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THE AIR EXCHANGE EFFICIENCY OF THE DESK DISPLACEMENT VENTILATION CONCEPT

THEORY, MEASUREMENTS AND SIMULATIONS

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ABSTRACT

The concept of *air exchange efficiency* of ventilation, a quantity entirely determined by the spatial distribution of the local mean age of air, is discussed. A divergence-type conservation equation for the local mean age of air is derived. This equation is solved numerically for a room ventilated by the desk displacement ventilation concept, using a CFD-routine. The CFD-calculated mean-age-of-air pattern is compared with mean age results from tracer experiments in a corresponding laboratory configuration. It is found that the air exchange efficiency of the air flow pattern induced by the desk displacement unit is only slightly above 0.5, the value for perfect mixing ventilation, for cooling situations.

KEYWORDS

Air exchange efficiency, displacement ventilation, CFD-methods, tracer gas experiments.

INTRODUCTION

Two major purposes of ventilation are (a) removal of internally produced contaminants and (b) supply of fresh air. This paper deals with the second purpose only. The *Air Exchange Efficiency* is a dimensionless number expressing the effectiveness of renewal of the internal air population by the supply air.

The *desk displacement ventilation concept* is described in Loomans et.al. (1996). Any displacement ventilation system using low-velocity supply air diffusers is expected to create a stratified flow pattern showing pronounced spatial differences in local mean age of air, the air in the breathing zone having relatively low age. If the air in the breathing zone is relatively young, it is less likely to find relatively high contaminant concentration levels in this zone.

The purpose of this study is to investigate whether the desk displacement ventilation system indeed induces a room air flow pattern characterized by (1) pronounced spatial gradients in the local mean age of air and (2) a relatively low mean age in the heat source plume region. This investigation is made for one particular room geometry, for two values of the internal heat load and two supply air flow rate values.

THE AGE CONCEPT

The concepts of *age* and of *air populations* are extensively described in Sandberg and Sjöberg (1983). Some useful expressions to be used in the derivation of a conservation equation for the local mean age are repeated here for convenience: the *mean age* of an air population is defined as the *first moment* of the *age frequency distribution function* $\phi(\tau)$ of the population under consideration:

$$\bar{\tau} \equiv \int_0^\infty \tau \phi(\tau) d\tau , \qquad (1)$$

which can also be written as:

$$\bar{\tau} \equiv \int_0^\infty [1 - \Phi(\tau)] d\tau . \qquad (1a)$$

where $\Phi(\tau)$ denotes the *cumulative age distribution function* of the population under consideration. $\Phi(\tau)$ is the *dimensionless fraction* of air having age lower than τ in the air population under consideration. The age frequency distribution function $\phi(\tau)$ is the first derivative of $\Phi(\tau)$. If in (1a) $\Phi(\tau)$ is the cumulative age distribution function of the *total internal air population*, $\bar{\tau}$ denotes the mean age of all the air in the room under consideration. If in (1a) $\Phi(\tau)$ is the cumulative age distribution function of the *external air population*, $\bar{\tau}$ denotes the mean age of the air leaving the room, i.e., the local mean age of the air at the exhaust.

CONSERVATION EQUATION FOR LOCAL MEAN AGE OF AIR

It is straightforwardly possible to derive a conservation equation (balance equation) for the *local mean age of the air*. To obtain it, a conservation equation for the *local dimensionless fraction* of air having age higher than a certain value τ must first be formulated. This dimensionless fraction will be called the *older air fraction* for short. At any position $\underline{r}$ and time t, the fraction of air having age > τ is just the *complementary local cumulative age distribution function,* $1 - \Phi(\underline{r};\ \tau;\ t)$. To shorten notation, the arguments $\underline{r}$ and t will be omitted for all quantities under consideration.

