ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

3rd AIC Conference, September 20-23 1982, London, UK

PAPER 13

DEFINITION OF VENTILATION EFFICIENCY AND THE EFFICIENCY OF MECHANICAL VENTILATION SYSTEMS

MATS SANDBERG

The National Swedish Institute for Building Research, SIB,
P.O. Box 785, S-801 29 Gävle, Sweden. Tfn 026/10 02 20.

Synopsis

Air quality and the related definitions of ventilation efficiency are discussed generally. For ventilation systems in residental buildings a definition of efficiency is suggested that takes into consideration how ventilation air spreads within a dwelling. Included in the definition is the contamination exposure to a homogeneous (fills up the whole space) and dynamically passive and chemically inert source. For other sources it is only an air quality indicator. It is shown that a room-average of the efficiency can be determined by only measuring the concentrations in the exhaust ducts.

Measurements of the efficiency for exhaust, supply and combined systems show that for combined and supply systems the highest efficiency occurs, as expected, in those parts where the air is supplied. For these systems the efficiency is sensitive to the ventilation flow rate, while for the exhaust system the relative efficiency is more or less independent of the ventilation flow rate.

When doors between rooms are closed, the efficiency can be enhanced remarkably by suitable openings between the rooms.

Finally regarding varm-air systems it was found that the ventilation efficiency is very sensitive to the positioning of the supply and exhaust registers, the ventilation flow rate and the relative difference between supply air temperature and room air temperature. The greatest risk with warm-air systems is short-circuiting of both air and heat implying very inefficient systems.

A brief discharge has a duration much shorter than τ prolonged discharge has a duration much longer than

The exposure from a brief discharge is characterized maximum concentration and the time-integrated exposu area under the curve, see figure 2.

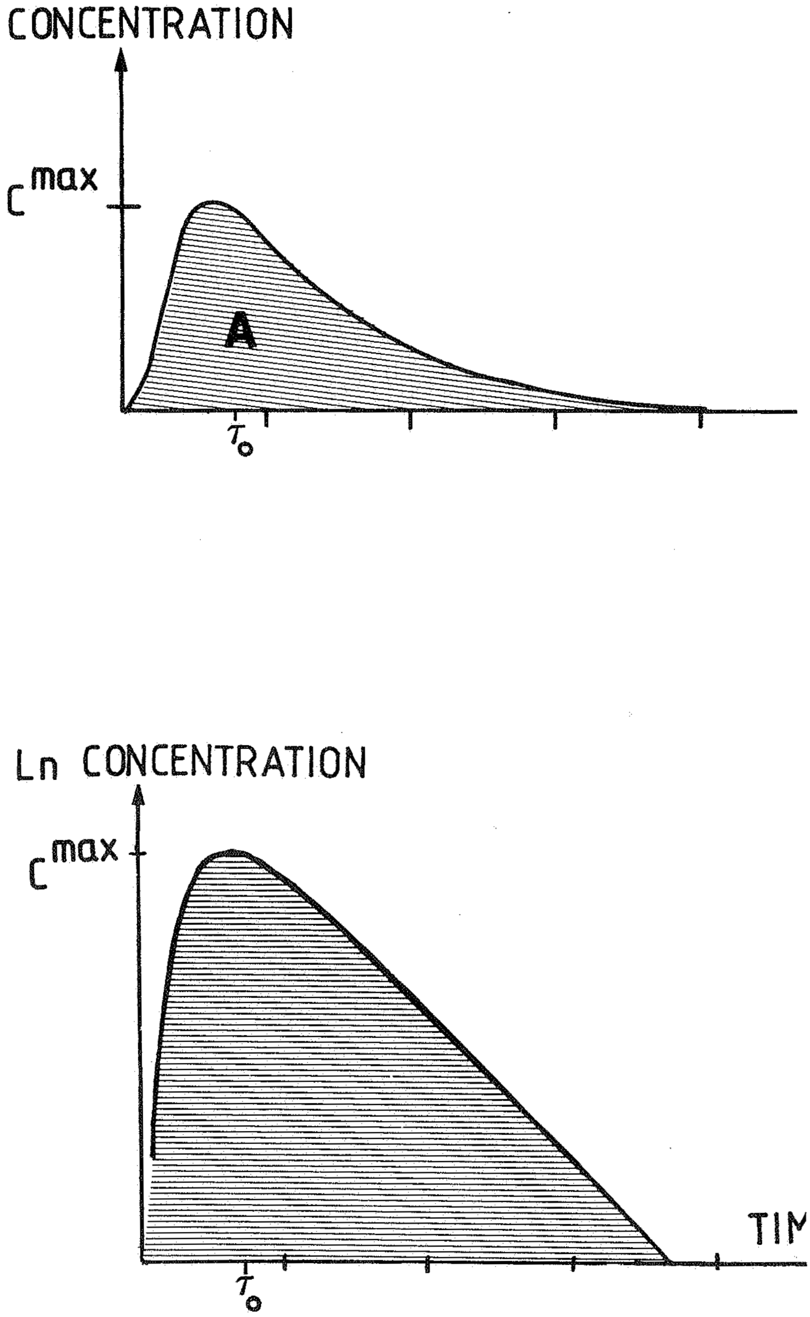


Figure 2. Brief discharge. Concentration versus tim time constant of the ventilation system.

The exposure from a prolonged discharge is fully characterized by its equilibrium concentration.

2.3 Absorbed dose

The absorbed dose is defined as the amount of pollutant deposited on external and in internal body tissues.

2.4 Effects

Effects on individuals are, among many factors, dependant on their activity levels, the time they spend in their dwellings and their susceptibility to the particular pollutant.

3. DEFINITION OF VENTILATION EFFICIENCY

As stated earlier the purpose of the ventilation system is to limit the contamination exposure from indoor pollutant sources. The definitions used should therefore reflect the systems performance with regard to this objective.

3.1 Stationary method

The contamination exposure from a prolonged discharge is satisfactorily described by its equilibrium concentration. An obvious, and much used, definition of ventilation efficiency is to define a stationary relative ventilation efficiency ^{s} at an arbitrary point in the dwelling as:

$$\varepsilon^s = \frac{C_e - C_s}{C_j - C_s} \times 100 \qquad (\%) \qquad (2)$$

where C_e is the concentration in the exhaust air duct, C_s is the concentration in the supply air duct and C_j is the concentration in the discussed point in the dwelling. The efficiency obtained by applying the definition (2) is both dependant on the properties of the ventilation system and the pollutant source. The magnitude of the stationary concentrations, and consequently the stationary efficiency, can also be obtained by other methods.

