Ventilation Flow Organization for Efficient Elimination of Contaminated Air

Sture Holmberg[a]

[a] National Institute for Working Life, Sweden
Published online: 08 Jan 2015.

PLEASE SCROLL DOWN FOR ARTICLE

NOTES

Ventilation Flow Organization for Efficient Elimination of Contaminated Air

Sture Holmberg

National Institute for Working Life, Sweden

Displacement ventilation and well-organized ventilation flow structures are emphasized. Perhaps the biggest advantage of displacement ventilation is its increased effectiveness in removing pollutants from a ventilated space and the efficient use of ventilation air. Several questions on how the systems should be designed to achieve optimal efficiency are still unanswered. Small variations in room geometries and air supply arrangements can totally change the conditions. Results from this investigation show the importance of an even distribution of the incoming supply air, numerically calculated age-of-air values and the influence of residual tracer concentrations on measured mean values for the age of air.

ventilation principles   age of air   air change efficiency   air distribution   contaminant control

1. INTRODUCTION

The age-of-air concept is widely used when evaluating the efficiencies of different ventilation principles and systems. Low mean values of the age of air are needed to ensure good air exchange. The age parameter gives valuable information on how often the room air is fully or partly renewed. From earlier publications, we know that the mean arrival time of the supplied ventilation air to a local control volume in the room is an indicator of the local age of air (Sandberg, 1992). The local values vary with the local air exchange. Mixing and flow recirculation in a room influence the local ages and the local elimination of polluted air. Good ventilation cannot be achieved by only changing (increasing) ventilation flow rates. An intelligent choice of ventilation air flow principle can only be made after knowing the influence of the air flow pattern on the air quality in a room. The correct choice also provides improved thermal comfort and lower running costs.

2. NET INFLOW OF SUPPLY AIR AND FLOW PATTERN ORGANIZATION

The net inflow of supply air to a local control volume directly influences the local age of air in that volume. In a strict displacement flow pattern (Figure 1a), the

youngest (incoming) air pushes out the oldest air. Thus, there is no recirculation and the flow is uni-directional. The mean age of air in the room is then half of the residence time of the outgoing air. In a fully mixed room, the mean age and mean residence time are equal. Thus, the local mean age $\bar{\tau}_p$ is constant in the whole room (Figure 1b).

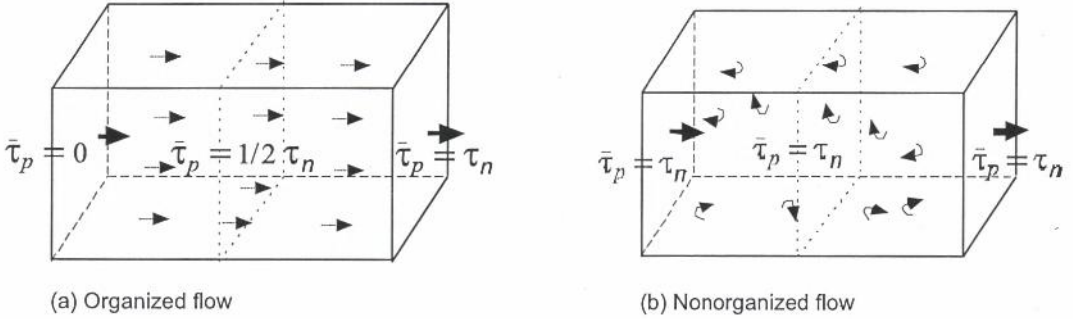(a) Organized flow   (b) Nonorganized flow

Figure 1. Local mean ages of air $\bar{\tau}_p$ at different locations with different flow types. (a) Displacement flow with strict flow organization, (b) Mixing without special organization of flow. *Notes.* τ_n—nominal time constant, total room volume V per total flow rate q.

