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Ventilation Performance and Indoor Air Quality in Workstations under Different Supply Air Systems: A Numerical Approach

Key Words
Ventilation
Indoor air quality
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Workstation

Abstract
This paper describes the results of a computational fluid dynamics study to assess the air freshness and percentage of dissatisfied people due to air quality in a partitioned office with different supply air diffusers. The numerical model involves the finite-volume approach of solving governing equations for mass and momentum, assuming that the buoyancy effects are negligibly small in comparison to the inertial effects. The k-ε two-equation model of turbulence is used to predict the turbulence transport of flow properties. Two typical layouts that provide six individual workstations are studied. The results show that for displacement ventilation and wall jet diffusers, with the exhaust opening placed on the wall opposite to the supply opening, arranging chambers in the central area of the office may be better. When the exhaust opening is placed on the same wall as the supply diffuser, arranging chambers near side walls may be more favourable. The ceiling-mounted four-way diffuser is found to be more suitable for a partitioned office than the wall jet and displacement diffusers.

Introduction

The most efficient technique to achieve acceptable indoor air quality in buildings is to remove all pollution sources. However, source control cannot be 100% effective, thus some exposure of occupants to indoor air contaminants is expected. The purpose of ventilating a room is to properly distribute fresh air to the occupied zone and remove indoor air contaminants. Ventilating rooms on the basis of hygienic demands needs a large amount of energy since rooms are filled with electrical equipment, such as computers, printing and copying machines, as well as other general office equipment. Traditionally, ventilation systems have been designed under the well-mix assumption. This oversight is unacceptable when evaluating newly developed systems and resolving problems related to indoor air quality. Since air serves not only as a diluter, but also as a carrier of energy and contaminants, improving our understanding of how ventilation air is distributed and how the contaminants are dispersed in buildings is a key factor in contaminant control.

When a room is to be partitioned into individual chambers, the partitions must be arranged so as not to create dead zones within the occupied space, nor trap con-

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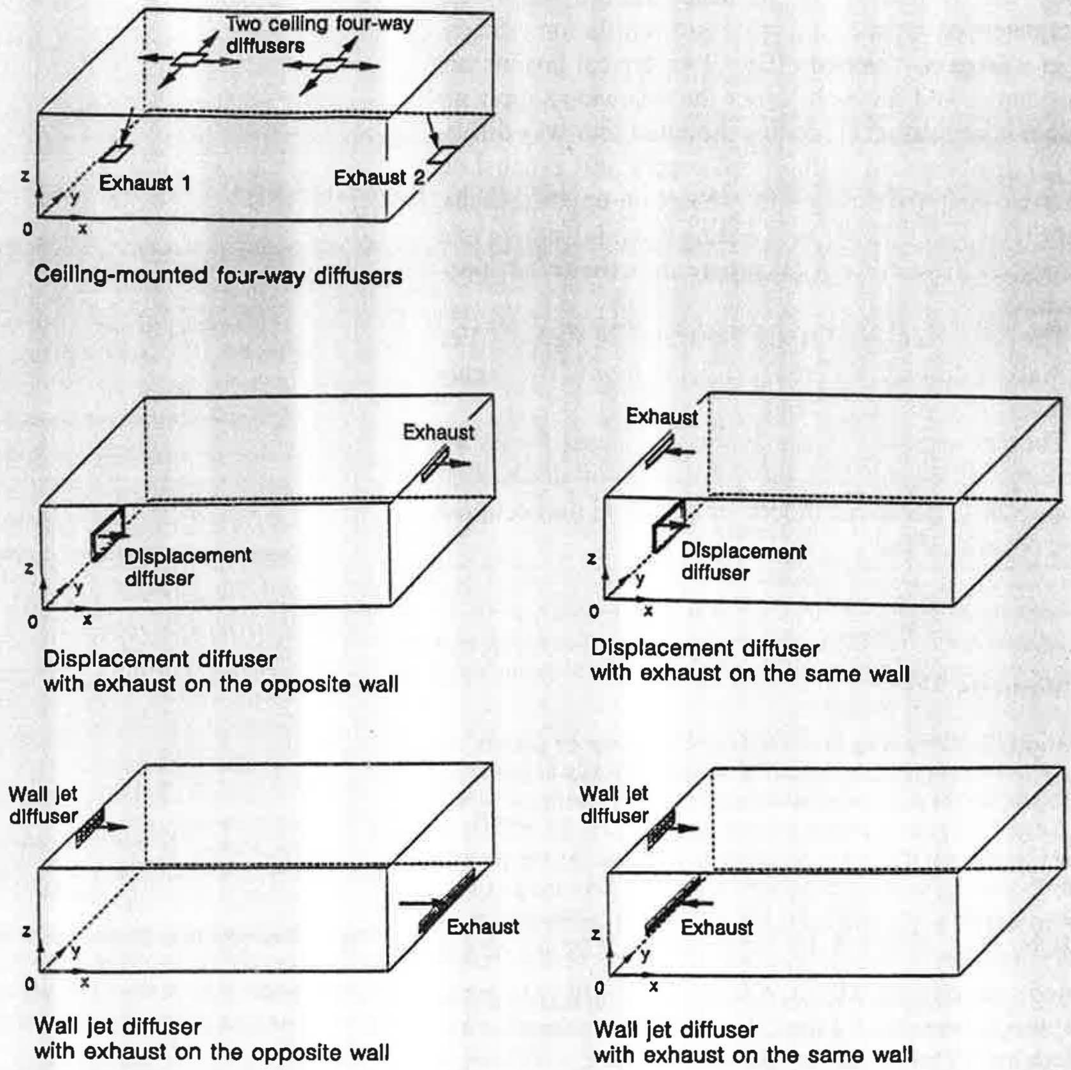

