EFFECTIVE VENTILATING SYSTEMS
Characterization and Design Implications

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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 effectiveness 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).

Ventilation Effectiveness and Design rules

Air Exchange Efficiency and Ventilation Effectiveness

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. The definitions are demonstrated in fig. 1, 2 and 3, plug- or piston flow and general turbulent flow conditions (air and contaminants), respectively.

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

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

F(t) is the cumulative fraction of air having age less than or equal to t. Using tracergas or measureing the contaminants:

$$F(t) = C(t)/C(\infty) \quad ; \text{ step-up} \qquad (2)$$
$$F(t) = 1 - C(t)/C(0) \quad ; \text{ step-down}$$

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

$\bar{\eta}_a = \frac{\tau_n}{2\langle\bar{\tau}_i\rangle} = 1$

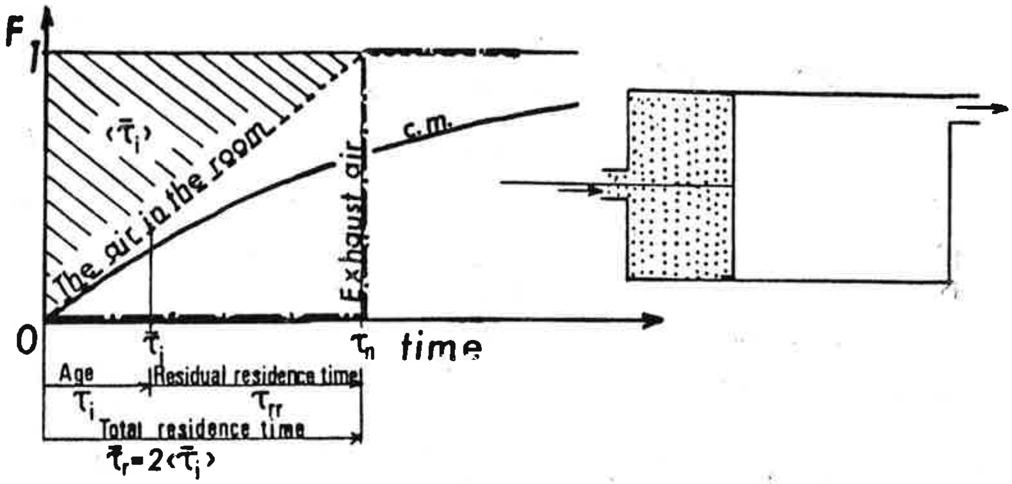


Fig. 1. Parallell plug-flow showing the use of the age concept.

$$\bar{\tau} = \int_0^{\infty} F'(t)t\,dt = \int_0^{\infty}(1 - F(t))\,dt \qquad (3)$$

The time-maan age is the area between F=1 and the F(t)-curve, called the "area above" the curve. Generally, $F_i(t)$ is constructed from the $F_e(t)$-curve in the following way:

$$\langle\bar{F}_i(t)\rangle = S(t)/S(\infty)$$
$$S(t) = \int_0^{t}(1 - F_e(t))\,dt \qquad (4)$$

⟨ ⟩ is the symbol for space average.
Subscript i = internal
Subscript e = exhaust