For nonideal (practical) ventilation applications, measurements or numerical calculations are used to predict the age and residence times of the air. With a concentration decay (step-down) method (Holmberg, 1992) the local mean age is found from

$$\bar{\tau}_p = \frac{\int_0^{t_{CUT\text{-}OFF}} c_p(t)\,dt}{c_0} \qquad (1)$$

where $t_{CUT\text{-}OFF}$—integration (measurement) cut-off point, c_0—initial concentration (of tracer gas) in the room and

$$\int_0^{t_{CUT\text{-}OFF}} c_p(t)\,dt = \text{used area under the decay curve.} \qquad (2)$$

When a net inflow of fresh air reaches the measured local region, the initial concentration c_0 begins to decline, the decay being proportional to the net inflow of fresh air. This decay is, thus, a measure of how fast the old (contaminated) air is exchanged, and reflects the mean age of air in the region. A net inflow of fresh air, therefore, results in a concentration decay of the old air indicator $c_p(t)$. Figure 1a shows that the mean age of air in the whole room is the mean of the local values from room inlet to room outlet. The mean room value can, thus, be calculated as an average of the local values. Therefore, the ideal displacement flow arrangement gives the mean age of air in the room, $<\bar{\tau}>$ as $\frac{1}{2}\tau_n$. For ideal mixing (Figure 1b), $<\bar{\tau}> = \tau_n$.

The age of the room air can also be determined from numerical simulations. Local mean ages are calculated from a concentration set-up in the Navier-Stokes transport equations (Davidson & Olsson, 1987):

$$\frac{\partial c}{\partial t} + \frac{\partial (\rho u_i c)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma_c \frac{\partial c}{\partial x_i}\right) \tag{3}$$

A homogeneous concentration of the initial room concentration, $c(x, y, z) = c_0$, is assumed. A transport equation for finding the local mean age of air $\bar{\tau}_p$ can be obtained by integrating Equation 3 from $t = 0$ to $t = \infty$ (Sandberg, 1987; Sandberg & Sjöberg, 1983). This gives

$$\frac{\partial (\rho u_i \bar{\tau}_p)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma_{\bar{\tau}_p} \frac{\partial \bar{\tau}_p}{\partial x_i}\right) + \rho \tag{4}$$

This equation provides a steady-state numerical method for predicting the local mean age and the room mean age in a ventilated space. It will be used in further examples.

3. OPTIMAL FLOW ORGANIZATION

Fresh supply air reaching a local room volume will not have much effect on the local concentration if the flow structure is poor. An efficient flow structure is one where fresh air eliminates contaminated air and rapidly fills up the volume. At least one volumetric unit of fresh air must be used to eliminate one contaminated unit. This is the theoretical optimum for the flow in local zones and in the room as a whole (Figure 2a).

Recirculation counteracts the fresh air exchange process. Contaminant removal is not optimal in a mixed flow system where part of the fresh (young) air is removed in the exhaust outlet. In an optimal system, internal (old) air is given a high priority for
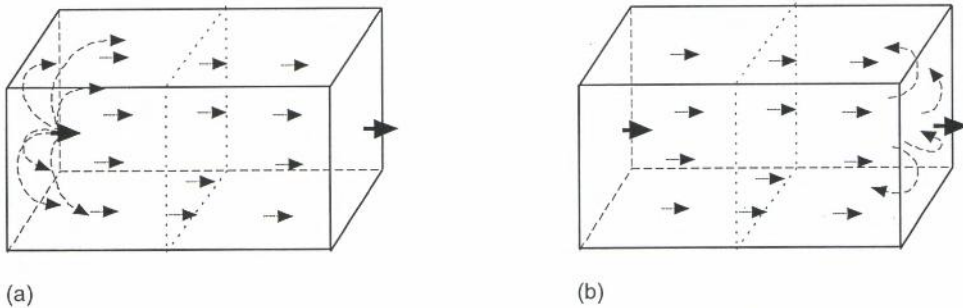

(a)   (b)

Figure 2. For good air change efficiency, fresh air needs to reach the whole room volume. (a) A good distribution of the incoming air is a key factor. (b) Recirculation in the room should be avoided, as it disturbs optimal flow and creates local and global mixing.

leaving the room, and external (incoming air) a low priority. Recirculation and mixing, thus, mean an increase in the local mean age of air in the affected regions of the room. In a contaminated environment, the contaminant concentration may reach dangerous levels (Figure 2b).

3.1. Fresh Air Distribution

If fresh air passes through a control volume without eliminating old air, a type of short circuit occurs and the flow is not optimally organized. The incoming fresh air must have access to all local volumes of the room, otherwise a delayed air exchange results.