Fig. 1. Type and location of ventilation diffuser and exhaust.

taminants within the chambers. Different supply diffusers have a corresponding optimum office partition layout. At times, an office may need a particular layout for a particular purpose. In such a case, the type and location of ventilation diffusers becomes very crucial in order to distribute fresh air properly and remove the pollutants. The air diffusion in a room is influenced by the complicated interaction of many parameters, such as the ventilation system, room geometry, room layout, thermal condition. For a particular room, the air supply parameters, including the type, location and dimensions of the diffuser, and the room layout are crucial. Haghighat et al. [1] experimentally studied the impact of office furniture, workstation layouts, diffuser types and location on indoor air quality and thermal comfort conditions in workstations. Bauman et al. [2] experimentally investigated the air quality in workstations formed by partitions. Similarly, numerical work has been conducted by others to study the performance of supply air systems and related parameters [3–7]. These authors concerned themselves with empty rooms. For a partitioned room, optimizing air distribution systems and selecting a suitable layout for an existing ventilation system are important aspects to be considered by designers.

This paper reports the results of a detailed numerical study that evaluated the influence of the supply air parameters on indoor air quality and ventilation efficiency in a large partitioned office. Two typical layouts are considered; and for each layout the following supply air system is simulated: (1) ceiling-mounted four-way diffuser; (2) displacement diffuser: (a) supply and exhaust on the same wall; (b) supply and exhaust on opposite walls, and (3) wall jet diffuser near ceiling level: (a) supply and exhaust on the same wall, (b) supply and exhaust on opposite walls.

The five arrangements are illustrated in figure 1. For the wall jet diffuser, different configurations of the supply opening are compared as well.

The performance of the system is judged by its air exchange efficiency and the percentage of dissatisfied people due to perceived indoor air quality in the occupied zone of each office.

