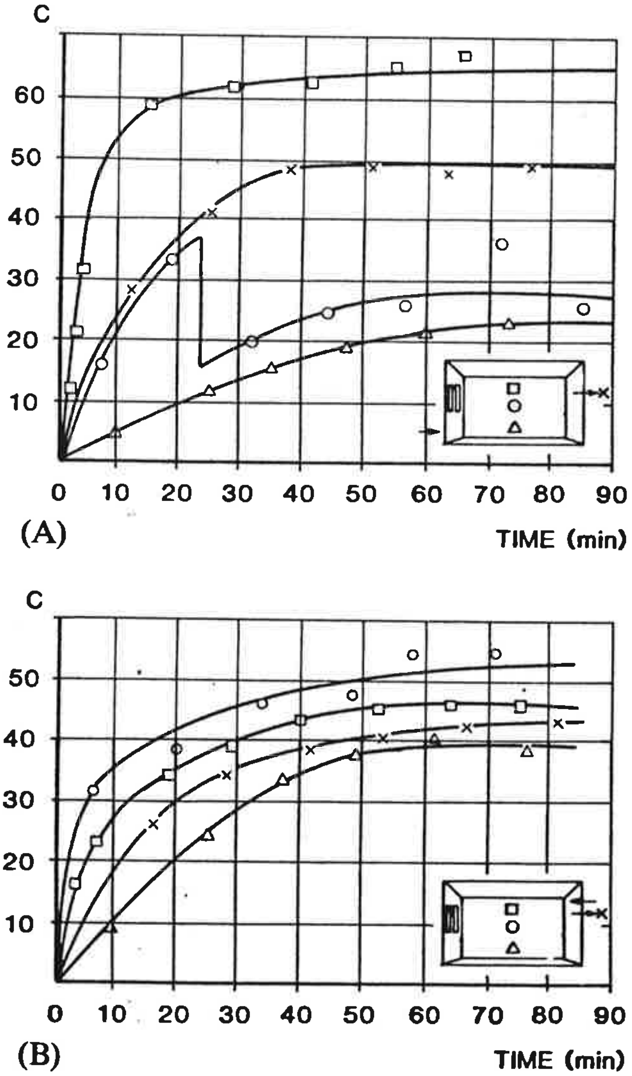


Fig. 7 (A) and (B). Tests with a person working at the desk, tracer gas emitted above the subject's head. Summer case, supply air is a temperature 5 °C below room air and window surfaces are 10 °C over room air temperature. The two parts show different locations of probe.

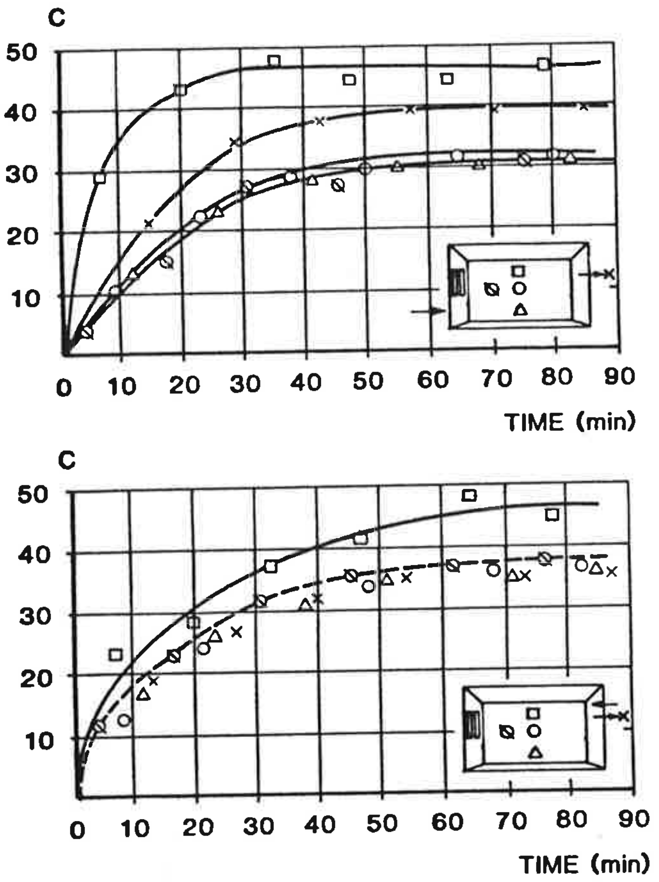


Fig. 8 (A) and (B). Tests with a person working at the desk, tracer gas emitted above the subject's head. Winter case, supply air is the same temperature as room air and window surfaces are 10 °C below room air temperature.