The conservation equation for the quantity $1 - \Phi(\tau)$ states: The sum of the *local time derivative* of the fraction of older air, $1 - \Phi(\tau)$, and the *divergence of the local flow density* of the older air fraction in the flow field, is equal to the local *source term* of "older" air. In formula:

$$\frac{\partial(1-\Phi(\tau))}{\partial t} + \nabla \cdot \underline{j}_{(age>\tau)} = \phi(\tau), \qquad (2)$$

where

$$\underline{j}_{(age>\tau)} = \underline{u}[1-\Phi(\tau)] - D\nabla[1-\Phi(\tau)] \qquad (3)$$

denotes the sum of the *convective* and *diffusive* local flow densities of the older air fraction, i.e., of air having age > τ. The quantity $\underline{u}$ is the air velocity, whereas D denotes the effective (turbulent) diffusion coefficient. The source term in expression (2), i.e., the right hand side of (2) is the fraction of air whose age *surpasses* τ per unit of time, and this fraction is just the age frequency distribution function $\phi(\tau)$. Combining (2) and (3) one obtains:

$$\frac{\partial(1-\Phi(\tau))}{\partial t} + \nabla \cdot [\underline{u}(1-\Phi(\tau))] + \nabla \cdot [-D\nabla(1-\Phi(\tau))] = \phi(\tau) \qquad (4)$$

showing that the left hand side of the balance equation is a complicated differential operator working on the older air fraction $1 - \Phi(\tau)$. The mathematical structure of (4) is the usual one for a transport equation. As the differential operator in (4) only contains derivatives with respect to time t and spatial coordinates (∇ is the gradient operator), one obtains, on integrating the entire equation (4) over τ from 0 to ∞ and using (1a), the differential equation:

$$\frac{\partial\bar{\tau}}{\partial t} + \nabla \cdot [\underline{u}\bar{\tau} - D\nabla\bar{\tau}] = 1, \qquad (5)$$

which is the required transport equation for the local mean age of the air $\bar{\tau}$. In a stationary air flow pattern, all time derivatives vanish and (5) reduces to

$$\nabla \cdot [\underline{u}\bar{\tau} - D\nabla\bar{\tau}] = 1, \qquad (6)$$

an expression earlier obtained by Sandberg (1981) in a very different way. As the transport equation for the local mean age $\bar{\tau}$ has the usual *divergence* form, it can be relatively easily added to Computational Fluid Dynamics routines.

CFD SOLUTION OF LOCAL MEAN AGE

There are in principle two ways to solve the local mean age transport equation (3) or (4) numerically using existing Computational Fluid Dynamics routines. The first one, only applying to CFD routines of which a source code is available, consists of writing a subroutine for $\bar{\tau}$ analogous to subroutines for e.g. velocity components, turbulence quantities or contaminant concentrations, which are already part of the CFD program. The second one, also applicable if no source code is available, is to use the conservation equation for contaminant concentration, which reads, for stationary flow patterns:

$$\nabla \cdot \left[\underline{u}C - D\nabla C\right] = \dot{\mu}(\underline{r}) \qquad (7)$$

where C = C($\underline{r}$) is the local contaminant concentration at coordinate $\underline{r}$ and $\dot{\mu}(\underline{r})$ is the local contaminant emission density at $\underline{r}$, i.e., the amount of contaminant generated per volume unit and per time unit. Now consider a situation of spatially homogeneous time-independent internal contaminant emission in the flow pattern, i.e., $\dot{\mu}$ is a constant independent of coordinate $\underline{r}$ and time *t*. In this situation, equation (7) can be divided by $\dot{\mu}$ to obtain

$$\nabla \cdot \left[\underline{u}\frac{C}{\dot{\mu}} - D\nabla\frac{C}{\dot{\mu}}\right] = 1, \qquad (8)$$

which, on comparing it with (6), suggests the identification

$$\bar{\tau} = \frac{C}{\dot{\mu}}. \qquad (9)$$

The identification (9) is only valid however if not only the differential equations (6) and (8) are identical but also the *boundary conditions* to $\bar{\tau}$ and $C/\dot{\mu}$ correspond. This implies that at the air supplies the contaminant concentration (like the local mean age) should be put to zero.