3.2 Transient method

The magnitude of the stationary concentrations at an arbitrary point can be calculated on a basis of the time-integrated exposure from a brief discharge. The following relation is proven theoretically to be valid, see /2/.

$$C_j^s = \frac{\dot{m}}{\left(\frac{m}{A_j}\right)} \qquad (3)$$

$\dot{m}$ = The pollutant production rate, kg/s

m = The amount of pollutant discharged in a brief discharge, kg

A_j = The time-integrated exposure obtained in an arbitrary point from a brief discharge, kg/m^3.h.

The quantity $\frac{A_j}{m}$ is in reference /1/ called **the transfer index.**

An advantage of using the transient concentration technique is that it is faster than equilibrium methods. After a while the monitored concentration decays exponentially and the remaining part of the exposure is easily calculated, see figure 2.

3.3 Distribution of the supplied air

One of the most important factors determining the air quality is the 'distribution pattern' of the supplied outdoor air within the dwelling. The air should be distributed in a fashion that removes the pollutant as quickly as possible from the dwelling.

The distribution of the supplied air can be described in different statistical/physical terms. One is the mean age of the air, in chemical engineering parlance often called the mean-residence time. The age is defined as the time that has elapsed since the air came into the room. The mean age of the air at an arbitrary point is easily measured by the tracer gas technique. One possible method is a 'purge' run. The whole space is filled with tracer gas and mixed by mixing fans to a uniform concentration. The mixing is stopped and the decay of the gas concentration is monitored at the selected point. By using the initial concentration (C(0)) and the area A_j under the curve, i.e. the time-integrated exposure, we calculate the mean age $\bar{\theta}_j$ at the actual point as:

$$\bar{\theta}_j = \frac{A_j}{C(0)} \qquad (h) \qquad (4)$$

If we invert (4) we get the local ventilation rate r_j:

$$r_j = \frac{1}{\bar{\theta}_j} \qquad (1/h) \qquad (5)$$

and if we finally multiply this by the volume, V, of the dwelling we get the effective flow rate:

$$Q_j^{eff} = V \times r_j \qquad (m^3/s) \qquad (6)$$

When the mixing is complete the effective flow rate at each point is equal to the supplied flow rate and the local ventilation rate is equal to the nominal air change rate n (supplied flow rate divided by the volume of the room). The mean value of the mean age for the whole dwelling can be obtained by monitoring the gas concentration in the extraction duct, see Appendix 1.

The area under the tracer gas curve gives us in this case, according to (3), the stationary concentration from a pollutant source that fills up the whole space. For such sources knowledge about the local ventilation rate is sufficient for determining the air quality. For other sources the local ventilation rate is only an air quality indicator.

The reference 'Air distribution pattern', though far from the best, is complete mixing. Therefore we define a transient relative ventilation efficiency as

$$\varepsilon_j^t = \frac{r_j}{n} \times 100 \qquad (\%) \qquad (7)$$

where n is the nominal air change rate.

An alternative term for the efficiency (5) could perhaps be 'the air distribution efficiency'.
When the mixing is complete the efficiency (5) is 100%, and the theoretical upper limit of the efficiency occurs for 'piston flow'. In case of 'short-circuiting' the efficiency is lower than 100%.

3.4 Characterization of pollutants in dwellings

The indoor environment normally includes a complex mixture of pollutants. Apart from cooking odours, the pollutant source in residental buildings normally has a spatially diffuse character. Examples of diffuse sources are people moving around, formaldehyde evaporating from chipboard or radon emitted from the building material.

A designer of a ventilation system for a residental building does not normally know in advance which pollutants the ventilation system is to remove. Furthermore, in national standards the demands on the ventilation are not stated in terms of limitation of contamination exposure but as a minimum ventilation rate. Therefore it is felt that the source-independant efficiency defined by (5) is a suitable basis for selecting a ventilation system.

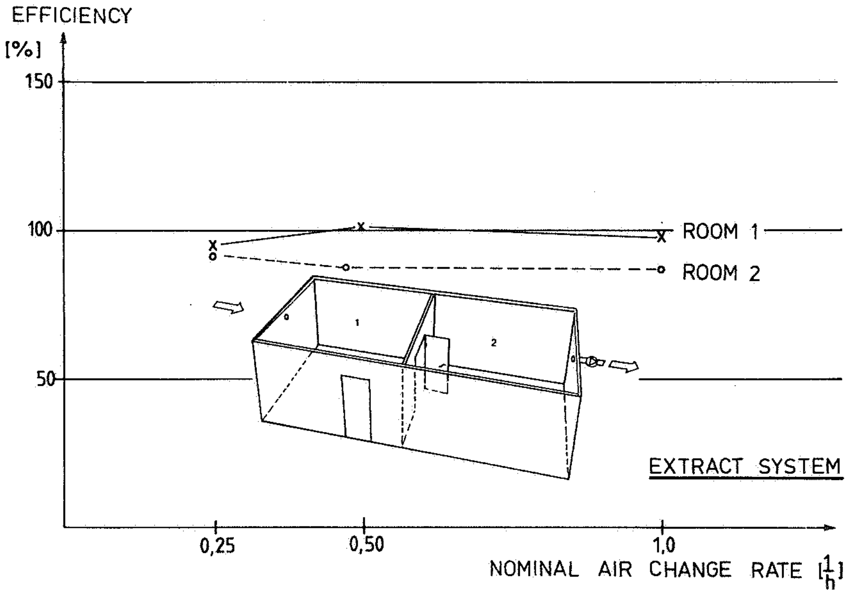
4.0 MEASUREMENTS

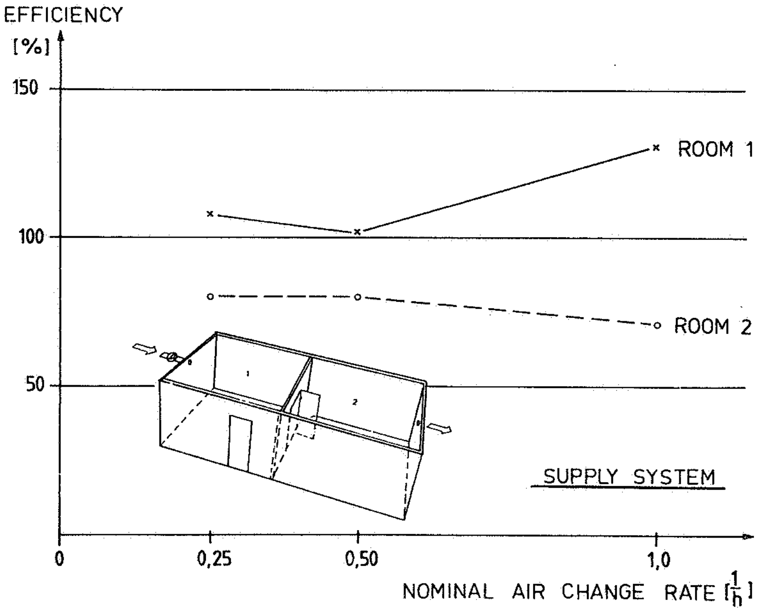
The ventilation efficiency and in some cases the temperature efficiency (to be defined below) of different systems have been monitored in the Laboratory for Heating and Ventilation.

