THE EFFECTIVENESS OF DISPLACEMENT VENTILATION.

A. Roos

Eindhoven University of Technology, Eindhoven, The Netherlands.

ABSTRACT

The *effectiveness of ventilation* related to the two primary tasks of ventilation, (i) the supply of fresh air, and (ii) removal of contaminants, is investigated. To allow a quantitative description of ventilation performance, several *effectiveness numbers* are discussed, and their dependence on air flow characteristics is explained. The effectiveness of displacement ventilation regarding renewal of the internal air population is analyzed both experimentally and by means of Computational Fluid Dynamics simulations.

INTRODUCTION

A healthy indoor environment, and good indoor air quality in particular, is of essential importance to society, economy and quality of life [1]. To a large extent, indoor air quality is determined by *ventilation.*

Ventilation has two *primary tasks*, both related to indoor air quality. These are *supply of fresh air* and *removal of contaminants.* Ventilation is also used for additional tasks, e.g. cooling. To achieve good indoor air quality without excessive energy consumption requires *effective* ventilation. To judge whether ventilation is functioning effectively in an actual situation requires *quantitative criteria* for ventilation effectiveness.

A set of ventilation effectiveness related quantities is discussed in this paper regarding the two primary ventilation tasks mentioned above. Of special interest is the relation between these quantities, the main characteristics of the air flow pattern and (where applicable) the spatial distribution of the internal contaminant emission.

Displacement ventilation is the common name for a ventilation principle based on supply of cool air at low altitude in a room, with relatively low supply air velocity of typically 0.15 - 0.20 *m/s*. The *undertemperature* of the supply air gives rise to a *stratified* air flow pattern consisting of a lower air layer of relatively cool and clean air, separated by a rather sharply located *interface* from an upper air layer containing relatively warm and contaminated air. Heat sources in the room, particularly persons, cause upward *induction* of relatively cool and clean air from the lower layer to a larger altitude, in particular to *breathing height* near the persons in the room. The upward induction of air gives rise to so-called *heat plumes*. As most heat sources, and persons in particular, are also the major contaminant sources in a ventilated room, the emitted contaminants are transported directly to the upper air layer by the upward flow in the heat plumes. Contaminants are exhausted from the upper air layer.

Due to its working principle, the name displacement ventilation is in fact misleading and would apply properly to plug flow ventilation in cleanrooms instead. A useful name for the ventilation principle described in the previous paragraph would be *heat source induced ventilation.* The effectiveness of this type of ventilation is of particular interest. The effectiveness related to supply of fresh air (more precisely: related to *renewal of the internal air population*) for this ventilation type is investigated both experimentally and by means of CFD (Computational Fluid Dynamics).

The objective of this research concerning displacement ventilation is to obtain insight in its effectiveness related to the internal air population renewal, i.e., to the supply of fresh air. In particular, two questions are investigated: (1) whether air population renewal occurs more efficiently for displacement ventilation compared to mixing ventilation, and (2) the way this efficiency depends on the air change rate. The effectiveness of displacement ventilation concerning removal of contaminants is outside the scope of this paper and remains subject for further research.

VENTILATION EFFECTIVENESS - RELATED QUANTITIES

A variety of ventilation effectiveness numbers can be found in literature. See for example [2] and [3] for overviews. In this paper, a clear distinction is made between effectiveness numbers related to air population renewal and flow pattern characteristics only, and those related to contaminant emission distribution as well.

The *age concept* plays a major role in the definition of several effectiveness numbers. The age concept is extensively described in [4]. The spatial distribution of *local contaminant concentration* is of crucial importance to several other ventilation effectiveness numbers.

A total of five ventilation effectiveness - related quantities will be briefly discussed here, in particular concerning their relation to air flow characteristics and the spatial distribution of the internal emission of contaminants. An extensive discussion on this subject, for the five quantities considered, is given in [5].

The *spatial distribution* of the *local mean age-of-air* in a steady state air flow pattern provides information concerning the efficiency at which the total internal air population in the room is renewed by supplying new air. As is worked out in [5], the room average mean age of the air is minimal for a given air change rate if the *oldest air* is removed through the exhaust. The *air exchange efficiency* is equal to the ratio of this minimum possible mean age of the total internal air population and its actual mean age. So the air exchange efficiency has a maximum possible value of 1. It is derived in [5] that in case of perfect mixing ventilation, its value equals 0.5. Both the mean age-of-air pattern and the air exchange efficiency are *global* effectiveness quantities, i.e., related to the entire room volume. Only these two quantities are used in the experimental and CFD investigation on the effectiveness of displacement ventilation.

The *purging flow rate* and the *purging time* are *local quantities* related to a finite scale portion of the flow pattern under consideration. Both quantities are properties of the local flow pattern, but in their definition, an artificial homogeneous contaminant source coinciding with an area element in the flow field is used. This is worked out mathematically in [5] in substantial detail. The purging flow rate can be thought of as the effective air volume flow rate through the area element including the effects of diffusion and turbulence on local air redistribution. The purging time can be thought of as the time required to redistribute the air locally to a prescribed degree. In the mathematical analysis worked out in [5] it is shown that both purging flow rate and purging time are strongly related to the *relative strength* of diffusion and turbulence on one hand, and the local air velocity field on the other hand, on the length scale of the area element under consideration.

