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A COMPARATIVE STUDY OF THE PERFORMANCE OF GENERAL VENTILATION SYSTEMS IN EVACUATING CONTAMINANTS

Mats Sandberg and Mats Sjöberg
The National Swedish Institute for Building Research, Gävle, Sweden

Abstract

Based on the age concept, the performance of the following three principle ventilation schemes have been monitored (supply air terminal - extract air terminal); ceiling-ceiling, ceiling-floor, floor-ceiling. All systems used only air for both heating and cooling. Contaminants with both greater, less and approximately the same density as air were released at a point source. The test were both carried out in an empty room and with a person (heated mannekin) in the room.

Introduction

The flow rate of outdoor air supplied and the 'air exchange rate' have up to now been the design-parameters normally used for assessing the air quality. The underlaying assumption is that both the air and the contaminants are uniformly spread over the whole ventilated space. However, this assumption is not always fulfilled, nor is complete mixing the most efficient ventilation principle. The application of the age concept (3, 4) offers both pertinent design-parameters and methods for quantifying the performance of ventilation systems in evacuating contaminants.

Basic Concepts

Indoor contaminants in office and residential buildings appear normally at low concentrations and are often weakly dynamically active (mostly due to a temperature difference). During the day we spend our time at various locations in a room or an apartment. Therefore the most adequate single quantity, when assessing health effects, is probably the mean value of contaminant exposure both with regard to time and space.

The following relation holds between the *stationary room-average concentration* $\langle c \rangle$ and the mean-age of the contaminant when it *leaves* the room (turn-over time), τ_t^c (3, 4)

$$\langle c \rangle = \tau_t^c \, \frac{\dot{m}}{V} \qquad (1)$$

where $\dot{m}$ is the contaminant production rate and V is the total net volume of the ventilated space. The mean-age of air when it leaves the room is equal to the *nominal time constant* of the ventilated system (Q is the flow rate of air):

$$\tau_n = V/Q \qquad [h] \qquad (2)$$

When the contaminant is completely mixed to the same concentration within the whole volume then its turn-over time is equal to τ_n. The air flow pattern occuring in the room is quantified by the mean-age of the air $\langle\bar{\tau}\rangle$ in the room.

The mean-age of the air is easily obtained by using tracer gas technique. When the bulk of the air in the room is extracted via well defined extract points then the mean-age of the air in the room can be obtained by recording the tracer gas concentrations in the extract-air ducts (3, 4, 5). For a dynamically passive contaminant (no buoyancy) which is generated at each point within the room it holds that its turn-over time is equal to the mean-age of the air in the room (5, 6). Therefore, the room-average concentration due to this particular source is totally governed by how the supplied air is spread within the room. The rate of the evacuation of any contaminant after the release of the contaminant has ceased is in the main governed by the air flow pattern occuring in the room.

Piston flow ($\langle\bar{\tau}\rangle = \tau_n/2$) gives rise to the fastest exchange of the air in the room and is therefore used as a reference in the following definition of the *air exchange efficiency:*

$$\varepsilon_a = \frac{\tau_{n/2}}{\langle\bar{\tau}\rangle} \times 100 \qquad [\%] \qquad (3)$$

Results

The tests were carried out in a single room with a volume of 38 m^3 and with the terminals located at the back wall. The occupancy was simulated by a heated mannekin (SIBMAN) in a sedentary posture. To simulate a heavy contaminant (●) pure N_2O (density 1.84 kg/m^3) was used.

This is a very extreme density for a contaminant generated in a residential or office building. As a light contaminant (○) with similar properties as tobacco smoke a mixture of N_2O and He (density 1.14 kg/m^3) was used. An almost passive contaminant (◑) was also obtained by mixing N_2O and He.

The contaminant was released in the centre of the room at a height of 1.2 m above floor level. With the mannekin in the room the contaminant was released closer to its face.

The flow rate of air amounted to 75 m^3/h (τ_n = 0.5 h) except in one case at which it was doubled to 150 m^3/h (τ_n = 0.25 h).