For all results presented below the definition (7) of the ventilation efficiency, i.e. the transient relative efficiency, has been used. Some of the results presented below have earlier been presented in references /3, 4/.

4.1 A comparison between different whole-house ventilation systems

A small house measuring (width x length x hight) 4.55 x 8.42 x 2.75 m with two rooms of equal size has successively been equipped with an extract, supply and a combined system respectively. The efficiency has been monitored under isothermal conditions in one point in the middle of each room at about 1.7 m above the floor level. The nominal ventilation rate, n, has been varied systematically between 0.25 - 1 air changes per hour. The results are shown in figure 3.





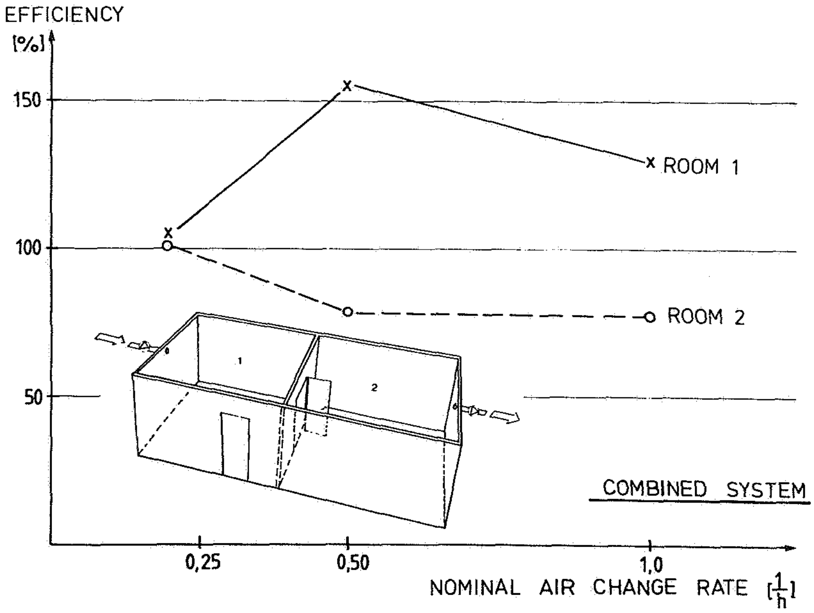


Figure 3. A comparison between extract, supply and a combined system respectively. Door between rooms open.

Figure 3 shows that the extraction system gives about the same efficiency in both rooms and the relative efficiency is rather independant of the nominal ventilation rate. This is according to what we should expect. The under-pressure created by the ventilation system gives rise to an inflow of air through the evenly distributed leakages in the building material. However the air meets the least resistance in the purpose provided opening in room 1 and therefore we get a slightly higher efficiency in this room.

The supply system gives a much larger efficiency difference between the the two rooms. This is due to the fact that the supply of air is now concentrated to the supply register in room 1.

The combined (balanced) system gives, apart from the lowest ventilation rate, the highest efficiency of all systems.

4.1.1 Combined system with both supply and extraction in the same room

Figure 4 showns the monitored efficiency when the air is both supplied to and extracted from the same room.

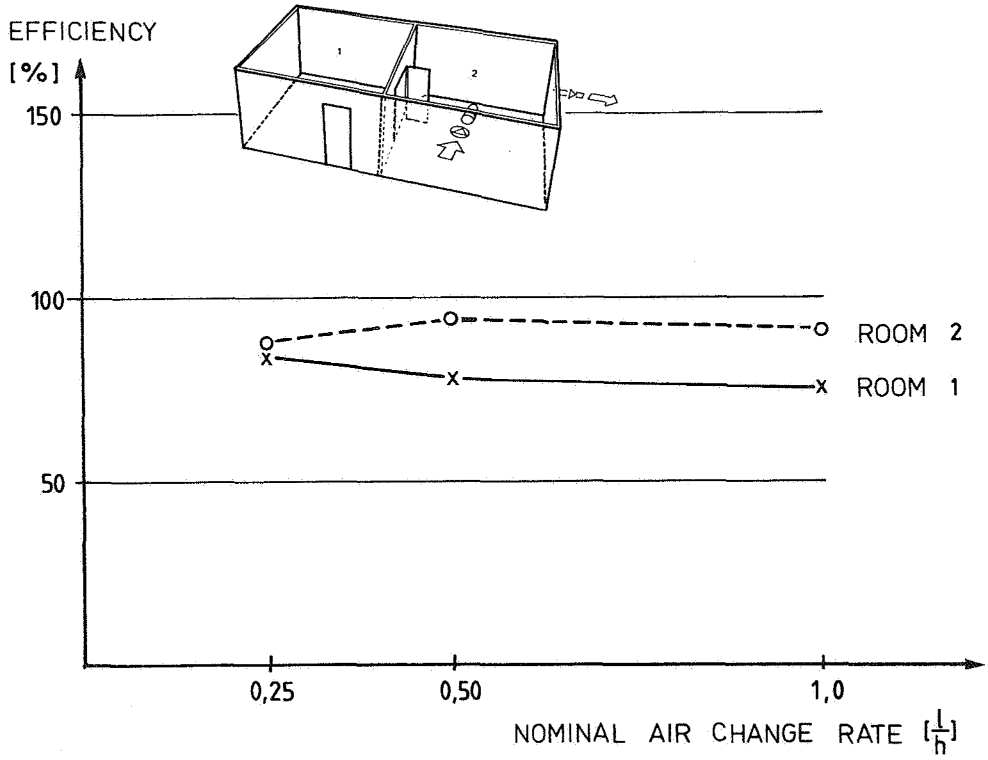


Figure 4. Combined system. Supply and extraction registers in the same room. Door between rooms open.