$$\langle\bar{\tau}_r\rangle = 2\langle\bar{\tau}_i\rangle \qquad (5)$$

$\bar{\eta}_a = \frac{\tau_n}{2\langle\bar{\tau}_i\rangle} = .5 - 1$

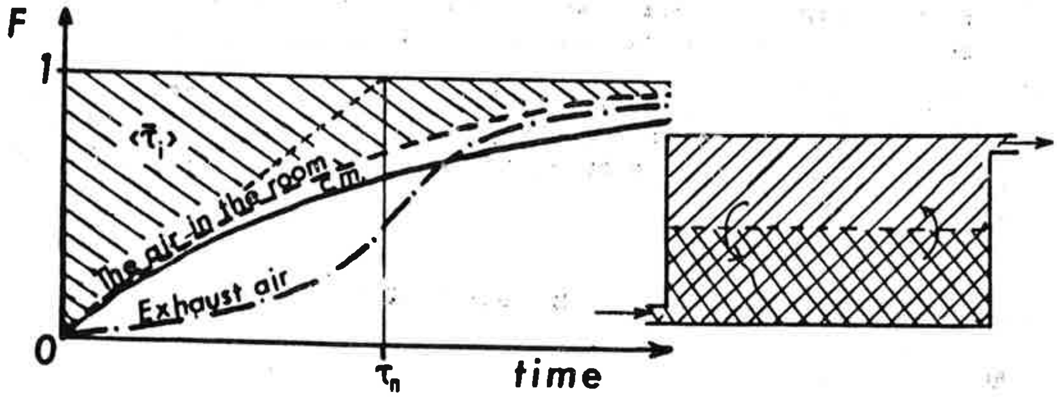


Fig. 2. Turbulent flow in a ventilated room showing the general use of the age concept.

$\bar{\eta}_a$ = Average air exchange efficiency

$$\bar{\eta}_a = \frac{1/\langle\bar{\tau}_r\rangle}{1/\ \tau_n} = \frac{\tau_n}{2\langle\bar{\tau}_i\rangle}\ 100\ (\%) \qquad (6)$$

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

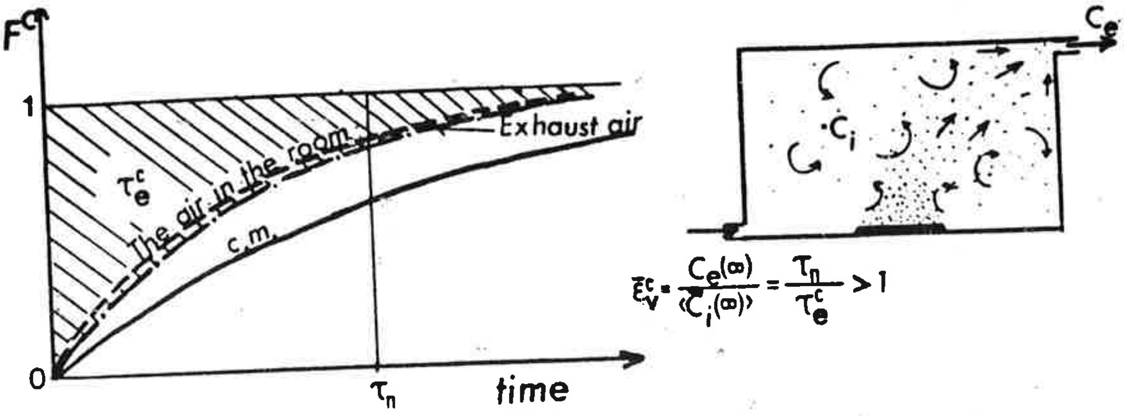


Fig. 3. Flow-pattern of contaminants in a ventilated room showing the use of the age concept.

For the contaminant flow:

$$\langle \bar{C}_i(\infty)\rangle V = \tau_e^c \dot{V}_c \qquad (7)$$

Where: $\dot{V}_c$ = contaminant production rate (nm^3/s) .

$$\bar{\varepsilon}_e^c = \frac{\tau_n}{\tau_e^c} = \frac{C_e(\infty)}{\langle \bar{C}_i(\infty)\rangle} \quad \text{= Average ventilation effectiveness} \qquad (8)$$

Super- and subscript c denotes contaminant flow.

Design Rules

Rule no. 1 for designing effective ventilating systems is defined to design for air exchange efficiencies above 50% and for local age in the breathing zone less than the average age.

Rule no. 2 for effective ventilating system design is defined to design for ε_v^c greater than 1 and for lower concentrations of contaminants in the zone of occupation than the room average, fig. 3.

Note that 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.