To illustrate what has just been said, three examples are shown in Figure 3. By changing the air supply unit (diffuser), the efficiency of the ventilation air flow through the room is altered from a very inefficient ventilation flow with an air change efficiency ϵ_a of 31% (Figure 3a) to a very efficient flow with an air change efficiency of 67% (Figure 3c). Figure 3b shows mixing with an air change efficiency of 50%. It is a reference case. Figure 3 shows examples of numerical two-dimensional calculations. Equation 4 is used for the age-of-air calculations. They are given as a mean of the local room values and reflect the air change efficiency in the room. The finite-volume CFD (Computational Fluid Dynamics) code used for the

(a) $\epsilon_a = 31\%$ L

(b) $\epsilon_a = 50\%$ L

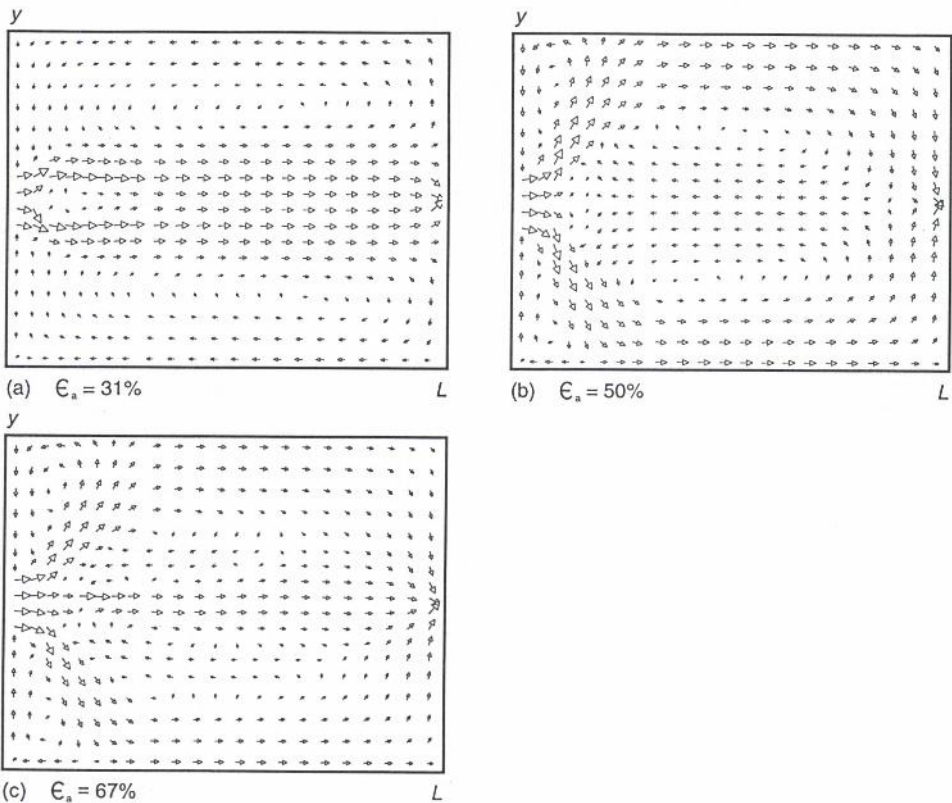(c) $\epsilon_a = 67\%$ L

Figure 3. Different flow patterns through a ventilated room showing the influence of air distribution and recirculating flow on the room air change efficiency, ϵ_a.

numerical calculations, the room geometry, the flow conditions, and the ventilation efficiency parameters are described elsewhere (Holmberg, Paprocki, & Tang, 1994; Holmberg & Tang, 1992). A standard k-ϵ turbulence model is used in the numerical predictions (Jones & Launder, 1972).

3.2. Recirculation

An efficient flow is characterized by one-way orientation and short recirculation zones. Note that recirculation at the beginning of the chamber, where the age of the air is still low, does not have much effect on the total efficiency. The recirculation near the inlet in Figure 3c is fairly strong, but the total air change efficiency is still high at 67%. What contributes to inefficient flow is recirculation of old air. This is shown in Figure 3a, where old air recirculates all the way from the exhaust side back to the supply side of the chamber.