With both the supply and extraction registers placed close to each other the best possible performance we can expect is a uniform dispersion of the air throughout the dwelling. In other words, it is a question of minimizing short-circuiting as much as possible. The efficiency is, as expected, highest in room 2, wher the air is supplied, but the efficiency in room 1 is surprisingly high.

4.1.2 Combined system with supply and extraction of air in different rooms. Door between the rooms closed

In this case the door is closed and the air is transferred between the roms through a narrow slot under the door. The efficiencies obtained are shown in figure 5.

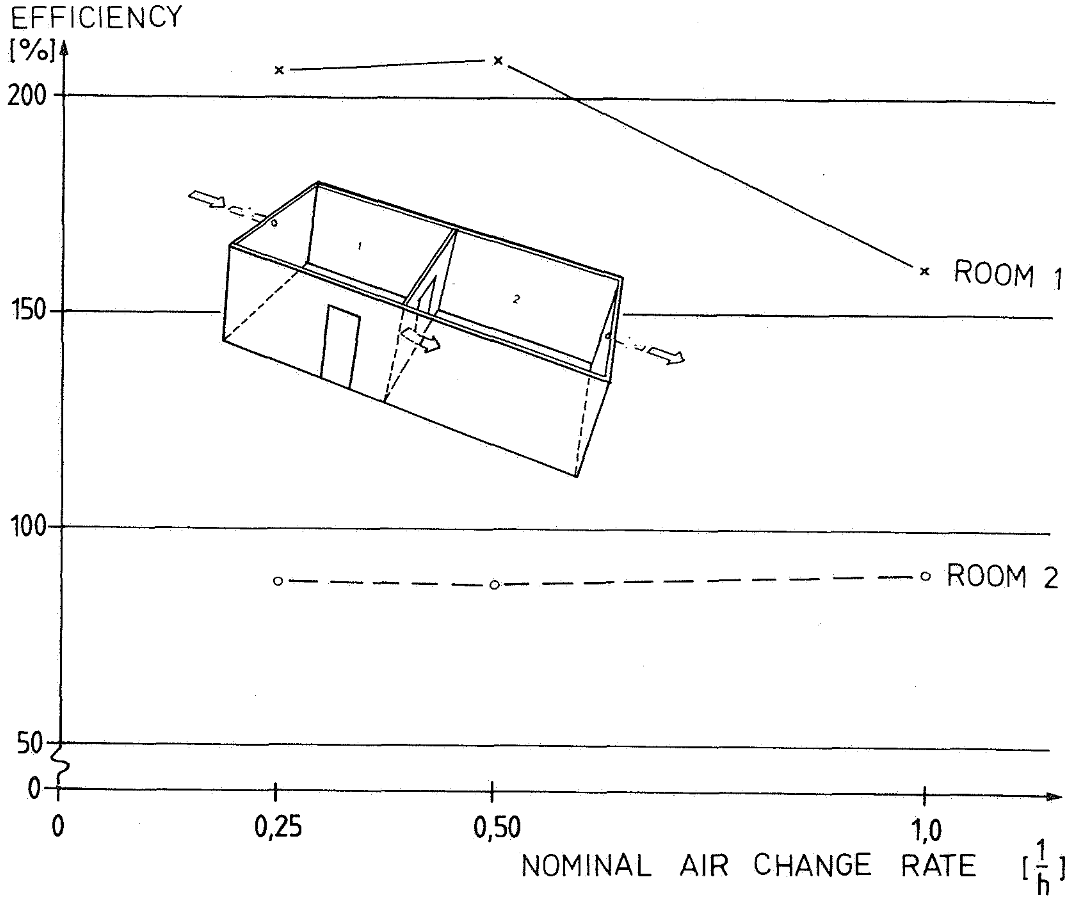


Figure 5. Combined system. Door between rooms closed. A narrow slot under the door.

Compared to the case shown before, i.e. with the door open, the efficiency is now strikingly higher in room 1. The explanation is how the slot under the door works. The area of the slot is so small, and accordingly the air velocity high, that it acts like a one-way valve for the air. The air is only transferred from room 1 to room 2 and not in the opposite direction. This implies that the dwelling is now ventilated 'in sequence' and we achieve a quick removal of the gas. This is an illustrative demonstration that a ventilation system's main purpose is to remove the pollutant as quickly as possible and not to dilute the contaminant.

4.2 Warm-air systems

In a warm-air system the ventilation system has a dual task. It must both provide heat and 'fresh' air in the occupied zone. The ability to supply air is, as before, expressed by definition (5) of the ventilation efficiency. A ventilation system's ability to supply heat may be expressed by a temperature (thermal) efficiency, ε_T, similar to the definition (2) of the stationary ventilation efficiency:

$$\varepsilon_T = \frac{T_e - T_s}{T_j - T_s} \times 100 \qquad (\%) \qquad (8)$$

T is the stationary temperature.

A small temperature difference between the supply air and the occupied zone implies a high utilization of the energy provided. The measurements have been made in a room measuring (width x length x hight) 3.6 x 4.2 x 2.5 m. The occupied zone is defined as the volume up to 1.8 m above the floor level.

4.3 System A

In this system the supply as well as exhaust air registers were placed above the occupied zone. This system is a typical short-circuiting scheme or undirectional air flow system. Regarding the transient ventilation efficiency the best we can achieve is to disperse the supplied air uniformly in the occupied zone, i.e. complete mixing (100% efficiency) is the best feasible. The results obtained are shown in figure 6.