Figure 2 shows the recorded turn-over time of the contaminants as a function of the mean-age of the air in the whole room. The vertical axis on the right hand side gives the room-average concentration in relation to the concentration obtained at complete mixing of the contaminant within the whole room. In the counter-flow case the contaminant initially moves away from the extract air terminal and in a direction opposite to the air movements set up by the ventilation system. The evacuation of the contaminants is delayed and the turn-over time of the contaminants, τ_t^c, becomes larger than the room-average age of the air in the room.

When we have a parallel flow system the contaminant move directly towards the extract air terminal. Now the turn-over time is less than the mean-age of the air in the room. Particularly the combination of a light contaminant and floor-ceiling system operating as a cooling system give rise to a fast evacuation of the contaminant. Further on we will scrutinize the performance of this particular system. In an empty room a heavy contaminant is evacuated very quickly by a ceiling-floor system. However, with a person in the room, the contaminant is sucked into the boundary layer flow surrounding the person, see figure 3, and spread upwards. That is, the system is turned into a counter-flow system. This demonstrates the importance of to consider the effect of the secondary flows set up by different sources within the room.

The right hand figure in figure 2 shows the performance of the ceiling-ceiling system. This system is called an indifferent flow system because the bulk of the air in room does not have any specific direction of movement. When short circuiting of the air occurs the heavy contaminant is almost locked in within the stagnant lower zone. However, the lighter contaminant penetrates more easily the upper zone. In spite of the fact that we have short-circuiting of the air we obtain a rather efficient removal of the lighter contaminant. However, it is premature to conclude that a ceiling-ceiling system, despite short-circuiting of the air, always efficiently evacuates lighter contaminants. Results from tests regarding ceiling-ceiling systems reported in (7) show that a contaminant with lower density than air might well be 'locked in'. The findings reported therein show that the behaviour is very sensitive to the mutual location of the supply and extract air terminals. There are indications that this layout, with both terminals located on the same wall, is perhaps the best possible among the ceiling-ceiling systems.

Ventilation by stratification

Floor-ceiling systems operating at cooling conditions give rise to a stratification, with a lower zone with displacement flow, and an upper recirculation zone with uniform mixing. The heavy ventilation air flows like water out on the floor, se figure 3. When the air arrives at a person the ventilation air is entrained into the boundary layer flow surrounding the whole body. Starting from the feet, progressively more air is entrained. At a certain height the entrained flow rate becomes approximately equal to the supplied flow rate (8). Above this zone recirculation take place resulting in a well mixed zone. We know that the total flow rate of air generated by a man in a sedentary posture amounts to 100-200 m^3/h (2). The figure on the left hand side in figure 4 shows the recorded relative concentration at a supplied flow rate of air equal to 75 m^3/h ($\tau_n = 0.5$ (h)). The right hand figure shows the recorded concentrations when the mannekin is in operation. The concentration at the breathing zone (1.2 m) is increased. This can be ascribed to the effect described above. However, as seen from figure 4, when the flow rate is doubled to 150 m^3/h then the 'clean' air zone is pushed upwards to a height well above the breathing zone.

It is possible that a lower air flow rate than stated above is sufficient to sustain a high air quality. This surmise is based on the fact that we know that a part of the air inhaled by a man is taken from the boundary layer (1) surrounding the man. The boundary layer air flow is fed from below by clean air. Therefore it is possible that the contaminant concentration inhaled is lower than in the air surrounding the head.

Conclusions

In the tests we found that the parallel-flow systems where the air and the contaminants move in the same direction gave rise to the lowest average room concentrations, i.e. the shortest turn-over times. This implies that a light contaminant in particular is best evacuated by a floor to ceiling system when there is a cooling load. However, a certain minimum air flow rate is needed to sustain high efficiency and special attention is needed to ensure thermal comfort. For parallel-flow systems the room-average age of the air was always greater than or equal to the turn-over time of the contaminants. This implies that for design of parallel flow systems one can use the room-average age as an upper estimate of the turn-over time of a contaminant (i.e. the room average concentrations). In general, it is important to consider the effects of the secondary flows (e.g. self-concection from a person). A system that works as parallel flow system in an empty room may, with a person in the room, be turned into a counter-flow system.