For the velocity profiles (Figure 4), this means that negative velocity zones should as soon as possible rearrange into positive ones. Figures 4a and 4b show the velocity profiles for the flows in Figure 3a, Figure 4a being from the middle of the room ($x = 0.5\ L$) and Figure 4b at three-quarters of the room length ($x = 0.75\ L$). The recirculation is strong in both positions. The flow pattern in Figure 3c behaves differently as shown by the velocity profiles in Figures 4c and 4d. Here, the small recirculation zones in the middle of the chamber ($x = 0.5\ L$) becomes a fully positive profile by $x = 0.75\ L$.
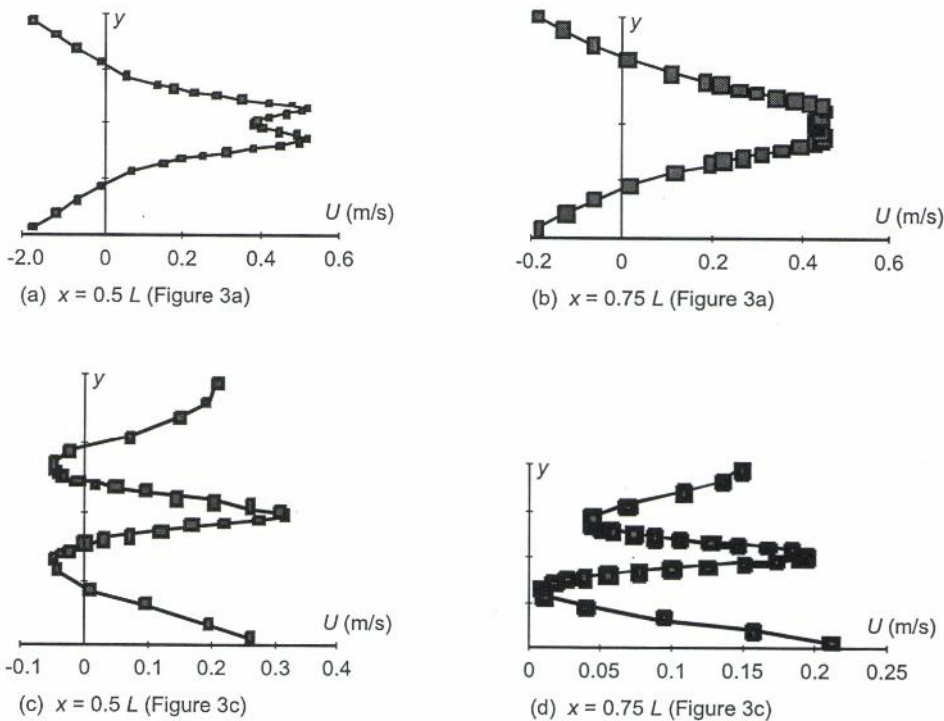

(a) $x = 0.5\ L$ (Figure 3a)

(b) $x = 0.75\ L$ (Figure 3a)

(c) $x = 0.5\ L$ (Figure 3c)

(d) $x = 0.75\ L$ (Figure 3c)

Figure 4. Velocity profiles at different room length positions (L) in Figures 3a and 3c.

3.3. Age of the Air

The ventilation efficiency parameter in this paper is the local age-of-air value in the different parts of the ventilated space. A complete (two-dimensional) picture of the efficiency can be given by local age-of-air contours (Figures 5 and 6), which correspond to the flow fields in Figures 3a and 3c. The contour key is normalized by

Contour Key	
1	0.27
2	0.80
3	1.34
4	1.87
5	2.41
6	2.94

Figure 5. Normalized local age-of-air values for the flow pattern in Figure 3a. A mean room value of 1.61 means 31% in terms of air change efficiency.