To summarize, the contaminant concentration transport equation can be used to calculate the spatial distribution of the local mean age of the air if (a) the contaminant emission density $\dot{\mu}$ is taken spatially homogeneous and (b) zero contaminant concentration is put as a boundary condition at the air supplies. The local mean age pattern is then the contaminant concentration pattern scaled with $\dot{\mu}$.

THE AIR EXCHANGE EFFICIENCY

The *Air Exchange Efficiency* is a dimensionless number indicating how effectively the internal air population is continuously renewed by the supply air flow. It is defined as

$$\varepsilon_a \equiv \frac{\tau_n}{2\bar{\tau}} \qquad (10)$$

indicating that it is inversely proportional to the mean age $\bar{\tau}$ of the total internal air population. The air exchange efficiency is maximized if $\bar{\tau}$ is minimized. This is the case if the exhaust air flow consists of exactly the oldest air in the internal air population. This is valid for a *perfect displacement flow* (a flow type impossible in practice as it implies zero diffusion). The quantity τ_n in the numerator of (10) is the *nominal time constant.* It is the reciprocal of the air change rate, and equals $V/\dot{V}$, where *V* is the room volume and $\dot{V}$ is the supply air flow rate. One can straightforwardly derive that $\bar{\tau}$ = 0.5 τ_n for a perfect displacement flow, resulting in an air exchange efficiency of 1. In a *perfect mixing flow* (characterized by a spatially homogeneous distribution of the local age spectrum of the air) $\bar{\tau}$ = τ_n, so the air exchange efficiency is 0.5 .

In an actual displacement ventilation flow pattern, the air is neither rigidly displaced nor perfectly mixed. In a properly functioning displacement ventilation, the air flow pattern is stratified, showing a layer of relatively young and clean air under a layer of relatively old and contaminated air. It is therefore expected that actual displacement flow patterns have air exchange efficiency values between 0.5 and 1.0, because the volume average mean age of the air $\bar{\tau}$ is expected to be lower than the nominal time constant τ_n , due to expected large vertical gradients in the local mean age-of-air.

THE DESK DISPLACEMENT VENTILATION CONCEPT

The desk displacement ventilation concept was developed in an attempt to combine the advantages of displacement ventilation and individual local climate control. It introduces the supply air below the desk, applying the rules set by the displacement ventilation principle: introduction of air over a relatively large area at low impulse.

EXPERIMENTAL SETUP

The spatial distribution of the local mean age of the air (which determines the air exchange efficiency) is investigated for a desk displacement ventilation geometry schematically depicted in Figure 1.

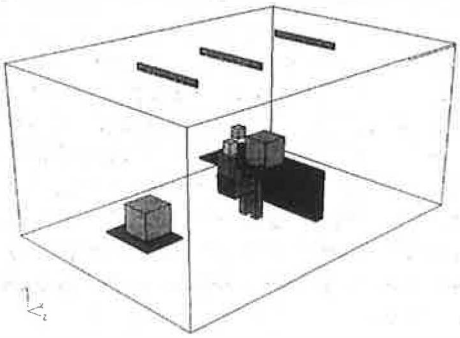

Figure 1 Experimental geometry

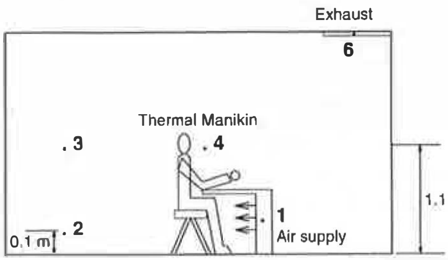

Figure 2 Location of test points

This investigation is conducted by *step-response* tracer gas experiments in the test room, as well as numerically, using a CFD code. The location of points where tracer gas step-response curves are recorded is indicated in Figure 2.

Technical data of climate room

The dimensions of the climate test room are 5.16×3.60×2.50 m^3. A displacement unit is positioned centrally in the room. The dimensions of the perforated air supply grid are 1.0 m (width) and 0.3 m (height). The displacement unit is situated directly below a desk having dimensions 1.7 m (width), 0.75 m (height) and 0.9 m (length). A thermal manikin producing a heat load of 125 W is situated behind the desk on a chair. Technical data about the manikin and additional heat sources are summarized by Loomans and Rutten (1997) and Loomans (1998), respectively.