References

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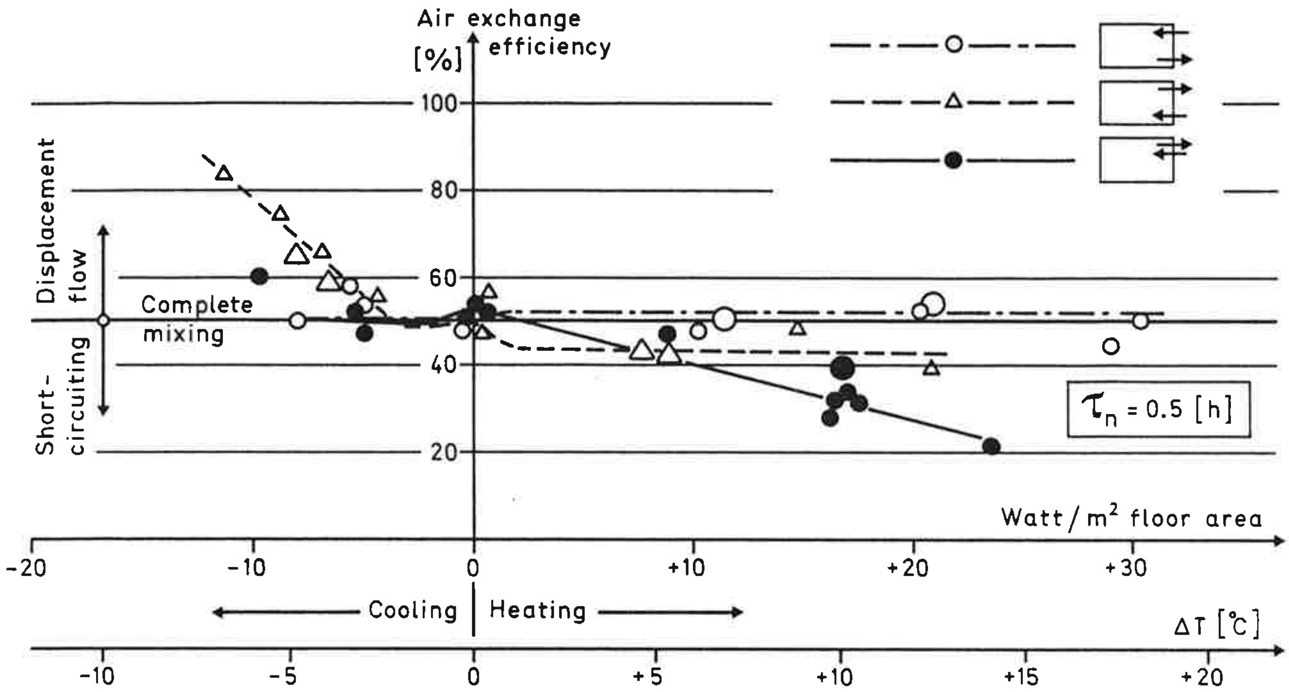

Fig. 1. Air exchange efficiency versus the temperature difference, ΔT, between the supply- and extract air. Large symbols indicate tests with a person (SIBMAN) in the room.