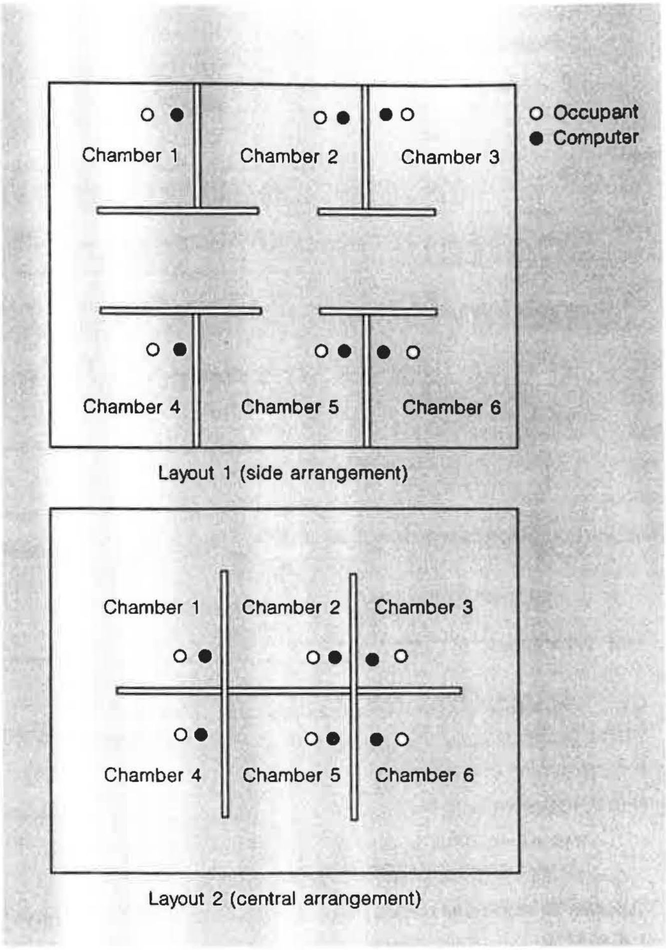

Fig. 2. Two-partition layouts.

Methods

Models for Computing Flow Field and Evaluating Air Quality

Air movement in buildings can be described by a set of conservation equations for mass, momentum and energy. In ventilated rooms, the natural convection effects are not significant in comparison to forced convection if there is no strong heat source. As the present study focuses on the influence of supply air parameters and partition layout on indoor air quality, the buoyancy effect is assumed to be negligibly small. As a result, the energy equation is not included in the present study.

The three-dimensional conservation equations for mass, momentum, energy, contaminant concentration, turbulence energy and dissipation rate of turbulence energy can be expressed in a common form as:

$$\nabla \cdot (\rho V \varphi - \Gamma_\varphi \nabla \varphi) = S_\varphi$$

where ρ is the air density, V is the air velocity vector, Γ_φ is the diffusion coefficient, S_φ is the source term of general flow properties, and φ can be any one of l, u, v, w, k, ε or C (i.e CO_2 concentration). When φ = 1, the equation reduces to the continuity equation.

The computational fluid dynamics model developed by Jiang et al. [8] and validated by Haghighat et al. [9] is applied. The solving procedure follows the SIMPLE algorithm [10], that is, the velocity and continuity equations are solved simultaneously, and pressure correction terms are introduced to ensure mass conservation. Because of the non-linearities in the fundamental differential equations, the solution process requires an iteration approach. Subsequently, each equation is linearized and solved sequentially until a convergent solution is obtained. The turbulent transport is modelled by the high Reynolds number *k*-ε two-equation model developed by Launder and Spalding [11]. With the *k*-ε model, turbulent transport is taken into account via a turbulent viscosity in the form

$$\nu_T = C_\mu k^2/\varepsilon$$

The *k*-ε model can be applied only in the high Reynolds number region found in fully turbulent flows remote from walls. Thus, for wall flows, this model is used in conjunction with the wall functions which bridge the wall boundary conditions to the computing points in the fully turbulent region.

The grid used in the flow field is approximately 25 × 25 × 25 (it varies from case to case). The number of iterations required to obtain convergence is also case dependent. For most cases, about 2,000 iterations were needed for convergence with the mass residual less than 0.001.

The age of air concept was used to evaluate the ventilation performance and the spatial variability of the ventilated space [12]. For assessing the perceived indoor air quality in the room, the perceived indoor air quality model (well mixed) introduced by Fanger [13] was used:

$$c_j = c_o + 10\frac{G}{Q}$$

where c_o is the perceived outdoor air quality (decipol), G denotes the total odour sources (olf) and Q is the ventilation rate (l/s). The per-