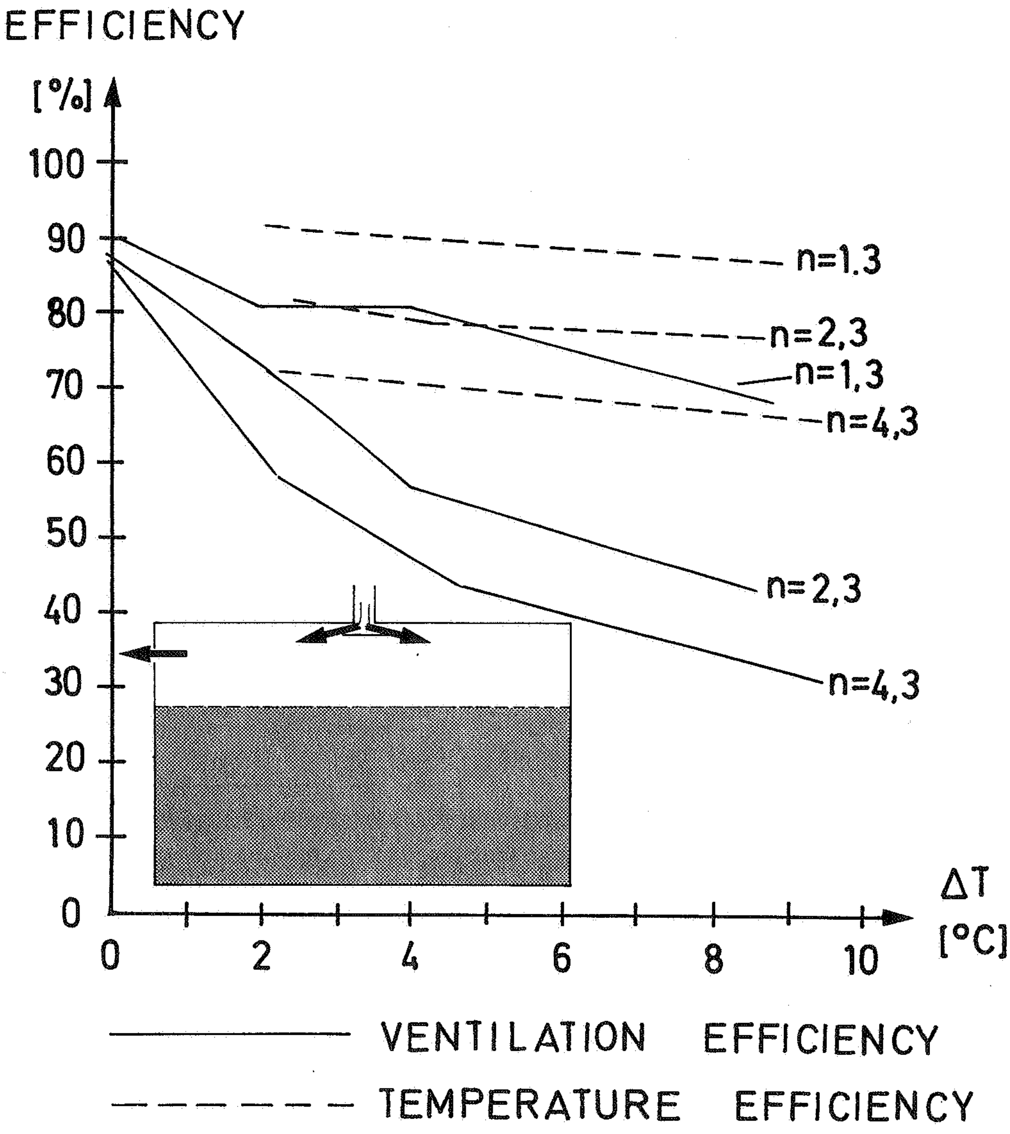


Figure 6. The transient relative ventilation efficiency and the stationary temperature efficiency in the occupied zone (shaded area).
ΔT is the temperature difference between the supply and extraction duct.
n is the nominal air-change rate.

Figure 6 shows a heavy thermal stratification effect with an increase in the supply air temperature. The increase in the nominal air change rate affects the ventilation efficiency in a perhaps somewhat unexpected manner. The ventilation efficiency decreases when the ventilation air flow is increased.

The temperature efficiencies show a similar pattern.

4.4 System B

In this system the exhaust register has been moved to the floor level. With this placing of the supply and exhaust registers complete mixing is the poorest operational mode. The result obtained for this system is shown in figure 7.

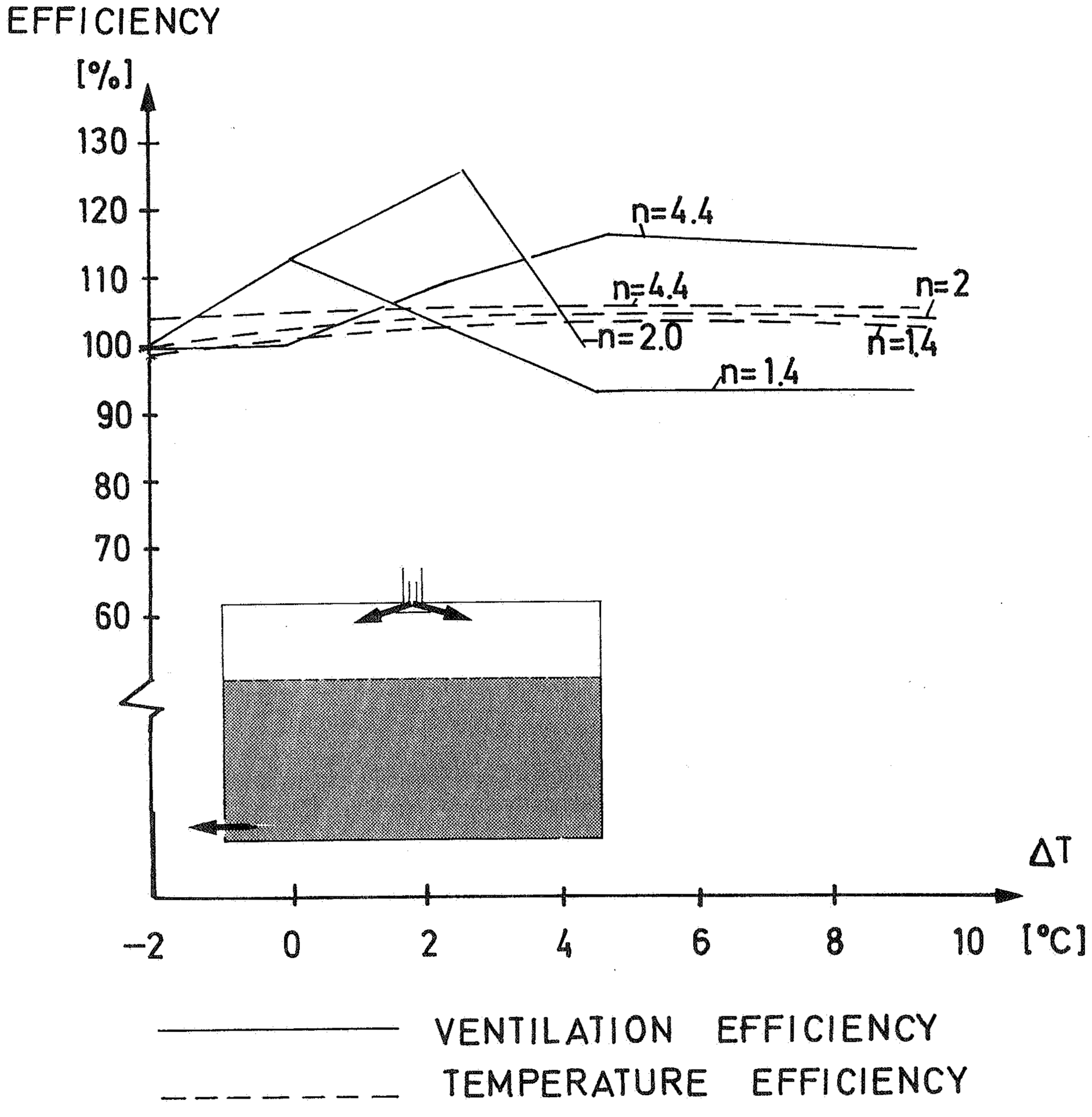


Figure 7. The transient relative ventilation efficiency and the stationary temperature efficiency in the occupied zone (shaded area).
ΔT is the temperature difference between the supply and extraction duct.
n is the nominal air-change rate.