The steady state spatial distribution of local contaminant concentration comes about due to both the entire air flow pattern in the room and the spatial distribution of the internal emission of contaminants. The ratio between the resulting contaminant concentration at the air exhaust (which in turn is the ratio of the total contaminant emission strength inside the room and the supply air volume flow rate) and the room volume average contaminant concentration is called *contaminant removal efficiency*. The exact mathematical relation between contaminant removal efficiency, air flow pattern characteristics and the spatial distribution of contaminant emission is worked out in [5]. The contaminant removal efficiency is a global quantity. It should be emphasized that, although both purging flow rate and purging time are pure flow field properties, they contain information on local spread of contaminants as well.

Consider next the particular case of displacement ventilation. The flow pattern in rooms with displacement ventilation usually has the following major characteristics. Near the air supply unit, a moderate air velocity region of very young air is located. Further from the air supply unit, a low velocity (typically < 0.1 *m/s*) region forms the remainder of the lower air layer containing relatively cool, clean and young air. Above heat sources, substantially stronger upwardly directed air flow occurs in *heat plumes*. The air in heat plumes is also relatively young but gets substantially warmed and contaminated. Outside the heat plumes, an upper air layer containing relatively old, warm and contaminated air comes about, where air velocities are very low (typically a few *cm/s*).

For the five effectiveness-related quantities described above, the typical displacement ventilation flow pattern characteristics have the following consequences. The stratification of the flow pattern will cause a strong vertical gradient in local mean age-of-air near the interface separating the two layers. Severe horizontal gradients in local mean age-of-air are expected near the edge of heat plumes. The entire mean age-of-air pattern is expected to be very inhomogeneous. The *air exchange efficiency* is expected to be significantly above 0.5 (the perfect mixing flow value) but still far below 1 (the perfect plug flow value). The *contaminant removal efficiency* is expected to be significantly larger than 1, the value occurring for perfect mixing. Unfortunately, experiments had to be restricted to mean age-of-air only, whereas CFD-calculations were restricted to the age-of-air pattern and the air exchange efficiency. It is expected from the theoretical analysis worked out in [5] that *purging flow rate* and *purging time* are severely inhomogeneously distributed throughout the entire flow pattern. This is however yet to be investigated.

EXPERIMENTAL WORK ON DISPLACEMENT VENTILATION

The local mean age of the air was measured at a set of test points in an experimental room ventilated by displacement ventilation, for one particular typical office room geometry, for several values of the air change rate. These local mean age-of-air values were obtained by tracer gas *step-up* and *step-down*-response experiments. The principle of obtaining local mean age-of-air values using these tracer gas methods is extensively worked out in literature, see for example [4], [5], [6] and [7].

The geometry of the experimental room is depicted in figure 1.

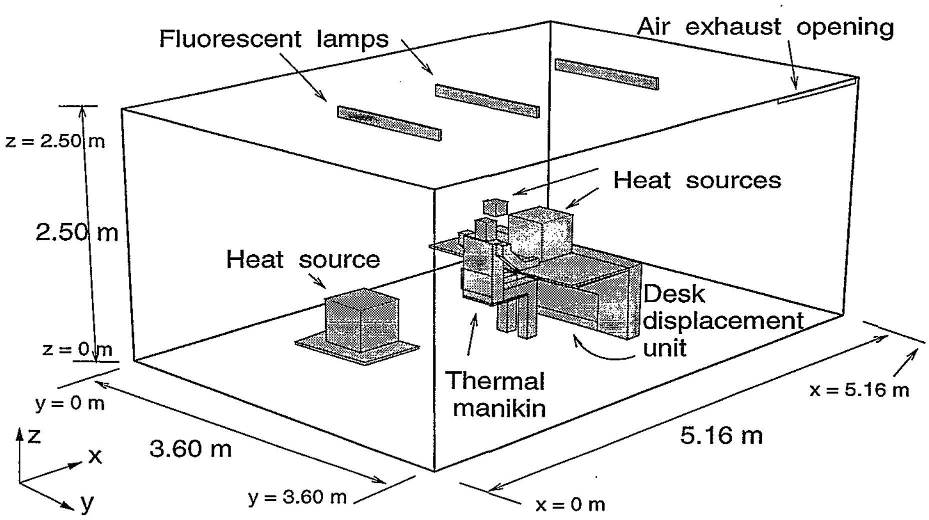

Figure 1 : Geometry of experimental room used in tracer gas step - response experiments to determine the local mean age of the air.

The location of the test points where air samples were taken during the tracer gas experiments is depicted in figure 2.