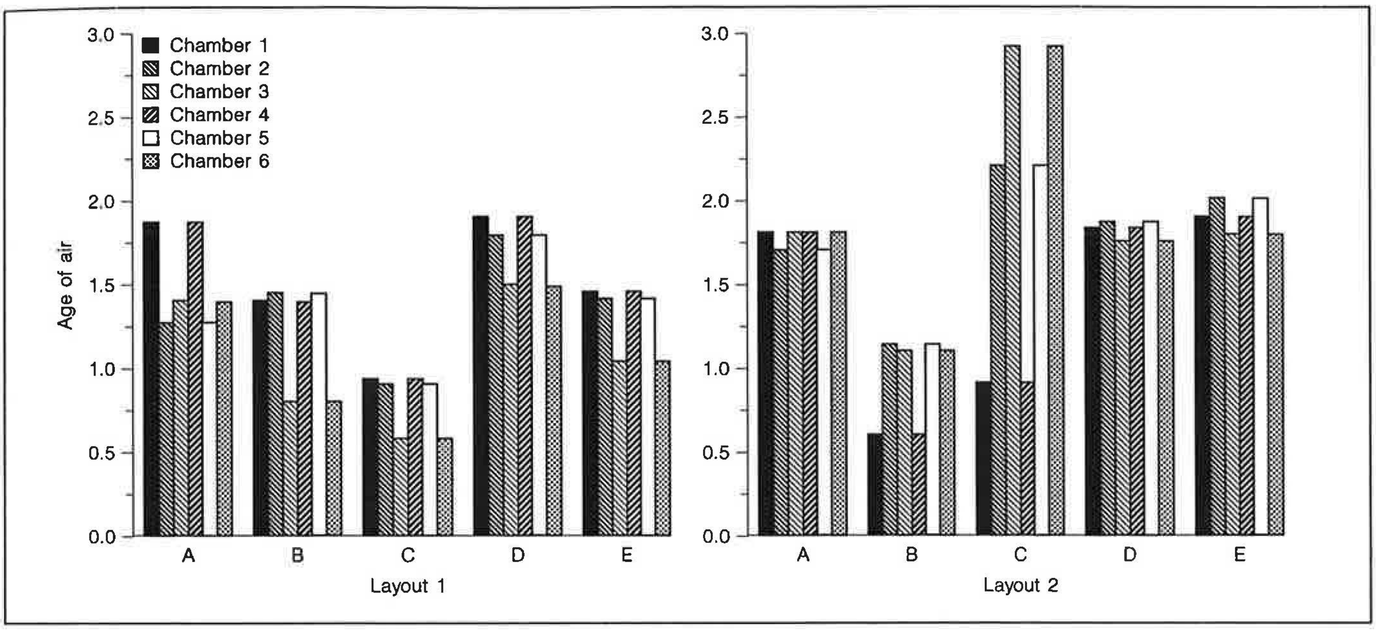

Fig. 3. Average age of air in each chamber for five types of ventilation systems. A = Ceiling-mounted four-way diffusers; B = displacement diffuser with exhaust on the opposite wall; C = displacement diffuser with exhaust on the same wall; D = wall jet diffuser with exhaust on the opposite wall; E = wall jet diffuser with exhaust on the same wall.

centage of dissatisfied people in the room (PD) can then be determined by the method of Fanger [13]:

$$PD = \exp(5.98 - (112/c_j)^{0.25})\ (\%)$$

If the room air is not well mixed, the PD is a function of position. In the present study, the average value of PD in the occupied zone (from the floor level to a height of 1.9 m) in each chamber is computed, and is taken to evaluate the perceived air quality in each chamber.

Parameter Specification

The dimensions of the office presented in figure 1 are 10 m in length, 7.8 m in width and 3 m in height. The office accommodates 6 occupants. Figure 2 illustrates two typical partition layouts designed for this purpose. In layout 1, the chambers are arranged along the perimeter of the office. In layout 2, the chambers are in the central region, leaving an aisle around the perimeter. The partitions, 1.5 m high, are placed so as not to leave a gap above the floor.

The occupants, one in each chamber, are considered to emit 1 olf odour per person without aerodynamic blockage. There is also a computer in each chamber, simulated by 1 olf pollution. The positions of the occupants and computers are marked in figure 2. The office floor is covered with carpet evenly emitting 0.04 olf odour/m^2.

The air supply rate is 3.1 air change per hour (ach) with a temperature of 20°C. An isothermal condition is assumed in the present study.

Results

Different Diffusers and Exhaust Locations

The assessment, as mentioned above, is based on the three indoor air quality indices; (1) the overall perceived air quality in the entire office; (2) the average age of air in each chamber (under 1.9 m), and (3) the average percentage of dissatisfied people due to perceived air quality in each chamber (under 1.9 m).

Figure 3 shows the average age of air in each chamber, defined by layout 1 and layout 2 respectively, for the five supply diffusers.

When the ceiling diffuser is used, the age of air in chambers 1 and 4 in layout 1 is higher than in chambers 3 and 6, although their positions relative to the supply and exhaust are symmetric. This is due to the door openings of chambers 3 and 6 being 0.5 m wider than those in chambers 1 and 4 (fig. 2). In layout 2, the age of air is very uniform throughout the six chambers.