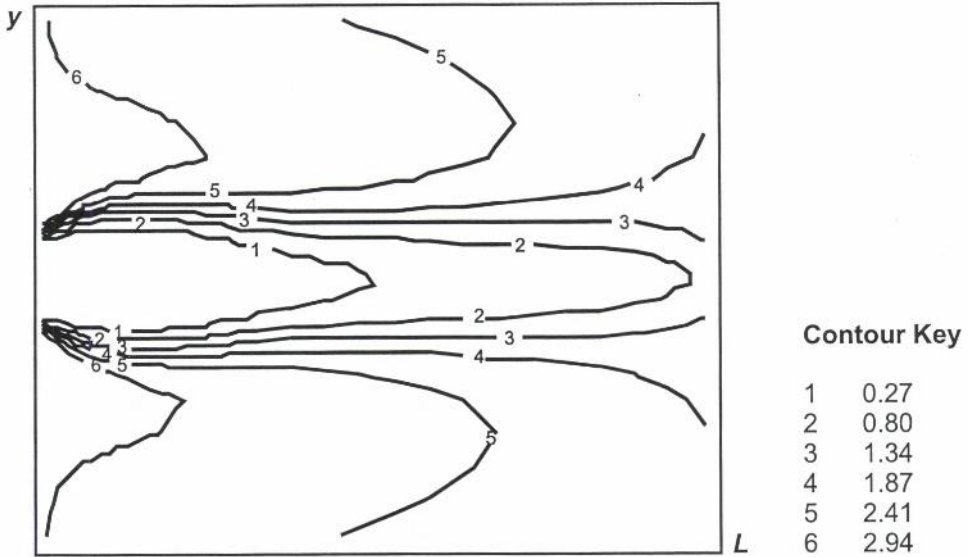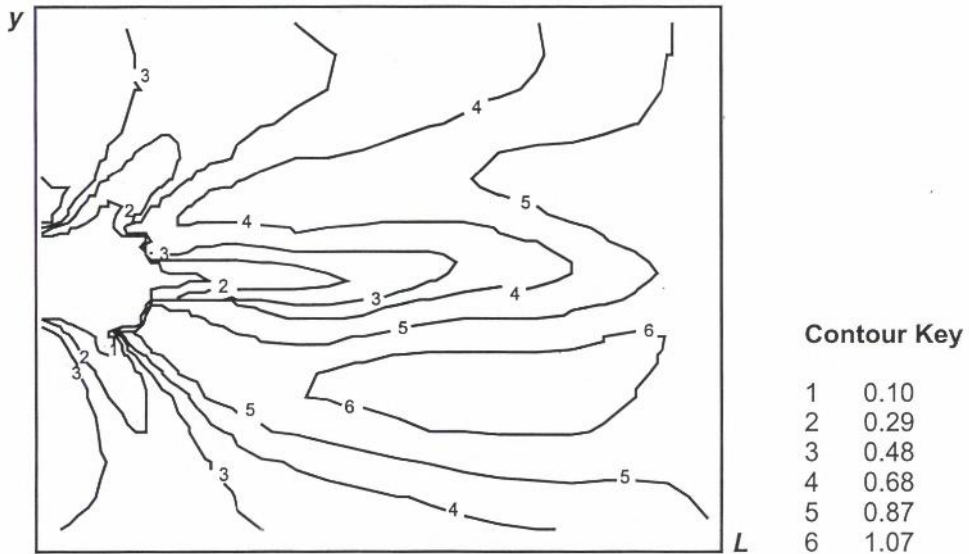| Contour Key	
1	0.10
2	0.29
3	0.48
4	0.68
5	0.87
6	1.07

Figure 6. Normalized local age-of-air values for the flow pattern in Figure 3c. A mean room value of 0.57 means 67% in terms of air change efficiency. The local age increases almost linearly with the room length L. Inside a small recirculation zone (contour 6), the local age-of-air values are greater than 1.

the nominal time constant τ_n. Figure 5 shows the unfavorable influence of recirculation. On either side of the inlet are contours (contour 6) with a local age of nearly three (2.94) nominal time constants. This value is approximately six times higher than that achieved with a more favorable air distribution in Figure 6.

The theory and examples just given show the consequences of choosing different air distribution principles. High velocity gradients and high turbulence intensity in the supply air often generate disturbances that lead to mixing and recirculation in the flow field. The diffuser design is important for the air distribution. To demonstrate this, a summary of a previous investigation on diffusers will be given here.