Coordinates of test points.

Test point 1 is located at the air supply grid, whereas test points 2 and 3 are mounted behind the manikin at heights of 0.1 m and 1.1 m, respectively. Test point 4 is mounted near the head of the manikin. Not indicated in Figure 2 is test point 5, which is located at the supply air intake outside the test room, and is used to measure the background CO_2-concentration in the ambient air. The coordinates of the test points are summarized in Table 1.

In Table 1, y is the vertical coordinate, x is the horizontal coordinate parallel to the figure, and z is the horizontal coordinate perpendicular to Figure 2. The

Table 1 Coordinates of test points.

Test point	x [m]	y [m]	z [m]
2	0.54	0.1	1.8
3	0.57	1.1	1.8
4	2.48	1.1	1.8
6	4.66	2.485	3.6

origin of the coordinate system is at one of the lower corners of the test room.

Technical aspects of tracer gas experiments.

In this case study, *step-up* and *step-down* experiments were undertaken. Carbon dioxide, CO_2, was used as tracer gas by supplying an *excess* amount of CO_2 to the supply air, which was significantly higher than the usual *background* CO_2-concentration in the ambient air. Usually, the supplied excess CO_2-concentration was around 2000 *ppm*. To obtain a constant CO_2-flow rate to the supply air duct, a mass flow controller was used. An automatic gas sampler/monitor was used to take air samples at the test points and determine their CO_2-concentration.

Obtaining mean age values from step response curves.

A numerical integration algorithm was written to calculate local mean age values from tracer gas concentration response curves. In a step-up (step-down) experiment, the tracer gas concentration response curve, normalized by dividing the CO_2-concentration values by the step height, is just the *local (complementary) cumulative age distribution function* at the test point under consideration, appearing in (1a). To evaluate (1a) numerically, a trapezium rule - based routine was written . The integration algorithm is constructed such as to correct for slow variations in the background CO_2-concentration recorded at test point 5.

RESULTS OF EXPERIMENTS

A set of combined step-up / step-down tracer experiments was conducted for the desk displacement ventilation geometry depicted in Figure 1. The input parameters which were varied within the set of experiments are the *air change rate per hour* (ACH) and the *total internal heat load* (*Q*). The air supply temperature, ΔT, is defined as the temperature difference

Table 2 Summary of cases analyzed.

case	heat input [W]	air change rate [h^{-1}]	T_{inlet}-T_{wall} [°C]
1	125	1	-3.0
2	150	1	-2.5
3	500	2	-2.5
4	500	2	-3.0

Table 3 Experimentally obtained mean age-of-air values (in minutes) at test points.

	Test point			
Case	2	3	4	6
1	6 ± 2		13 ± 3	27 ± 3
2	8 ± 2	75 ± 5	34 ± 6	66 ± 4
3	14 ± 3	72 ± 5	47 ± 5	71 ± 5
4	7 ± 2	27 ± 3	14 ± 3	29 ± 2

between the supply air flow and the (climatized) room walls. The following four cases were analyzed, see Table 2.

For these cases, 2 or 3 combined step-up / step-down tracer experiments were conducted. Local mean age-of-air values were calculated based on *excess tracer concentration* response curves (corrected for background fluctuations in tracer concentration). It was observed that at test point 2, step-down response data were not reliable, showing unrealistically high mean age values. Step-up data at test point 2, and all data at test points 3,4, and 6, were of considerable reproduceability. Local mean age-of-air values at the test points for the 4 cases of Table 2 are tabulated in Table 3. The estimated accuracy of the local mean age values is also indicated in Table 3.