With regard to the displacement diffuser, it is found that the age of air is quite non-uniform between chambers. When the exhaust opening is located on the wall opposite to the supply diffuser, layout 2 provides the freshest air to all chambers. If the exhaust is on the same wall as the supply diffuser, then layout 1 is preferred. It is noted that,

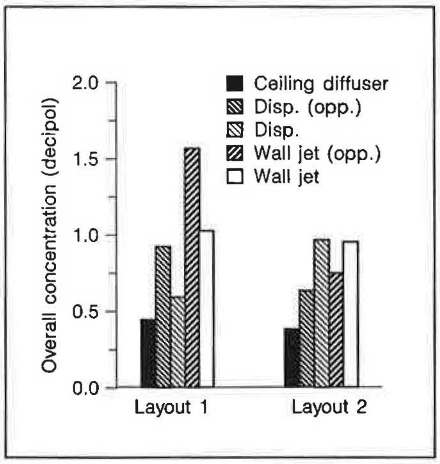

Fig. 4. Overall concentration in the office.

in layout 2, the age of air in chambers 3 and 6 is very high. This is due to the portion of supply air directly blocked by the partition near the supply diffuser, which may be evacuated from the office without having a chance to reach chambers 3 and 6.

For the case using the wall jet diffuser, the air exchange efficiency in layout 1 is better when the exhaust is located on the same wall as the supply diffuser than on the opposite wall. However, layout 2 is not very sensitive to the location of the exhaust as shown in figure 3. For both layouts 1 and 2, the age difference between the six chambers is smaller than that of the case using the displacement diffuser. This indicates that the use of partitions affects the uniformity of the supply air distribution more seriously when using the displacement ventilation system. The reason is that the displacement diffuser supplies air directly to the lower region of the office where the partitions are placed.

The overall perceived air quality in the office with different air supply diffusers is presented in figure 4. For both layouts, the ceiling diffuser gives the best overall removal effectiveness. In layout 1, the displacement diffuser with the exhaust on the same wall provides the second best removal effectiveness, while the wall jet diffuser with exhaust on the opposite wall results in the highest overall concentration (1.56). In layout 2, the situation is reversed; the overall contaminant removal is lower when the exhaust is on the opposite wall than on the same wall. In layout 2, the overall concentration is generally lower than that in layout 1. The difference in overall concentration level is quite small, indicating that layout 2 is less sensitive to the type of air diffuser used.

Figure 5 presents the average PD due to perceived air quality.

Ceiling Diffuser. The ceiling diffuser gives the highest removal effectiveness in the chambers for both layouts. Although the contaminant removal seems quite non-uniform from chamber to chamber, the PDs are all lower than 12%. In layout 1, the PD in chamber 3 is 3.5 times as high as that in chamber 1 although the average age of air in chamber 3, as stated before, is smaller than that in chamber 1. The reason for this may be that the ventilation air does not reach the sources at their particular positions. Although it is noted that chambers 1, 2 and 3 are geometrically symmetric to chambers 4, 5 and 6, respectively, the average PD in these corresponding chambers (for instance chamber 1 and chamber 4) are not the same. The reason for this is due to the non-symmetrical positions of the contaminant sources (occupants and computers). This also indicates the importance of properly located sources.

Displacement Diffuser. For layout 1, the displacement diffuser with the exhaust on the same wall is satisfactory in removing contaminants. The PD, ranging from 8.4 to 12.3, is also quite uniform between the six workstations. When the exhaust is on the opposite wall, the PDs in the chambers all increase, especially in chamber 1 where the PD rises from 12 to 20%. Layout 2 seems to be more suitable in such a case. As can be seen in figure 5, the average PD varies considerably from chamber to chamber for layout 2. For both exhaust positions, the PDs in chamber 2 are the highest among all the chambers, while in chambers 1 and 4, the PDs are much lower.

Wall Jet Diffuser. In layout 1, the PD in all chambers is relatively high. The wall jet diffuser with the exhaust on the opposite wall results in the highest PDs in the chambers, ranging from 20.0 to 26.7. When the exhaust is placed on the same wall, the situation is slightly improved; however, the PDs are still higher than the cases using the ceiling and displacement diffusers. This is especially so for chamber 1. For layout 2, the exhaust on the opposite wall again yields better results than placing the exhaust on the same wall. The differences in the average PD in the chambers are not very significant, which indicates that the value of the removal effectiveness in these chambers are similar.

The arrangement of supply diffuser and exhaust opening on opposite walls from each other is favoured in layout 2, but not in layout 1. Because the chambers in layout 2 are located in the central region of the office, the ventilation air, moving through the chambers directly to the exhaust opening, can dilute the contaminant more efficiently.