3.4. Symmetrical Air Distribution

In traditional mixing ventilation, mixing is a positive phenomenon. In displacement ventilation, mixing normally means a disturbance. A suitable design for the air supply diffuser was found by studying potential flow solutions around exhaust outlets (Holmberg et al., 1994). It was shown that a textile diffuser surface with a parabolic shape, shown in Figure 7, was able to distribute the incoming air in all directions. This prevented recirculating air from causing disturbances. The diffuser surface (interface) was designed to create equipotential pressure conditions inside the diffuser, which ensures equal initial velocities over the entire diffuser surface.
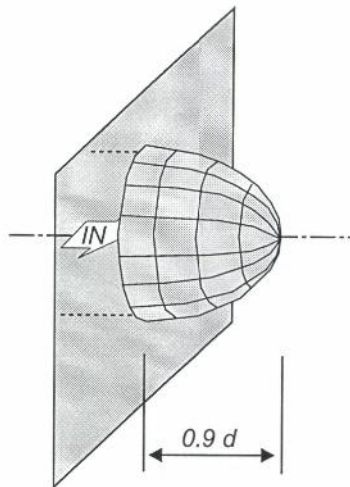
Figure 7. Diffuser design for optimal distribution of supply air (Holmberg, Paprocki, & Tang, 1994). Important diffuser parameters include the diffuser shape, the pressure drop over the diffuser, and the consistency of the diffuser (interface) material.

4. CONTAMINANT CONCENTRATIONS

4.1. Displacement and Mixing

The theoretical (ideal) displacement flow structure is an optimal flow structure, where the local concentration response to a stepwise change is fully achieved at time $t = \bar{\tau}_p$.

With theoretical displacement flow there is a sharp boundary between the front of incoming air and the contaminated air in the room. Concentrations in two room regions for both displacement and mixing flows are shown in Figure 8. The concentrations are shown for real times $t = 0.5\ \tau_n$ and $t = \tau_n$ after the concentration step change. The concentration of contaminants at a point goes from the initial concentration of unity to zero as the front passes that point. The time required to achieve low contaminant levels in the room varies with the flow type selected. This is shown by including the fully mixed flow below the displacement flow in the figure.
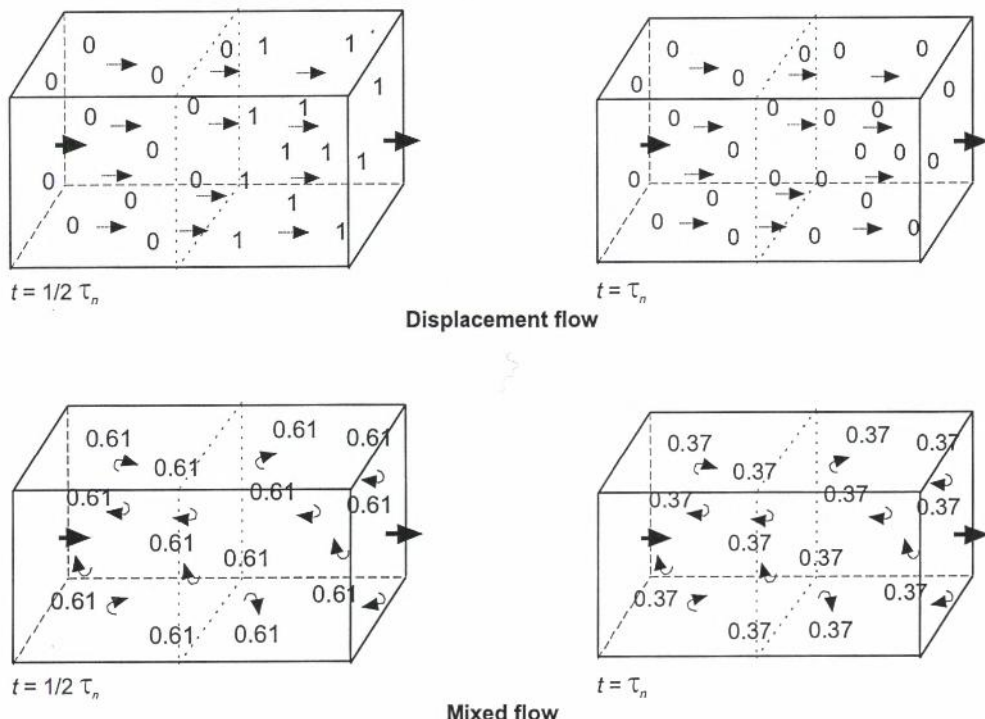

Figure 8. Concentration step-responses at $t = \frac{1}{2}\ \tau_n$ and $t = \tau_n$ for ideal displacement and mixing flows. With displacement flow the room is here divided into two age-of-air regions ($\bar{\tau}_p < 0.5\ \tau_n$ and $\bar{\tau}_p > 0.5\ \tau_n$). Notes. τ_n—nominal time constant, $\bar{\tau}_p$—local mean age.