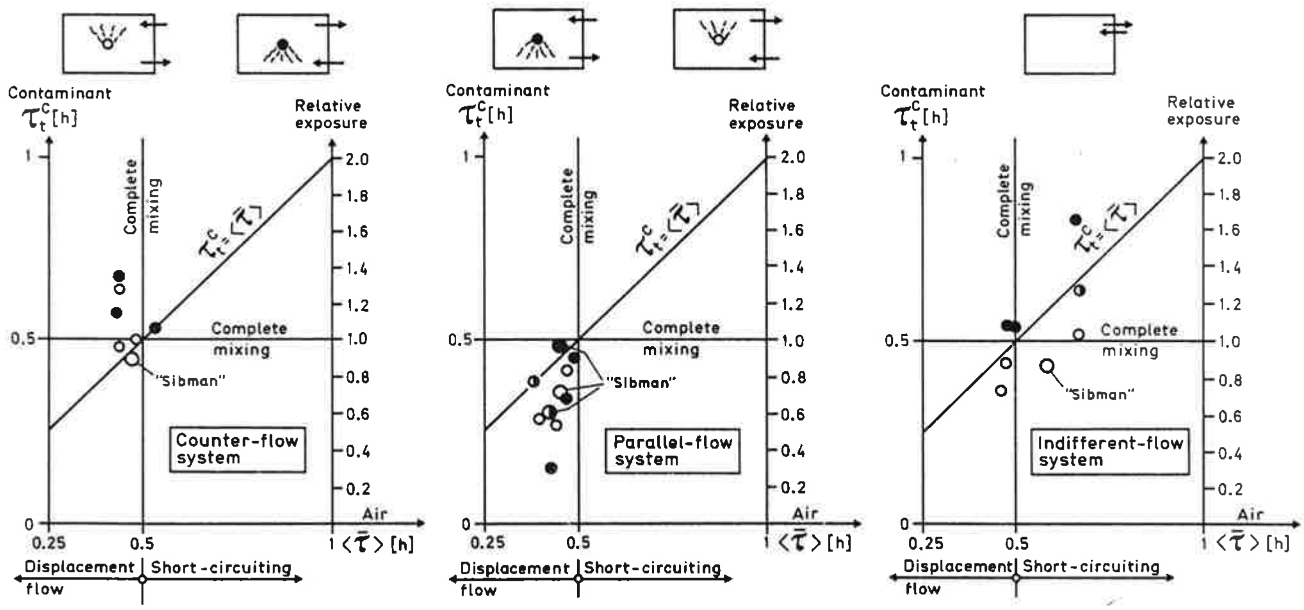

Fig. 2. Turn-over time of conatminants versus the mean-age of the air in the room. ◐ passive contaminant (no buoyancy).