Design Implications

General

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. Practical experience has shown that this requires a piston velocity from .25 m/s and up. The principle is therefore air consuming and of high cost. Areas of of application of this principle is clean rooms in hospitals, electronic and space craft industry etc. Further discussion of this technique is left out here because the design principles should be fairly well known.

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.

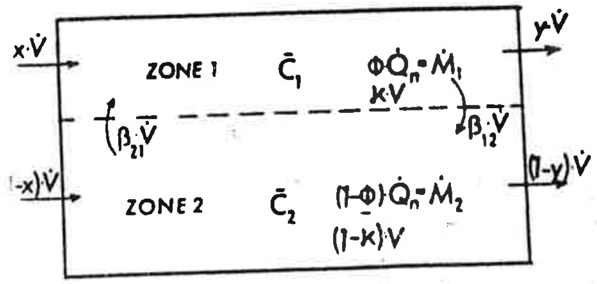
In applying vertical up displacement the air is filling the room from below due to gravity and "older" air is displaced upwards. Any heat source in the zone of occupation creates convective currents and contributes to carrying the air to the upper zone. In this way a temperature stratification will be 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.

To maintain the best stratification effect, all convective plumes should be feeded by the supplied "new" air to a height equal to the height of the zone of occupation. Conditions impairing the air exchange efficiency and the ventilation effectiveness are downward convective currents along surfaces that are colder than the air in the room. Underfeeding of the upward currents causes the same effect. Downdraught from the upper zone reduces the effectiveness and, at the same time, the necessary requirement of ventilation air to keep a certain stratification height. The ventilation effectiveness is at its highest when all plumes carrying contaminants are flowing directly to the axhaust.

In applying vertical-down displacement direction it is important to bear in mind that this principle has to overcome all covective currents from heat sources. The principle is advantages only when the main contaminant sources are danser than the room air, are located mainly below the breathing zone and there is a minor effect from heat sources in carrying the contaminants upwards. If the principle works as it should and there is little contaminant production in the upper zone the breathing zone should be designed to be in the upper zone.

Calculation procedures

Two-zone model. 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 recerculation 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.



$$\bar{C}_1 = K_1 e^{n\alpha_1 t} + K_2 e^{n\alpha_2 t} + \bar{C}_1^s \qquad \bar{C}_1^s = \frac{a_{10}a_{22} - a_{20}a_{12}}{a_{12}a_{21} - a_{11}a_{22}}$$

$$\bar{C}_2 = K_1\,{}^1k_2 e^{n\alpha_1 t} + K_2\,{}^2k_2 e^{n\alpha_2 t} + \bar{C}_2^s \qquad \bar{C}_2^s = \frac{a_{20}a_{11} - a_{10}a_{21}}{a_{12}a_{21} - a_{11}a_{22}}$$

$$\alpha_1 = \frac{1}{2n}\left((a_{11} + a_{22}) + \sqrt{(a_{11} - a_{22})^2 + 4a_{12}a_{21}}\right) \qquad {}^1k_2 = \frac{n\alpha_1 - a_{11}}{a_{12}}$$

$$\alpha_2 = \frac{1}{2n}\left((a_{11} + a_{22}) - \sqrt{(a_{11} - a_{22})^2 + 4a_{12}a_{21}}\right) \qquad {}^2k_2 = \frac{n\alpha_2 - a_{11}}{a_{12}}$$