Figure 7 shows that we almost always obtain a ventilation efficiency greater than 100%. The combined high nominal air change rate and high over-temperature give an exceptionally high ventilation efficiency. The explanation is the buoyancy effect and placing of the registers. Due to the buoyancy the supplied air sticks to the ceiling, but due to the placing of the registers the air is forced to pass through the whole room. The resulting flow is similar to a plug flow.
The temperature efficiency is just above 100%.

4.5 System C

In this system air is supplied at floor level next to the wall and is blown vertically up the wall. The exhaust air register is placed in the middle of the ceiling. This is again an undirectional air flow system and we should expect a ventilation efficiency greater than 100%. The results obtained are shown i figure 8.

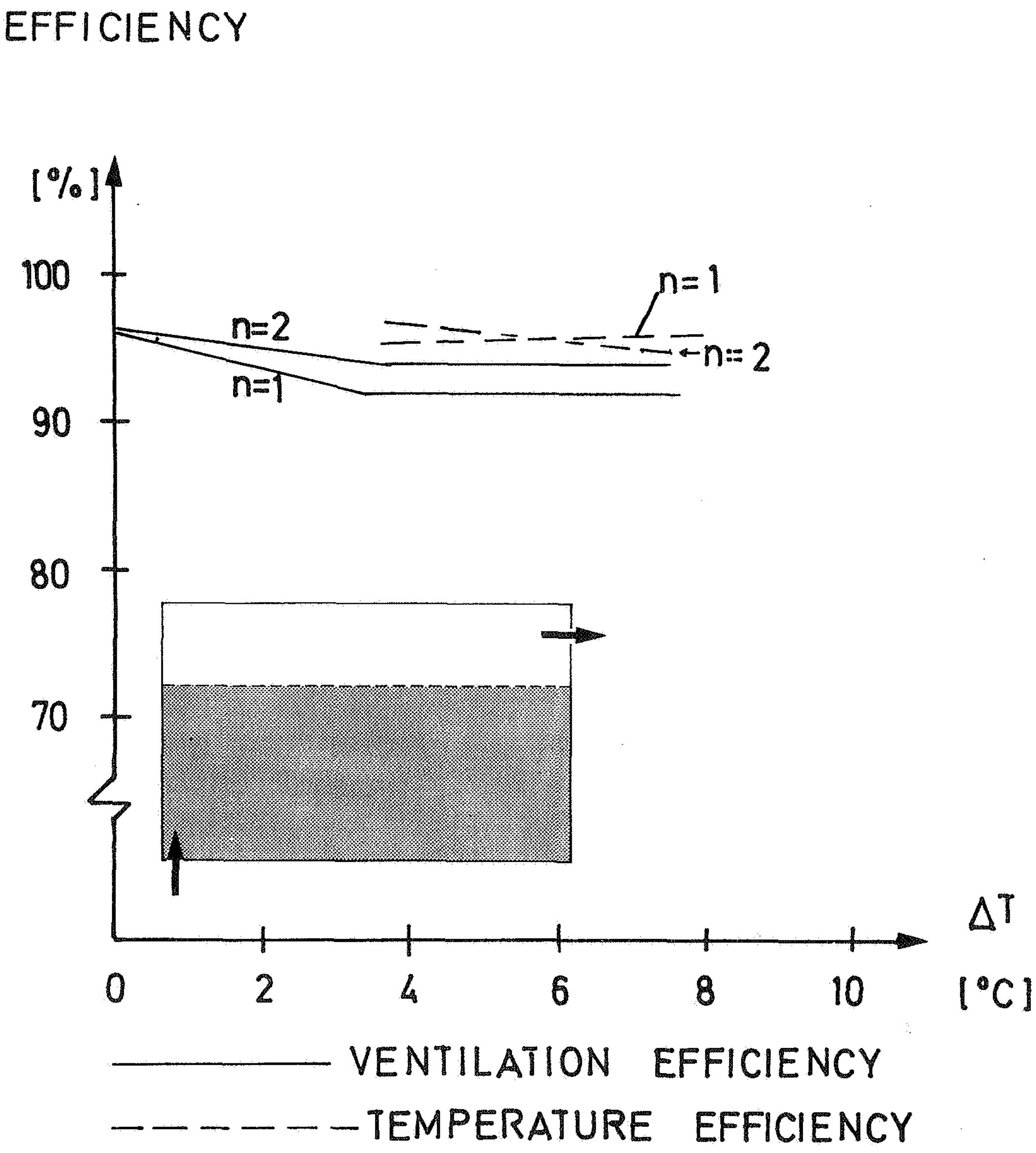


Figure 8. The transient relative ventilation efficiency and the stationary temperature efficiency in the occupied zone (shaded area).
ΔT is the temperature difference between the supply and extraction duct.
n is the nominal air-change rate.

Figure 8 shows that we get a ventilation efficiency less than 100% which is less than the expected efficiency. The explanation is probably a short-circuiting effect due to the fact that the supplied air partly goes as a wall jet directly to the extract air register. The temperature efficiency is however about 100%.

4.6 System D

The placing of the register is the same as for system D, but now the supplied air is blown horizontally along the floor. The results obtained are shown i figure 9.