The displacement flow system gives a zero concentration of contaminants within a nominal time constant, $t = \tau_n$. In the mixed-flow system, 37% of the initial concentration remains after the same time (Holmberg, 1992). The remaining contaminants decrease to a level of about 2% at $t = 4\ t_n$.

4.2. Concentration Tails

With ideal displacement flow, there is a sudden change in concentration when the fresh air front passes through the room during the nominal time constant, τ_n. By contrast, mixed flows have a long concentration tail. This must be considered when choosing the cut-off point in experimental investigations. Even small concentrations

remaining in a room have a considerable influence on the mean age of air in the room.

Equation 1 gives local mean ages of air in a room. The mean age of air in the entire room is calculated from

$$<\bar{\tau}> = \int_0^{t_{CUT\text{-}OFF}} t \cdot I(t)dt \tag{5}$$

where $I(t)$ is the internal age distribution (Levenspiel, 1962).

From Equation 5, the mean age of air in a tracer-gas concentration decay system can be written as

$$<\bar{\tau}> = \frac{\int_0^{i\tau_n} t \cdot c_e(t)dt}{\int_0^{i\tau_n} c_e(t)dt} \tag{6}$$

where $i—t_{CUT\text{-}OFF}/\tau_n$.

The exhaust concentration at time t in a mixed-flow system is

$$c_e(t) = c_0 \exp(-t/\tau_n) \tag{7}$$

Substituting Equation 7 into 6 and partially integrating (Tang & Holmberg, 1992) gives

$$<\bar{\tau}> = \frac{1 - e^{-i}(i+1)}{1 - e^{-i}} \tau_n \tag{8}$$

If the cut-off time is set to 4 τ_n, that is, $i = 4$, the mean age of air for ideal mixing flows becomes

$$<\bar{\tau}> = 0.925 \ \tau_n \tag{9}$$

This means that if 2% of a contaminant remains, the value of the mean age of air in the room will be influenced (increased) by 7.5%. The concentration decay must be measured or carefully estimated for a time period of approximately eight nominal time constants to eliminate errors when predicting the mean age of air in the room (Figure 9).

The area under the concentration curve can be written approximately as

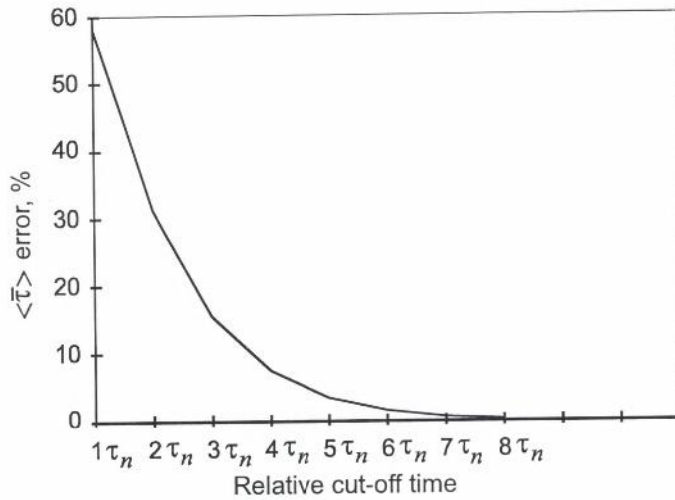$$\int_0^{t_{CUT\text{-}OFF}} c_e(t)dt \approx c_0\tau_n \tag{10}$$

Figure 9. Residual tracer-gas concentrations significantly influence measured age-of-air values in a room. A measurement period of at least 8 τ_n is needed for a good prediction of the age of air. *Notes.* τ_n—nominal time constant.

If expression 10 is not valid, short-circuiting or leakage is likely. With the former, tracer-gas remains in the room and locally concentrations are too high; with the latter, tracer-gas has leaked out and concentrations are too low.

5. CONCLUSIONS

Effective ventilation is not just a matter of forcing air volumes into a room. For good air quality, thermal comfort, and economy, good air distribution is essential. Recent research shows that the air flow through a room should be well organized, well spread, and that the incoming velocity should be even with a low turbulence intensity (Holmberg et al., 1994). Such a ventilation flow structure will also remove solid airborne particles from the occupied zone (Kulmala, 1995).