CO_2 concentration will probably be more even in the room than the results of the tests reported here. These tests perhaps better simulated the emission of body pollutants, or tobacco smoke, *not* in the respiratory air.

Because the concentrations depend on the air flow pattern in the room, tests were made for a winter case, a summer case, and two spring/autumn cases, one of them simulating solar radiation into the room. Two different ventilation arrangements were used, as illustrated in Fig. 6. Starting with zero concentration, the test continued until steady-state conditions were established for the concentration levels in the different parts of the room. The flow rate of tracer gas was not the same in the different tests.

The results from the tests are shown in Figs. 7–10. The concentration differences in the room are rather large in some cases (up to a factor of 3 for the summer case). For all the tests with the air supplied closer to the floor, the concentration at breathing level is lower than in the exhaust air, while the opposite is true for all tests but one with the air supplied closer to the ceiling. The concentrations are measured at too few points in the room to show anything but examples of the concentrations in the different zones. The large differences in each zone are shown in Fig. 7A, where a change of position of the probe resulted in a dramatic change in the measured concentration. The results also indicate better locations of the air terminal devices, for instance placing the supply at a lower level below the window and the exhaust higher up, closer to the ceiling. However, the graphs show that the problem warrants further studies and that significant advantages may be gained.

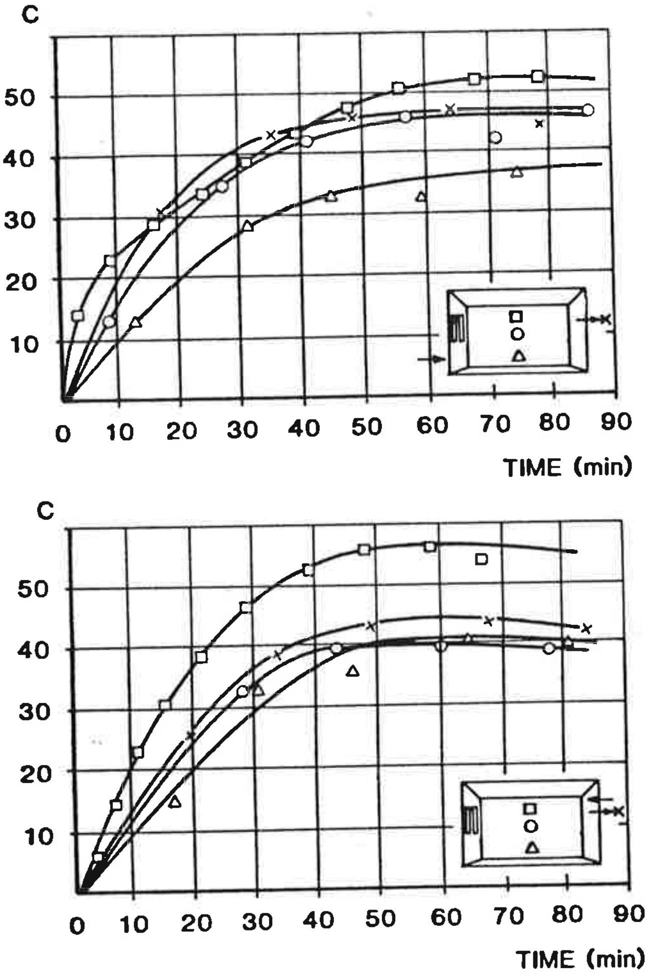


Fig. 9 (A) and (B). Tests with a person working at the desk, tracer gas emitted above the subject's head. Spring case, supply air is the same temperature as room air and window surfaces are 5 °C below room air temperature.