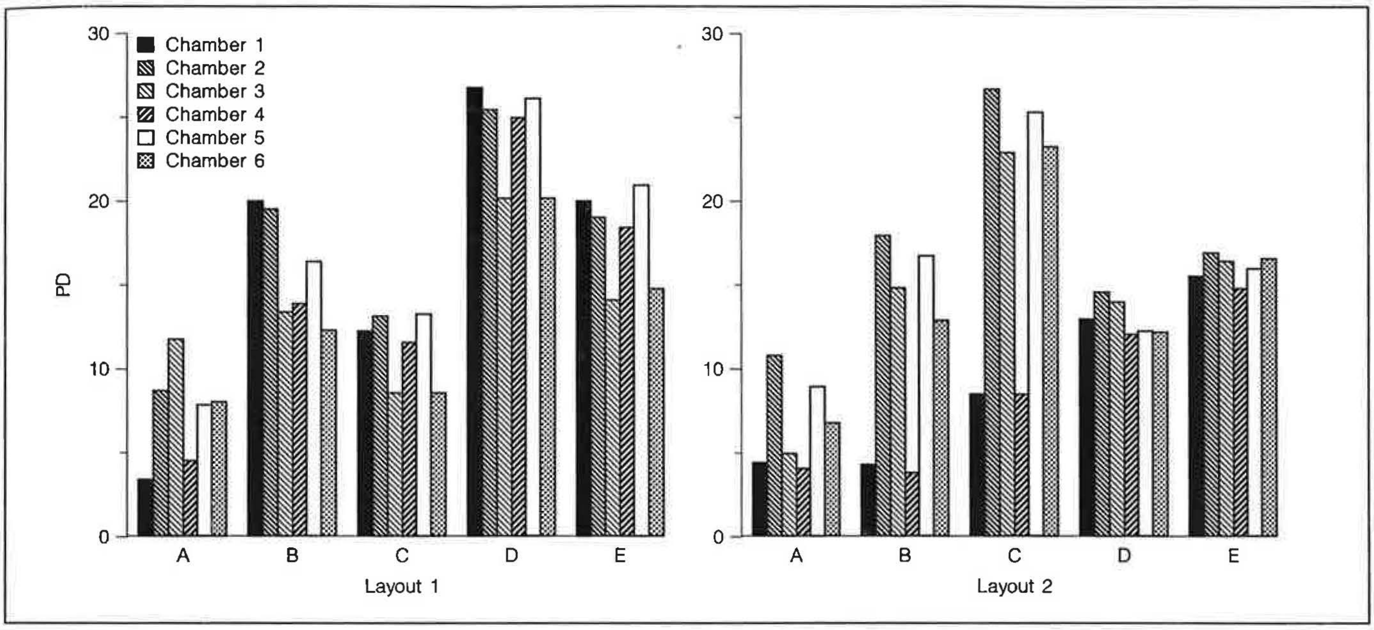

Fig. 5. Average DP in each chamber for five types of ventilation systems. A = Ceiling-mounted four-way diffusers; B = displacement diffuser with exhaust on the opposite wall; C = displacement diffuser with exhaust on the same wall; D = wall jet diffuser with exhaust on the opposite wall; E = wall jet diffuser with exhaust on the same wall.

Variation of Diffuser Configuration

In order to evaluate the influence of the supply diffuser configuration on air quality, two variations from the basic wall jet diffuser are considered, as indicated in figure 6. In the first variation, the width of the supply opening is doubled while its height is halved so that the total flow area remains unchanged. In the second variation, the supply opening is replaced by two smaller supply openings, the widths of which are reduced from 1 m to 0.6 m while the heights remain 0.2 m. The average age of air and PD in the chambers with the three wall jet diffuser configurations are presented in figure 7 and figure 8, respectively. In layout 1, the age of air and the PD in the chambers are all slightly reduced when the width of the opening is doubled. However, when two supply diffusers are used, the average ages of air and PD in the chambers are all increased, especially in chamber 3 where the PD is increased from 14 to 20.4% as shown in figure 8. The reason may be that the chambers in layout 1 are opened to the central aisle of the office to which the ventilation air easily flows if one supply opening is used. Moreover, the total surface area of the wall jets becomes large, which results in an increase of entrainment and a faster decay of