This paper shows the possibilities and difficulties in achieving optimal ventilation flow conditions. Methods are given for achieving a well-organized air flow. Difficulties arise in the form of flow disturbances when the theory is applied to different room ventilation situations. Turbulent fluctuations, thermal gradients, and sudden expansions of the air flow can cause unwanted disturbances. Unsuitable diffuser performance can increase room mixing and decrease the air change efficiency. Future research should be aimed at finding ventilation designs that are effective and practical.

LIST OF SYMBOLS

c concentration (g/m^3)
d (maximum) diffuser diameter (m)

i	$t_{CUT\text{-}OFF}/\tau_n$
I	internal (room) age distribution
k	turbulent kinetic energy (J/kg)
L	room length (m)
q	flow rate (m^3/s)
t	time (s)
$t_{CUT\text{-}OFF}$	integration (measurement) cut-off point (s)
u_i	mean velocity component in x, y, z directions (m/s)
V	room volume (m^3)
x, y, z	coordinates

Greek symbols

Γ_c	concentration diffusivity (m^2/s)
$\in$	turbulent energy dissipation rate (W/kg)
$\in_a$	air change efficiency; $\dfrac{\tau_n}{2<\bar{\tau}>}\,100\%$
ρ	density (kg/m^3)
τ_n	nominal time constant; V/q (s)
$\bar{\tau}_p$	local mean age (s)
$<\bar{\tau}>$	mean age of air in the room (s)

Subscripts

0	start
e	exhaust
p	point

REFERENCES

Davidson, L., & Olsson, E. (1987). Calculation of age and local purging flow rate in rooms. *Building and Environment, 22*(2), 111–127.

Holmberg, S. (1992). Mean age of room air $<\bar{\tau}>$ for ideal and non-ideal flow patterns. In *Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness* (pp. 173–176). Tokyo. Republished by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE; Publication No. 90363, 1993), Atlanta, GA: ASHRAE, 173–176.

Holmberg, S., Paprocki, A., & Tang, Y-Q. (1994). Diffusers for horizontal air flow. In *Proceedings, Roomvent '94, Air Distribution in Rooms, 4th International Conference in Kraków, Poland* (Vol. 2, pp. 230–241). Gliwice, Poland: Department of Heating Ventilation and Dust Removal Technology, Silesian Technical University.

Holmberg, S., & Tang, Y-Q. (1992). Radial spread of supply air and horizontal displacement ventilation. In *Proceedings, Roomvent '92, Air Distribution in Rooms, 3rd International Conference in Aalborg, Denmark* (Vol. 3, pp. 89–99). Lyngby, Denmark: Danish Association of Heating, Ventilation and Air-Conditioning Engineers (DANVAC).

Jones, W.P., & Launder, B.E. (1972). The prediction of laminarization with a two-equation model of turbulence. *International Journal of Heat and Mass Transfer, 15*, 301–314.

Kulmala, I. (1995). Numerical simulation of the capture efficiency of an unflanged rectangular exhaust opening in a coaxial air flow. *Annals of Occupational Hygiene, 39*(1), 21–31.

Levenspiel, O. (1962). *Chemical Reaction Engineering.* New York: Wiley.

Mierzwinski, S., Nawrocki, W., & Trzeciakiewicz, Z. (1994). Air exchange efficiency under displacement ventilation conditions. In *Proceedings, Roomvent '94, Air Distribution in Rooms, 4th International Conference in Kraków, Poland* (Vol. 2, pp. 103–112). Gliwice, Poland: Department of Heating Ventilation and Dust Removal Technology, Silesian Technical University.

Sandberg, M. (1987). What is ventilation efficiency? *Building and Environment, 16*(2), 123–135.

Sandberg, M. (1992). Ventilation effectiveness and purging flow rate—A review. In *Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness* (pp. 1–21). Tokyo.

Sandberg, M., & Sjöberg, M. (1983). The use of moments for assessing air quality in ventilated rooms. *Building and Environment, 18*(4), 181–197.

Tang, Y-Q., & Holmberg, S. (1992). *An experimental investigation of a horizontal displacement ventilation system* (Undersökningsrapport [Investigation report] 1992:2). Solna, Sweden: National Institute of Occupational Health.