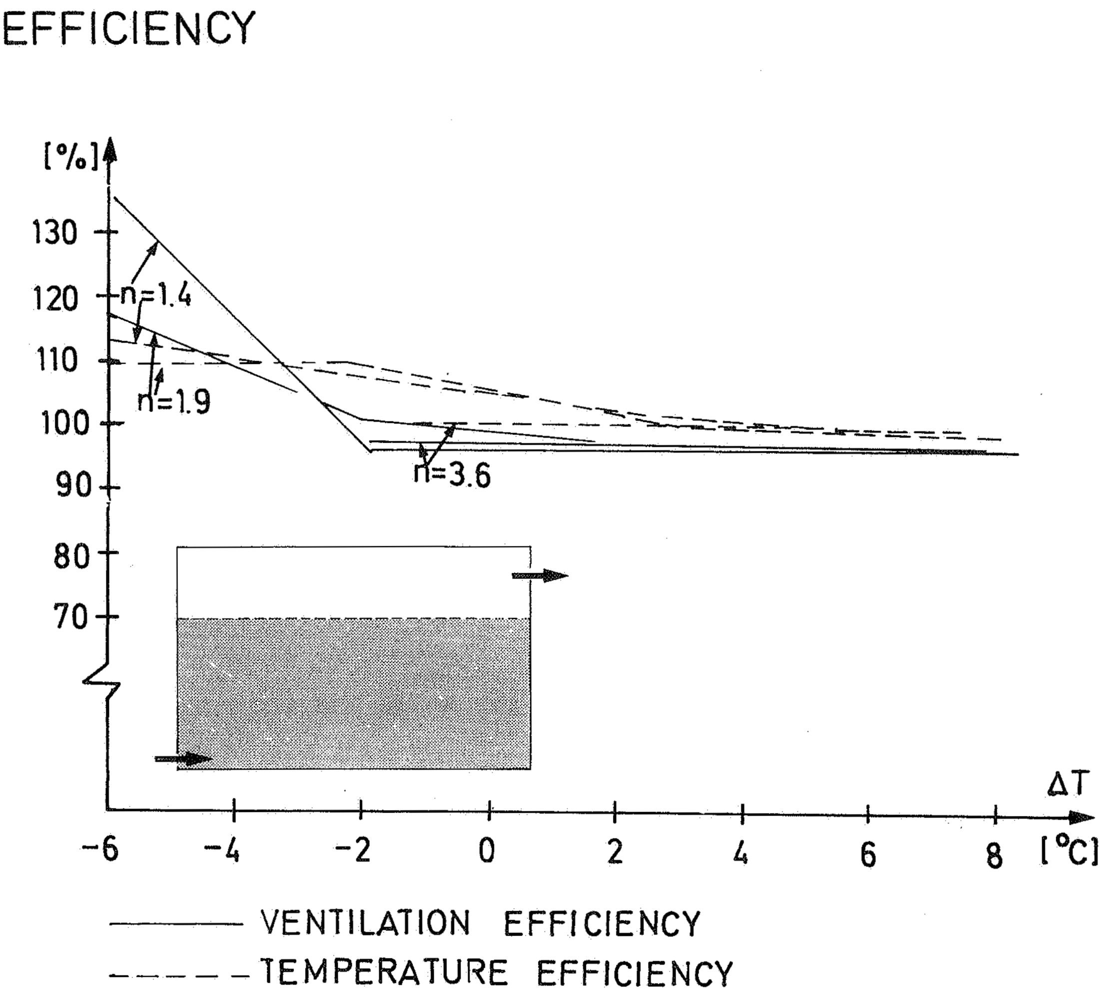


Figure 9. The transient relative ventilation efficiency and the stationary temperature efficiency in the occupied zone (shaded area).
ΔT is the temperature difference between the supply and extraction duct.
n is the nominal air-change rate.

Figure 9 shows that in the case of cooling the ventilation efficiencies are much greater than 100%. The explanation is the same as when system 2 is run as a warm air system; it can be ascribed to the buoyancy effect and the position of the registers.

Similar performances of warm-air systems have also been reported in reference /5/.

APPENDIX

Relationship between room-averaged ventilation rate and the moments of the concentration distribution in the exhaust duct

It will be supposed that the pollution (tracer gas) is transported by convection and diffusion (laminar and turbulent). Furthermore it is assumed that the velocity field is stationary. The concentration C at an arbitrary point (x, y, z) in the room obeys the conservation (transportion) equation:

$$\partial C/\partial \tau = - \nabla \cdot (\underline{U}C - D\ C) \tag{1}$$

where

$\underline{U}(x, y, z)$ = Local velocity vector

$D(X, Y, Z)$ = Local diffusivity

$\nabla = (\partial_x, \partial_y, \partial_z)$ = Nabla operator

τ = Time

The velocity and diffusivity vary with position but not with time and concentration.

The boundary conditions at the walls are (no mass flux):

$$D \frac{\partial C}{\partial \underline{n}} = 0 \tag{2a}$$

where

$\partial C/\partial \underline{n}$ denotes differentation along the normal to the wall.

Furthermore we assume that the concentration in the supply duct is zero.
Generally, at an arbitrary point, we define with regard to time the moments, $\mu^{(p)}$, of the concentration distribution as:

$$\mu^{(p)}(x, y, z) = \int_0^\infty \tau^p \cdot C(x, y, z; \tau)\, d\tau \tag{3}$$

The 0:th moment is the integrated exposure or area under the curve. The condition to be imposed on C as $\tau \to \infty$ is thus that these moments should exist and be finite.
Multiplying equation (1) by τ^p and integrating from 0 to ∞, we have

$$-p\mu^{(p-1)} + \nabla \cdot (\underline{U}\mu^{(p)} - D\ \mu^{(p)}) = 0 \quad p = 1, 2, 3 \tag{4}$$

and the condition (2a) becomes:

$$D\,\mu^{(p)}/\partial\underline{n} = 0 \tag{2b}$$

The moments in the supply duct are zero. To simplify we assume that there is only one exhaust duct.
By integrating the equation (4), subject to condition (2b), over the whole room volume, V, the room average < > of equation (4) becomes

$$\langle\mu^{(p-1)}\rangle = \frac{1}{p}\,\frac{Q}{V}\,\mu^{(p)}_{e} \tag{5}$$

where

$$\langle\mu^{(p)}\rangle = \frac{1}{V}\iiint\mu^{(p)}\,(x,\ y,\ z)dxdydz$$

$\mu^{(p)}_{e}$ = p:th moment in the extraction duct.

Q = Volumetric flow rate of air

The relation (5) shows that in principle we can retrieve the room average of any moment by monitoring the gas concentration in the exhaust duct.