Conclusions

In Scandinavian industry it is rather common to rely upon the known tendencies for stratification when designing ventilation systems. Our results indicate that for small office rooms, a ventilation scheme using the natural tendencies for stagnation might also be favourable. The supply air must then be brought directly into the working zone without causing draft problems. Tests indicate that it is possible for Swedish needs and within standards to design a building for low cooling loads and, if necessary, cool the building at night, when it is

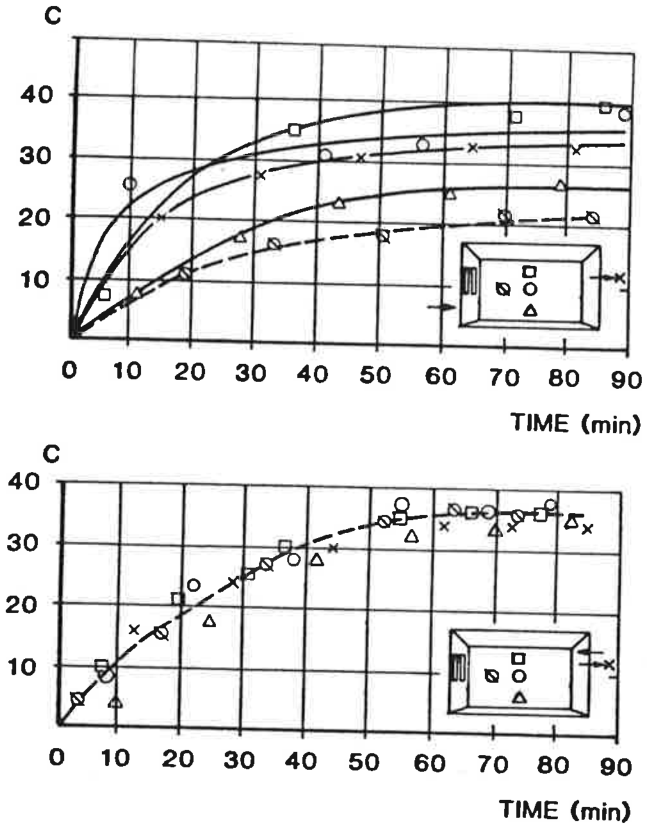
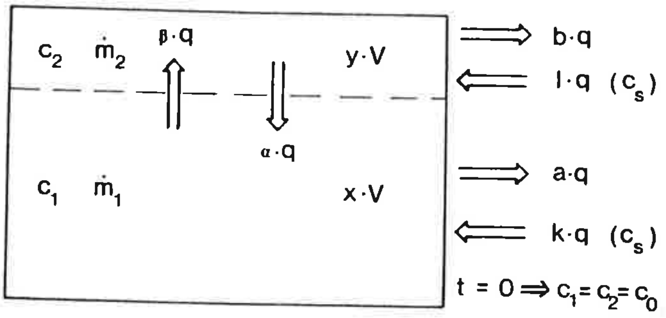


Fig. 10. Tests with a person working at the desk, tracer gas emitted above the subject's head. Spring case, supply air is the same temperature as room air and window surfaces are 5 °C below room air temperature. Simulation of 700 W solar radiation into the room.

empty. In Sweden, smaller flows than those used in our tests are normal in dwellings. It seems important that the stratification tendencies in such cases also be recognized in order to avoid poor ventilation.

Acknowledgement—The Swedish Council for Building Research, Sankt-Göransgatan 66, S-112 33 Stockholm, Sweden, sponsored this work.

Appendix 1. A Two-Box Model for Concentrations of Tracer Gas in a Room



$\dot{m}$ supply flow of tracer gas
q air flow
c concentration of tracer gas
V room volume
t time

$$c_1 - c_S = \frac{\nu_2 - \sigma_1}{z_2} \cdot A_1\, e^{-n\sigma_1 t} + \frac{\nu_2 - \sigma_2}{z_2} \cdot A_2\, e^{-n\sigma_2 t} + \left(\frac{1}{\sigma_1\ \sigma_2} \quad \frac{\nu_2}{x} \cdot \frac{\dot{m}_1}{q} + \frac{z_1}{y} \cdot \frac{\dot{m}_2}{q}\right),$$

$$c_2 - c_S = A_1\, e^{-n\sigma_1 t} + A_2\, e^{-n\sigma_2 t} + \frac{1}{\sigma_1\ \delta_2}\left(\frac{z_2}{x} \cdot \frac{\dot{m}_1}{q} + \frac{\nu_1}{y} \cdot \frac{\dot{m}_2}{q}\right),$$

$$A_1 = \frac{1}{\sigma_1 - \sigma_2}\left(\frac{1}{\sigma_1}\left(\frac{z_2}{x} \cdot \frac{\dot{m}_1}{q} + \frac{\nu_1 - \sigma_1}{y} \cdot \frac{\dot{m}_2}{q}\right) + (c_0 - c_S)(\nu_2 - z_2 - \sigma_2)\right),$$