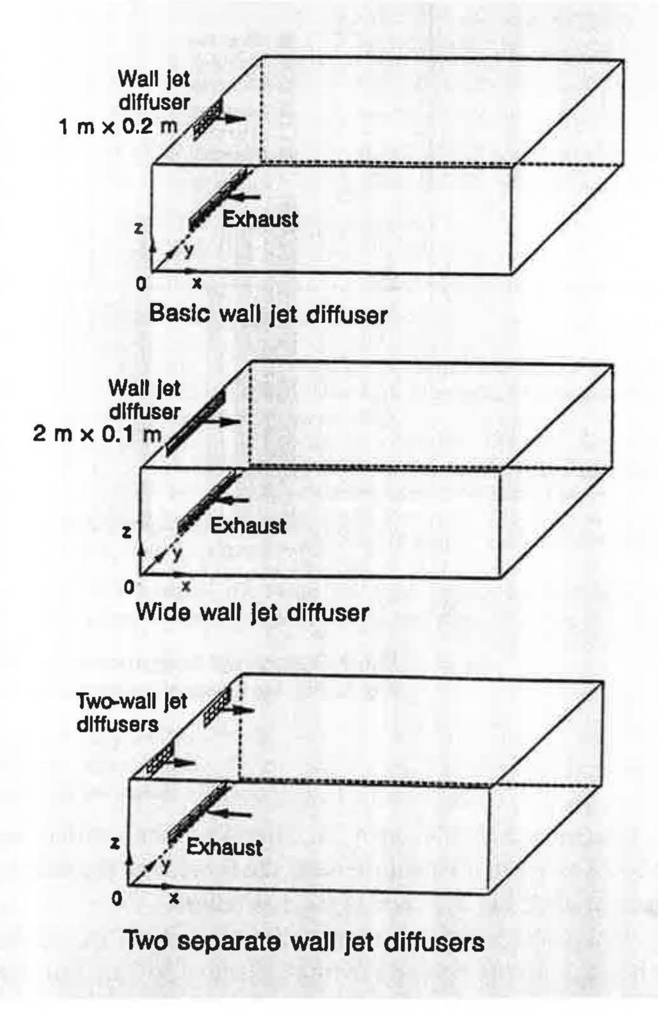

Fig. 6. Variation of diffuser configuration.

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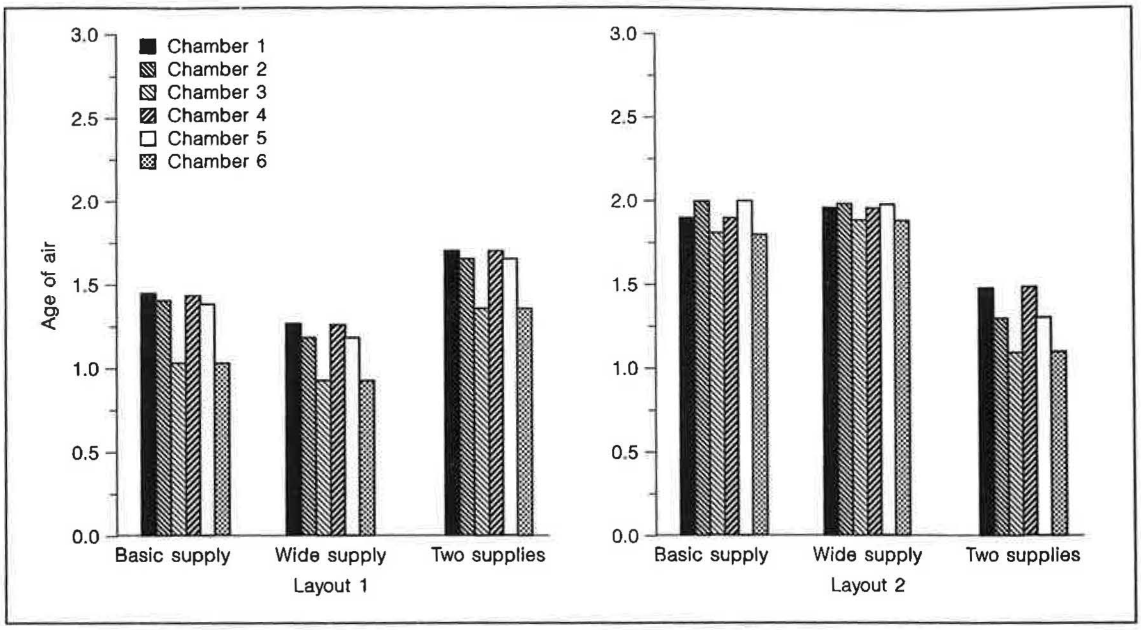