RESULTS OF CFD CALCULATIONS

The CFD code FLUENT/UNS (Fluent 1996) is used. To obtain contour diagrams of the local mean age-of-air, the entire flow pattern is first calculated. Second, the contaminant concentration resulting from a homogeneous contaminant

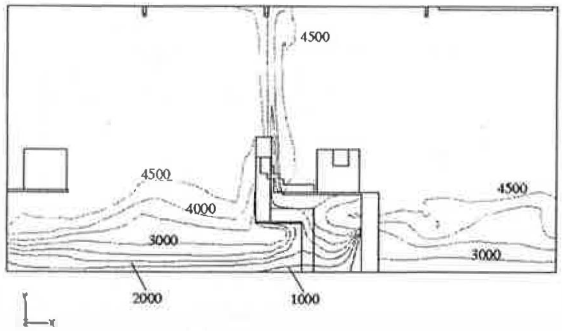

Figure 3a *Contour diagram of local mean age of air for case 3wf*

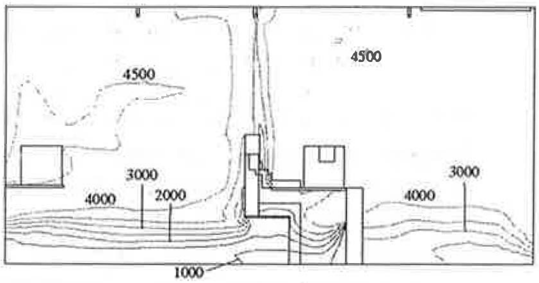

Figure 3b *Contour diagram of local mean age of air for case 3hc*

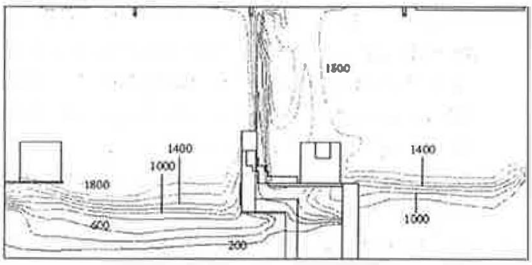

Figure 3c *Contour diagram of local mean age of air for case 4wf*

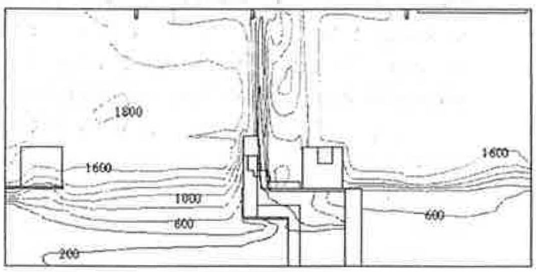

Figure 3d *Contour diagram of local mean age of air for case 4hc*

source term $\dot{\mu}$ (see expression (7) and (8)) is calculated to obtain the spatial distribution of the local mean age-of-air. Currently, only for the 500 Watt heat load cases (3 and 4) contour diagrams of the local mean age-of-air have yet been calculated. These contour diagrams are given in Figure 3a-3d. For both cases 3 and 4, two sets of calculations to obtain the air flow pattern were made. These calculations were based on two different sets of boundary conditions. In the *wf* variant, standard wall functions were applied. In the *hc* variant, boundary conditions were set up such as to increase the wall heat transfer. For more information, see Loomans (1998).

In Table 4, CFD-calculated local mean age-of-air values at test points 2,3,4 and 6 (see Figure 2) are tabulated. In Table 5, CFD-calculated volume average mean age values as well as air exchange efficiency values are given. The four cases under consideration are denoted 3*wf*, 3*hc*, 4*wf* and 4*hc*, The numbers 3 and 4 correspond to the case numbers in Table 2.

Table 4 *CFD-calculated mean age-of-air values (in minutes) at test points.*

	Test point			
Case	2	3	4	6
3*wf*	31	84	47	82
3*hc*	23	75	45	72
4*wf*	4	35	10	33
4*hc*	3	29	7	29

Table 5 *Air exchange efficiency values*

Case	Volume average mean age [min]	Air exchange efficiency [-]
3*wf*	76	0.47
3*hc*	66	0.54
4*wf*	27	0.52
4*hc*	22	0.64

DISCUSSION

Comparison of the experimentally obtained and CFD-calculated local mean age-of-air values for cases 3 and 4 shows that better agreement is found for the *hc* type CFD boundary conditions than for the *wf* type conditions.