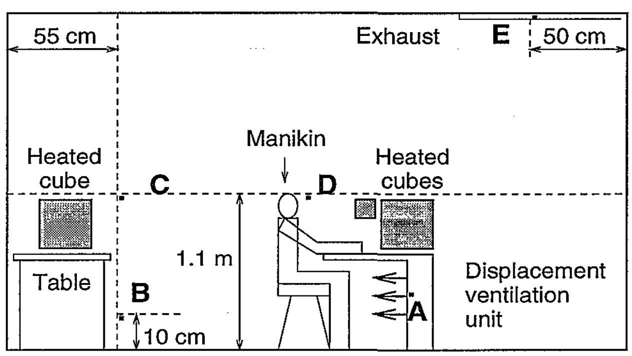

Figure 2 : Location of test points in experimental room used for local mean age determination by tracer gas step - response experiments.

A = at air supply
B = behind manikin, 10 cm height
C = behind manikin, 1.1 m height
D = at manikin head
E = at air exhaust

The room volume equals 46 m^3. The air is supplied with an *undertemperature* $\Delta T \approx -3^0C$. The total internal heat load is 500 Watt, and is dissipated in the thermal manikin (see figure 1,2) and additional electrically heated cubic bodies. The air supply unit is located below the table, the supply flow being directed towards the manikin. An extensive description of test room, manikin and measurement equipment is given in [5].

Local mean age-of-air values were obtained using tracer gas step response experiments in the test room, at test points *B*, *C*, *D* and *E*, the latter being located at the exhaust. The numerical procedure applied to calculate mean age-of-air values is described in [5]. Mean age-of-air values at *B*, *C*, *D* and *E* were obtained for four air change rate values.

The mean age-of-air pattern was calculated using a CFD-code. Local mean age-of-air values were obtained with CFD at the four test points for two air change rate values. An overview of mean age-of-air values is given in table 1.

Point $\bar{\tau}$ n	B Exp. (min.)	B CFD (min.)	C Exp. (min.)	C CFD (min.)	D Exp. (min.)	D CFD (min.)	E Exp. (min.)	E CFD (min.)
0.8 h^{-1}	18 ± 4	22	79 ± 3	60	51 ± 3	48	76 ± 3	71
1.7 h^{-1}	4 ± 2	-	37 ± 3	-	16 ± 3	-	34 ± 3	-
2.2 h^{-1}	3 ± 3	4	25 ± 4	22	9 ± 4	8	27 ± 3	26
3.5 h^{-1}	3 ± 2	-	11 ± 2	-	7 ± 2	-	17 ± 2	-

Table 1: Local mean age-of-air $\bar{\tau}$ (in minutes) at test points B,C,D and E, obtained experimentally and with CFD, for several values of the air change rate (n). All results are related to the geometry depicted in figure 1, with test points located as in figure 2.

Volume average mean age-of-air values and air exchange efficiency values were also calculated with CFD. These values are tabulated in table 2.

Air change rate n	0.8 h^{-1}	2.2 h^{-1}
Volume average mean age-of-air	66 min.	20 min.
Air exchange efficiency	0.54	0.64

Table 2: Volume average mean age-of-air and air exchange efficiency obtained with CFD, for two values of the air change rate.

DISCUSSION OF RESULTS

Consider first the air exchange efficiency values in table 2. For perfect mixing ventilation, the air exchange efficiency is equal to 0.5. For the displacement ventilation configuration of figure 1, CFD predicts air exchange efficiency values slightly exceeding 0.5, but far below 1. The results of table 2 suggest an increase in air exchange efficiency with increasing air change rate, which is physically plausible, since an increase in interface height is to be expected with increasing air change rate, at constant internal heat load.

Since the air below the interface is significantly younger than the air near the exhaust, the volume average mean age-of-air is expected to be significantly below the reciprocal of the air change rate, implying an air exchange efficiency substantially above 0.5.

Next, consider the mean age-of-air results in table 1. Results obtained from tracer experiments and by means of CFD are in good agreement, the only exception being test point C in the $n = 0.8\ h^{-1}$ case. Considering the mean age-of-air values at test points B, C and D in comparison to the mean age-of-air at test point E, it appears that the mean age decreases faster with increasing air change rate for test points B, C and D than for E (the exhaust). Considering the location of the test points in figure 1, the spatial age distribution arising from table 1 is physically plausible, since test point B, located 10 cm above the floor, is located in the layer of relatively cool and young air below the interface even in the $n = 0.8\ h^{-1}$ case. Only in the $n = 3.5\ h^{-1}$ case, the air at test point C is significantly younger than at the exhaust, indicating an upward shift of the interface to at least 1 m above floor level. The sharp decrease in mean age-of-air at test point D is likely to be caused by its location in the heat plume above the manikin.

These results indicate that (1) displacement ventilation is slightly more effective than mixing ventilation considering the internal air population renewal, (2) the efficiency of internal air population renewal by displacement ventilation significantly *increases* with increasing air change rate, due to the upward shift of the interface separating the air layers of younger and older air.

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