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

Superscript s= steady state

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

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

$$d\bar{C}_1/dt = a_{10} + a_{11}\bar{C}_1 + a_{12}\bar{C}_2 \qquad (9)$$

$$d\bar{C}_2/dt = a_{20} + a_{21}\bar{C}_1 + a_{22}\bar{C}_2$$

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

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

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

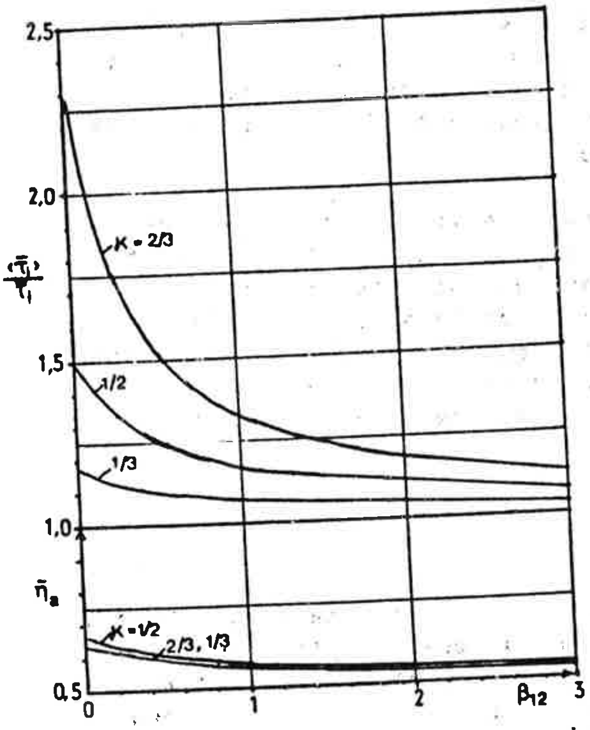


Fig. 5. Two-zone model. Curves showing the air exchange efficiency. $x = 0$; $y = 1$.

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_n. The air exchange efficiency 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. The ventilation effectiveness and the ratio between average and local concentrations (local means the zone of of occupation, in general zone 2) are given in fig. 6 as a function of β_{12} for different values of κ and ϕ. These figures show the importance of determining the air exchange between the zones, as well as the size of the zones and the load distribution. One main task for the designer is consequently, in addition to determine the load

$\dot{Q}_n$, to determine β_{12}, κ and ϕ. According to what is previously mentioned, this problem mainly consists of determining the convective currents and the source characteristics.

Convective flows. Relevant formulas for calculation of flow rates in convective currents are, for the purpose of evaluating β_{12} and stratification heights, the following:

Point heat sources, normal temperatures:

$$\dot{V}_k = 0{,}05\ Q_k^{1/3}(x + x_p)^{5/3} \qquad (m^3/s) \qquad (10)$$

Line heat sources, normal temperatures:

$$\dot{V}_k = 0{,}14\ \dot{q}_k^{1/3}(x + x_p) \quad (m^3/s \text{ og m source length}) \qquad (11)$$

Convective currents along cooled/heated surfaces, normal temperatures:

$$\dot{V}_k = 0{,}011\ (g\ \Delta T_f/T)^{0,4}\ x^{1,2} \quad (m^3/s \text{ og m width}) \qquad (12)$$

Q_k = convective heat output (kW)
$\dot{q}_k$ = convective heat output (kW/m)
x = vertical distance from source (m)
x_p = vertical distance to virtual line or point origin (m)
g = acceleration due to gravity (9,81 m/s^2)
T = temperature (K)
ΔT_f = difference in temperature between air and surface (K)