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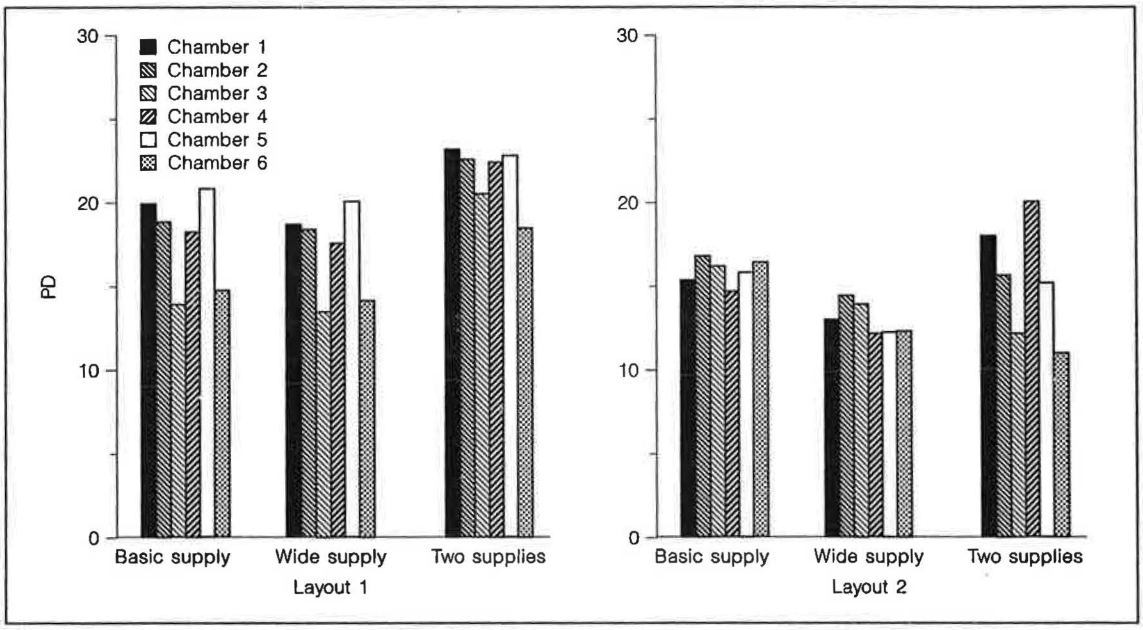

Fig. 7. Average age of air in each chamber for three types of wall jet diffusers.
Fig. 8. PD due to perceived air quality in each chamber with three types of wall jet diffusers.

supply momentum at each jet. Therefore, the ventilation effectiveness in the chambers on the far side of the office, such as chamber 3, is not as good as before.

In layout 2, the age of air almost remains the same when the supply opening increases from 1 to 2 m, but the PDs in the chambers are all reduced. In the case when two smaller supply openings are used, the age of air is diminished remarkably in all chambers. For layout 2, the PD increases in the chambers near the supply and decreases in the chambers near the opposite wall, as indicated in figure 8. The reason may be that when the wider diffuser or the two smaller diffusers are used, the supply air easily enters chambers 3 and 6 through their openings near the northern and southern walls.

Conclusions

From the cases studied, the following conclusions may be obtained:

- Generally speaking, the ceiling-mounted four-way diffuser is more suitable for a partitioned office than the displacement and wall jet diffusers.
- For both displacement and wall jet diffusers, layout 1 is favoured when the supply diffuser and exhaust opening are on the same wall, while layout 2 is more suitable when the exhaust is on the opposite wall.
- Layout 1 is not favoured when using the wall jet diffuser.
- Layout 2 is less sensitive to the type of air diffuser used than layout 1 and the overall concentration is generally lower.
- In the displacement ventilation system, the differences in the PD and age of air from chamber to chamber are large. This implies that the use of partitions significantly affects the uniformity of the supply air distribution.
- Wide air diffusers may be more suitable for both layouts. When two smaller diffusers near the side walls are used, the chambers should be placed in the central area of the office (layout 2).

The air diffusion and contaminant removal in buildings is influenced by many parameters. The interaction between these parameters is complicated. It is difficult to reach general conclusions that can be applied for the optimization of all office layouts. However, the present study demonstrates that numerical simulation is a practical and powerful tool for designers to use when optimising air distribution systems and for selecting an appropriate layout for an existing ventilation system. It is expected that indoor air quality will become an increasingly important consideration in the design process of ventilation systems and control strategies.

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