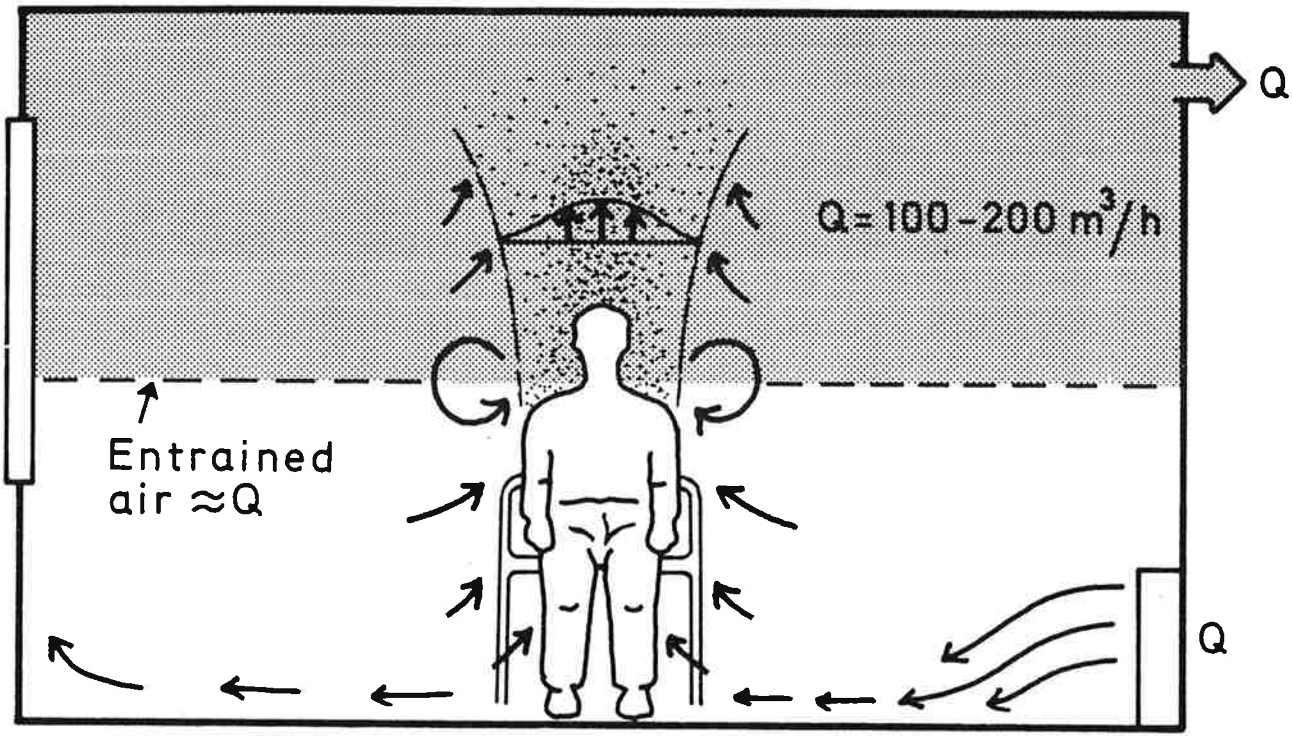

Fig. 3. Floor to ceiling system with cooling. Flow diagram.

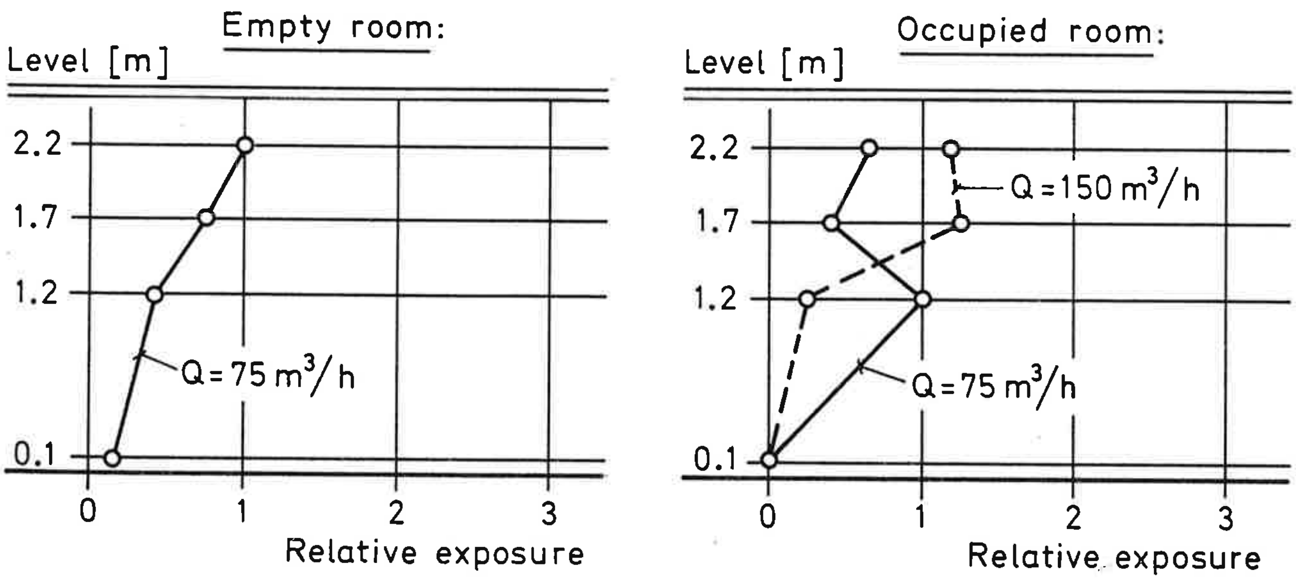

Fig. 4. Floor to ceiling system with cooling. Light contaminant. Recorded concentrations in the room. (The concentration at complete mixing of the contaminant is set equal to 1).