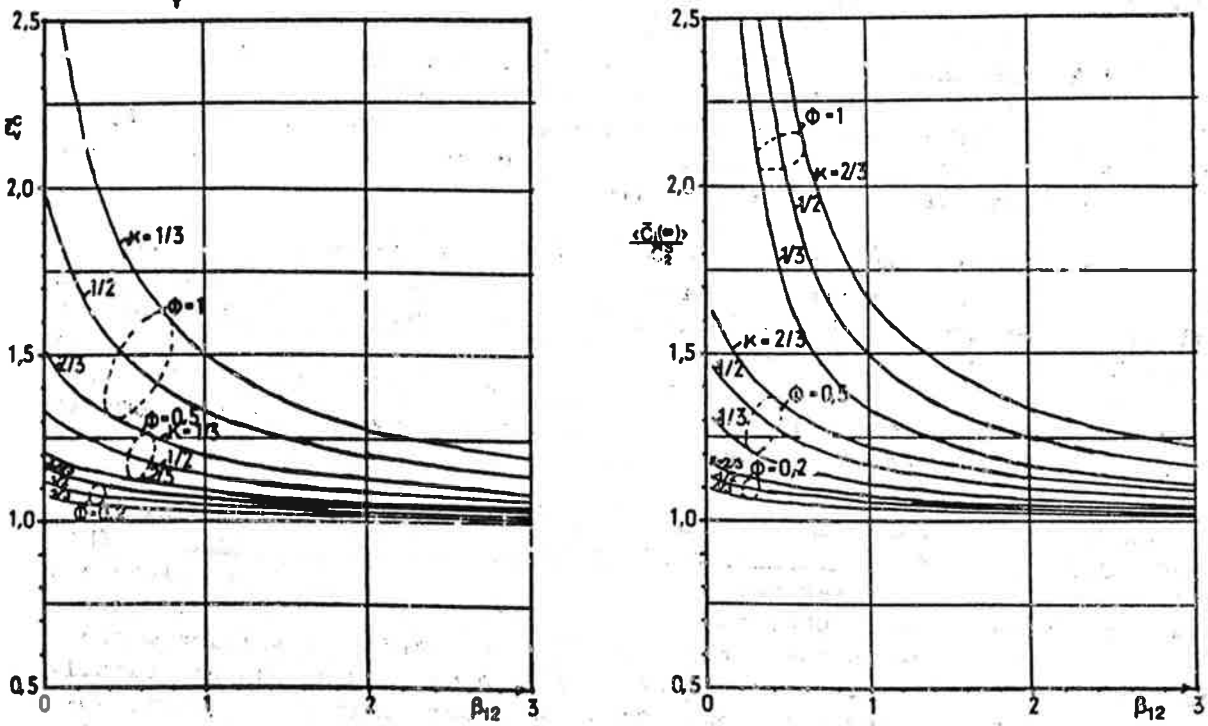


Fig. 6. Two-zone model. Curves showing the ventilation effectiveness. Average and local performance. $x = 0$; $y = 1$.

In addition to convective currents come momentum fluxes from contaminant sources (which may be identical to convective currents, like persons, hot industrial processes etc.), or normal air jets, (leakage from a pressurized vessel).

Coming to the evaluation of ϕ, several conditions have to be considered. One main thing is to locate the zone where the contaminants are actually spread. This may not be the zone where they are produced. A few good examples to be mentioned here are contaminants carried in convective plumes above persons, processes (welding plumes etc.), or carried upwards in jets caused by the contamination source. In these cases most of the contaminants are carried to the upper zone and hence ϕ approaches 1.

The most difficult situation, evaluating ϕ, is in cases where the contaminants are emitted scattered or the sources cannot be properly defined, like for instance radon, formaldehyde or other type of outgasing from building materials. In many of these cases ϕ may be set to 0.5. Neutral emission in the zone of occupation of contaminants having a weak buoyancy or even a negative one, may result in ϕ approaching zero. In some cases, however, the ventilation air currents, properly designed, may carry the contaminants rather direct to the upper zone, resulting in ϕ approaching 1. The process lay-out may considerably influence on the outcome.

Weak or negative contaminant buoyancy, where also the thermal conditions in the room are taken into account, are situations where vertical down displacement should be utilized. Properly designed the zone of occupation, i.e. the breathing zone, may then be located in the upper zone.

Methods of Air Supply

Through a porous floor. This is the best way with respect to aerodynamics and comfort. Supply-air velocities are very low. And the displacement effect is at its best. The method is in most cases prohibited of either practical or economic reasons.

A jet-type supply through nozzles, slots or grilles in the floor. These methods are easy to design and apply. Common air-jet theory applies. An important criterion is that the vertical throw (penetration height) should be no higher than the height of the zone of occupation. Note that the jets will daccelerate due to gravity.