If, for example we apply the relation (5) to a 'purge' run, i.e. the room is initially filled with tracer gas to give a uniform concentration C(0), we get the room-averaged ventilation rate. To see this we put p = 1 and divide both sides in equation (5) by the initial concentation C(0)

$$\langle\bar{\theta}\rangle = \left\langle\frac{\mu^{(o)}}{C(0)}\right\rangle = \frac{Q}{C(0)\cdot V} \tag{6}$$

Because all tracer gas must pass the extract duct we obtain the eguation:

$$Q\cdot\int_{o}^{\infty} C_e(\tau)d\tau = C(0)\cdot V$$

or

$$\frac{Q}{C(0)\cdot V} = \frac{1}{\int_{o}^{\infty} C_e(\tau)d\tau}$$

Therefore we can write (C) as

$$\langle\bar{\theta}\rangle = \frac{\mu^{(1)}_{e}}{\mu^{(o)}_{e}} = \frac{\int_{o}^{\infty} C_e(\tau)\cdot\tau\cdot d\tau}{\int_{o}^{\infty} C_e(\tau)d\tau} \tag{7}$$

and its inverse, the room-averaged ventilation rate <r> as

$$\langle r\rangle = \frac{1}{\langle\theta\rangle} \tag{8}$$

Relation (8) shows that by monitoring the gas concentration in the extraction duct and calculating the first moment and the area of the concentration distribution we can retrive the room-averaged ventilation rate. An experimental verification of relation (8) is shown in figure 1.

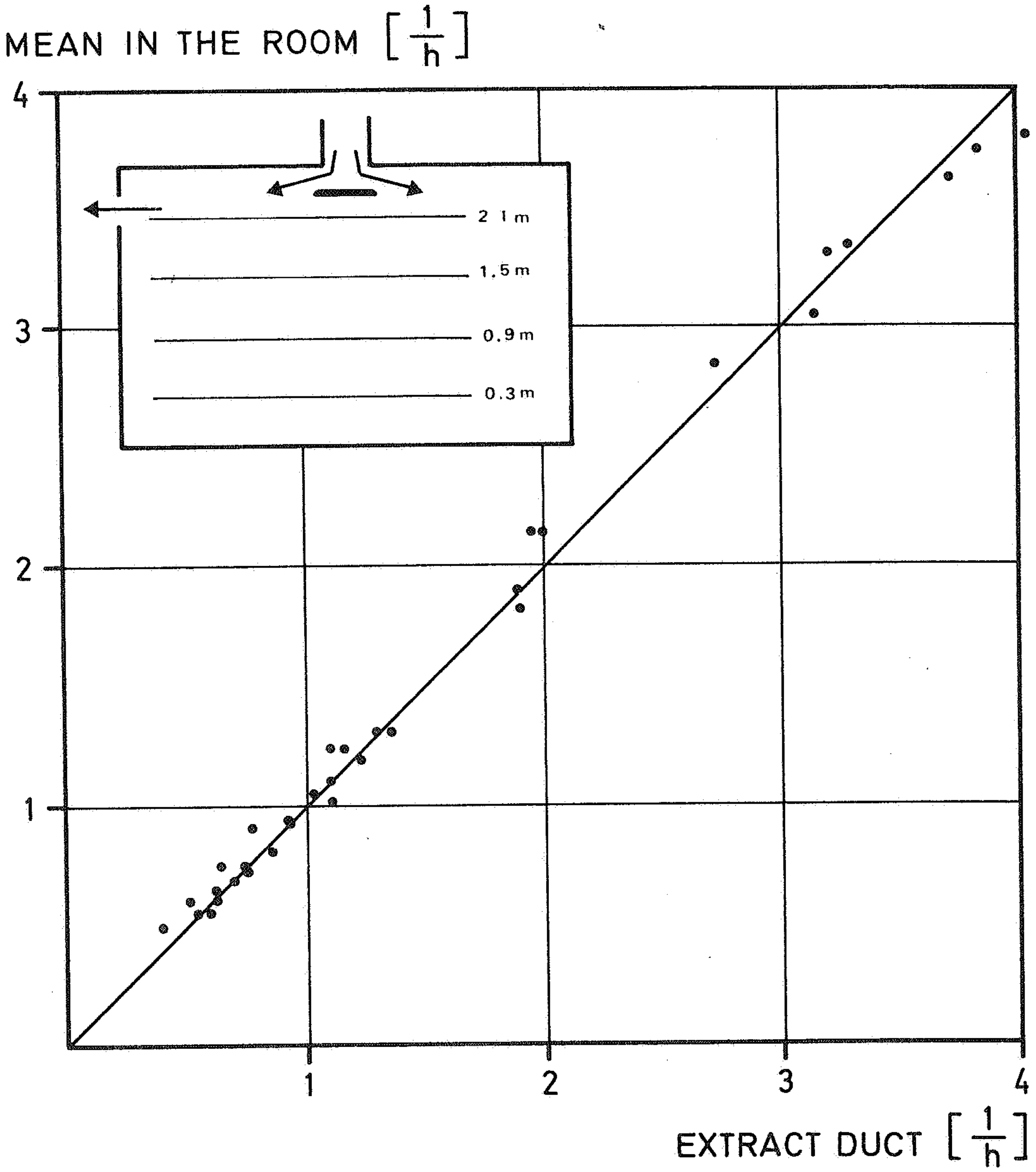


Figure 1.

Horizontal axis: Room-average ventilation rate obtained by measurements in the extraction duct and applying the relation (8) above.

Vertical axis: Room-average ventilation rate obtained by calculating the mean-values of the local ventilation rate at the four indicated levels.

Acknowledgements

The author wish to thank the following people for their contribution to this paper.

For carrying out the measurements:

Mats Sjöberg, SIB, Figure 2.

Svante Lindström, SIB, Figures 3 and 5.

Gian Vincenzo Fracastoro, Polyitecnico di Turino, Italy, Figure 4.

Per Björk, Royal Institute of Technology, Stockholm, Figures 6 to 9.

For drawing the graphs the author wish to thank

Karl-Einar Johannesson, SIB

and finally for typing

Inger Ivares, SIB.

References

1. LIDWELL, O.M.
"The evaluation of ventilation"
I. Hyg. Camb. 586 1960.

2. SANDBERG, M.
"What is ventilation efficiency?"
Building and Environment. Vol 16, No 2 1981, pp 123-135.

3. SANDBERG,M.
"Fläktstyrd ventilation - en analys av F-, T- och FT-system" (in Swedish).
VVS, No 3 1982, pp 60-63 and 70.

4. SANDBERG, M. and SVENSSON, A.
"The ventilation- and temperature-efficiency of Mechanical Ventilation systems".
Proceedings of CIB W67. Third International Symposium. Energy Conservation in the Built Environment. Vol 6. Dublin, Ireland 1982.

5. SKÅRET, E. and MATHISEN, H.M.
"Ventilation efficiency".
International symposium on "Indoor Air Pollution, Health and Energy Conservation". Amherst, USA 1981.