For test points 3 and 6 (see Figure 2), the agreement between measured and *hc* type CFD-calculated mean age values is very good, whereas *wf* type CFD-calculated values show significant deviations. This also holds for test point 4 in case 3 (the 1 h^{-1} air change rate case), whereas in case 4 (the 2 h^{-1} air change rate case) both the *hc* and *wf* CFD-calculated values are significantly lower than the experimentally obtained value. At test point 2, measured and calculated mean age-of-air values clearly disagree. For case 3, CFD-calculated values are almost twice the experimental values, whereas for case 4, they are only half as large. The differences result from the deviations as found in the validation of the flow field as described in Loomans (1998). The results indicate the importance of a correctly simulated flow pattern if the local mean age-of-air is to be determined.

Considering the local mean age-of-air values tabulated in Table 3, it is obvious that at test points 3 and 6, the local mean age is almost equal and shows no dependence on the internal heat load. In all cases, the mean age-of-air at test point 4 is significantly lower, typically 0.5–0.6 times the value at test points 3 and 6. At test point 2, located at 0.1 m height, the mean age-of-air is very low, order of magnitude 10 minutes or less, and does not significantly depend on the internal heat load or even the air supply rate. Apparently, only the local buoyancy-induced flow influences the mean age value at test point 2.

The air exchange efficiency, as calculated by CFD, is only slightly above the value 0.5 which is valid for perfect

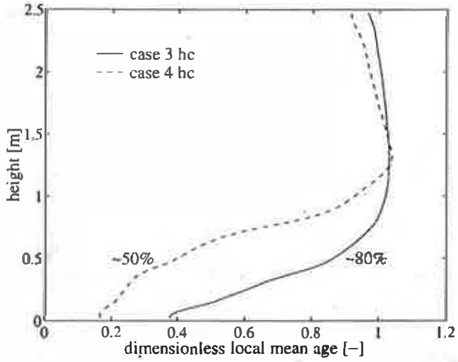

Figure 4 Vertical profiles of dimensionless mean age

mixing flow. An accurate estimation of the air exchange efficiency from the experimental local mean age values is difficult. The pattern of mean age values however indicate a stratified flow and suggest an air exchange efficiency slightly higher than 0.5, though far below 1. It is obvious from the CFD-calculations that in the 2 h^{-1} case, the air exchange efficiency is higher than in the 1 h^{-1} case.

For cases 3*hc* and 4*hc*, vertical profiles of the *dimensionless local mean age-of-air* (averaged over 6 vertical lines from floor to ceiling), i.e., the local mean age divided by the mean age at the exhaust, are drawn, see Figure 4. These vertical mean age profiles clearly show the stratification in the flow pattern. For the cases under consideration, the estimated cooled ceiling capacity level is approximately 50 % (3*hc*) and 80 % (4*hc*). The vertical gradient in the horizontally averaged mean age-of-air is larger in the 4*hc* case. A comparison with vertical dimensionless contamination profiles obtained by Krühne (1995) shows that dimensionless mean age profiles and contamination profiles depend on the value of the cooled ceiling capacity level in a qualitatively similar way.

CONCLUSIONS

The described method to calculate the local mean age-of-air numerically using CFD is shown to be applicable.

Local mean age-of-air and air exchange efficiency values are obtained both experimentally and numerically for a desk displacement ventilation geometry. Reasonable agreement was found except for a test point in the supply air layer near the floor. Both experiments and CFD-calculations show a relatively low mean age in the plume above a heat source (manikin), implying that low-age air near the floor is induced to moderate heights by the heat source.

The air exchange efficiency only slightly exceeds 0.5 and is larger for higher values of the supply air flow rate.

The vertical profiles of mean age and of contamination degree depend qualitatively similarly on the cooled ceiling capacity level.

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