A necessity is that the jet zone is defined as being outside the zone of occupation. In some cases, however, the jet zone may be used as local cooling air-douches. The temperature gradients outside the jet-zone are generally small and favour comfort. The method causes intense mixing turbulence and may, depending on the strength and stability of stratification, impair the ventilation effectiveness,including the heat removal effectiveness with regard to surplus heat.

Diffuse air supply through diffusers at floor level with horisontal direction of out-flow, at the walls or other convenient locations. The outlet part of the diffuser may either be a porous plate like a filter mat or a perforated plate. A characteristic feature with this method is that the negative buoyancy in the outflow cuses a downward acceleration which increases the air velocities at floor level and may cause draught. Usually the supply velocity should be lower than the upper limit for comfort. Another feature is a vertical temperature gradient that may be unfavourable.

If the convective plumes above the heat sources is dumped in the upper zone the temperature gradients in the zone of occupation would be small. In the close proximity of the floor there may be a wedge of cooler air, depending on the cooling load imposed by the system. Using perforated plates evens out this wedge. The same effect is obtained, entraining large quantyties of room air (8), applying special mixing and/or induction devices. In addition, such devices also straightens out the temperature gradient in the zone of occupation. The last effects improves comfort but unfortunately, it also generally impaires the system performance. The reason for this is inreased turbulence, also increasing the intrainment from the upper zone.

Performance documentation of air diffusion devices should contain the following information as a function of size and flow rate:

- Max. velocity in the near zone of the diffuser as a function of the temperature difference between the supply air and the air temperature 1,1 m above floor level.

- The size of the near zone including isovel envelope.

- The relative temperature increase in the near zone.

- Pressure drop and noise generation data.

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SUMMARY

E. Skåret: Effective ventilating systems. 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. The design procedure shall, among other things, contain a contaminant source analyses in order to design the ventilating system to create the most favourable flow pattern for the contaminants. The paper deals with design principles and problems related to displacement ventilating systems.

RESUME

E. Skåret: Systèmes effectifs de ventilation. De grands travaux au sujet de l'effectivité de ventilation ont été poursuivit en Norvège et en Suède, se servant de techniques de gazs traceurs, basé sur des concept fondamentaux de la physique et des mathematiques. Les resultats de recherche actuels, nous donnent la nature et le moyen de caracteriser, à l'aide de techniques à gazs traceurs, le courant d'air de ventilation, voire des contaminants, à travers une chambre ventilé. Le courant de déplacement à été prouvé être le meilleur principe de courant dans le domaine de la ventilation, de plus que le courant d'air le ventilation généralement doit être apporté aux zones d'occupation. Le procédé de planification doit, entre autre, comporter une analyse de la source contaminante afin de pouvoir planifier le système de ventilation pour ainsi créer la formé de courant la plus favorable aux contaminants. Ce travaille aborde les principes de planification ainsi que les problèmes dans les systèmes de ventilations à deplacement.

KURZFASSUNG

E. Skåret: Effektive Ventilationssysteme. Reichliche Arbeit auf dem Gebiet der Ventilationseffektivität wurde in Norwegen sowie in Schweden mit hilfe von Gaz "tracer" Technik die auf den grundlegenden Konzepte geleistet der Physik und Mathematik beruhen, durchgeführt. Der jetzige Stand Forschung ist das wir, mit der Hilfe der Gaz "tracer" Technik, die Natur und die Karakteristik der Strömung von Ventilationsluft b.z.w. der Verunreinigungen durch einen Raum bestimmen können. Es ist bewiesen worden das Verdrengungsventilation das beste Strömungsprinzip bezogen auf Ventilation ist, besonderes dass die Ventilationsluft allgemein an besetzten Zonen zugeführt wërden soll. Der Auswurfsvorgang wird unter anderem, eine Analyse der Verunreinigungsquellen enthälten, die ein Ventilationssystemauswurf der die meist vorteilhafte Strömungsbilder des Verunreinigungen erzeugt, schaffen kann. Diese Arbeit behandelt auswurfsprinzipe und Probleme die mit dem Verdrengungsventilationssystem verbunden sind.