$$A_2 = \frac{1}{\sigma_2 - \sigma_1}\left(\frac{1}{\sigma_2}\left(\frac{z_2}{x} \cdot \frac{\dot{m}_1}{q} + \frac{\nu_1 - \sigma_2}{y} \cdot \frac{\dot{m}_2}{q}\right) + (c_0 - c_S)(\nu_2 - z_2 - \sigma_1)\right),$$

$$\sigma_1 = \frac{1}{2}\left(\nu_1 + \nu_2 + \sqrt{(\nu_1 + \nu_2)^2 - 4(\nu_1\nu_2 - z_1 z_2)}\right),$$

$$\sigma_2 = \frac{1}{2}\left(\nu_1 + \nu_2 - \sqrt{(\nu_1 + \nu_2)^2 - 4(\nu_1\nu_2 - z_1 z_2)}\right),$$

$$z_1 = \frac{\alpha}{x};\ z_2 = \frac{\beta}{y};\ \nu_1 = \frac{a + \beta}{x};\ \nu_2 = \frac{b + \alpha}{y}.$$

Appendix 2. Evaluation of ϵ_1

The equations for c_1 and c_2 in Appendix 1 can be written

$$c_1 - c_{1\infty} = K_1 e^{-n\sigma_1 t} + K_2 e^{-n\sigma_2 t},$$

$$c_2 - c_{2\infty} = K_3 e^{-n\sigma_1 t} + K_4 e^{-n\sigma_2 t},$$

where $c_{1\infty}$ and $c_{2\infty}$ stand for steady state values ($t = \infty$) and $K_1 - K_4$ are coefficients, σ_1 is always bigger than (or equal to) σ_2. This means that $\exp(-n\sigma_1 t)$ approaches zero faster than $\exp(-n\sigma_2 t)$. Let t_p be the time when $\exp(-n\sigma_1 t_p) \cong 0$. For $t > t_p$:

$$c_1 - c_{1\infty} = K_2 e^{-n\sigma_2 t},$$

$$c_2 - c_{2\infty} = K_4 e^{-n\sigma_2 t}.$$

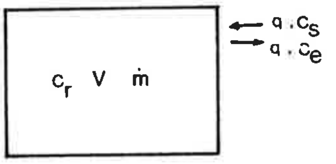
Plotted in a lin-log diagram this will give two parallel lines. The slope of the lines is $-n\sigma_2$ and does not depend on the way in which the tracer gas is emitted in the room (compare Appendix 1). But which physical meaning has the slope?

The decay of the transients in both boxes (or in all boxes in a multibox model) is governed by the box with lowest ventilation. During this quasisteady phase of concentration change the transients are proportional to each other. The two-box model gives, for instance,

$$c_1 - c_{1\infty} = \frac{K_2}{K_4}(c_2 - c_{2\infty}).$$

This also means that the transient parts of the concentration in the exhaust air and mean room concentration are proportional:

$$c_e - c_E = \epsilon_1(c_r - c_R).$$



A balance for the tracer gas gives

$$\frac{dc_r}{dt} + \frac{q}{V}c_e = \frac{q}{V}\left(c_S + \frac{\dot{m}}{q}\right).$$

In steady state, ($dc_r/dt = 0$), this gives

$$qc_E = qc_S + \dot{m}.$$

Putting $q/V = n$ those three equations above combine to

$$\frac{dc_r}{dt} + n\epsilon_1 c_r = n\epsilon_1 c_R.$$

For $c_r = c_{rp}$ at $t = t_p$, integration gives

$$c_r - c_R = (c_{rp} - c_R)e^{-n\epsilon_1(t - t_p)}$$
$$= (c_{rp} - c_R)e^{n\epsilon_1 t_p} \cdot e^{-n\epsilon_1 t} = Ke^{-n\epsilon_1 t}.$$

The result indicates that if the transients $(c - c_\infty)$ resulting from a step-change in emission rate of tracer gas are proportional to each other when measured in different points in a room (that is, they will form parallel lines when plotted in a lin-log diagram as a function of time), the slope of the lines is $-n\epsilon_1$.

For ventilation with clean air after termination of the emission of a pollutant or a tracer gas $c_E = c_R = 0$ and

$$\epsilon_1 = \frac{c_e}{c_r}.$$

ϵ_1 is, in this case, a direct measure of the ability of the ventilation to exhaust the most polluted air in the room. Perfect mixing means $\epsilon_1 = 1$.

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