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A CFD Analysis of Ventilation Effectiveness in a Partitioned Room

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Abstract

A numerical model has been developed to investigate the contaminant removal and air freshness in a ventilated two-zone enclosure. The average contaminants and the distributions of air age in each zone under variable positions of door, supply and exhaust are compared. The correlation between the average contaminants and each of the main parameters, such as door location, supply and exhaust positions etc., are presented, and the average air ages in both zones are illustrated against door position. It is found that the average air age in the upstream zone is less affected by the door position than that in the downstream zone, and that the door position near the side-walls seems to give better air circulation. It is also concluded that the supply and door positions affect the concentration in the upstream zone significantly, while the exhaust location does not seem to influence the average concentration in either the upstream or the downstream zone.

KEY WORDS:
Age of air, Computational fluid dynamics, Contaminant distribution, k-ε two-equation model, Turbulent flow, Partitioned enclosure, Ventilation effectiveness.

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Nomenclature

- A = area of control volume surface
- c = contaminant concentration
- C_μ = coefficient in k-ε model
- E = coefficient in wall function
- H = height of room
- h = height of openings
- k = kinetic energy of turbulence
- L = room length
- Q = air volume flow rate
- t = time
- U_I = air velocity at ventilation inlet
- x,y,z = Cartesian coordinate system
- w = width of opening
- W = width of room

Greek Symbols

- Δu = overall velocity correction
- ε = dissipation rate of turbulence energy
- κ = von Karman's constant (0.435)
- τ = time related to air age
- τ = shear stress

Subscripts

- D = door
- E = exhaust opening
- I = supply inlet
- p = grid node near wall
- p = grid node being computed
- s = wall surface
- t = turbulent

Introduction

The knowledge of ventilation effectiveness and airflow patterns is important in the development of control strategies for indoor air quality in an energy-efficient manner. Traditionally, the ventilation systems have been designed based on the assumption that the supply air and the pollutant are well mixed throughout the ventilated space. Current theoretical models and computation simulation programs are restricted by the same assumption (Haghighat, 1989). Recent investigations have brought the validity of this assumption under question and have shown that large errors could occur in their performance when perfect mixing assumptions are made (Haghighat et al., 1990a).

Moreover, as technology advances, modern ventilation systems tend toward a more compact and highly efficient design. Existing empirical approaches and simplified analysis are inadequate for assessing newly developed systems and resolving problems such as the "sick building syndrome". Advanced analysis is therefore required. It is of considerable interest to have a computational fluid dynamics (CFD) capability for simulating these applications as an alternative to the empirical approach.

The effectiveness of mechanical ventilation is usually measured by its capability to provide fresh air uniformly and to remove the contaminants within an enclosure. The ventilation air serves not only for dilution purposes but also as a carrier of the particles or gaseous contaminants. The freshness of the air in a ventilated space, to a certain extent, can be taken as an indicator of the effectiveness of the ventilation system.

When perfect mixing cannot be expected, a proper description of the transport properties of ventilation systems is needed. In this regard, a number of concepts has been developed (Liddament, 1987). Sandberg and Sjoberg (1983), and Skaret (1984) introduced the concept of "age of air" to assess an average ventilation system performance. The age distribution provides useful information for evaluating the uniformity of the air freshness within an enclosure.

The prediction of pollutant migration in a ventilated space is not an easy task. In a single enclosure, the main parameters which influence the effectiveness are the locations of supply and exhaust opening and the flow rate of ventilation air. When an enclosure is divided by a partition with a door opening in it, the door opening position is an additional parameter influencing the pollutant migration pattern, and therefore needs to be taken into consideration.

This paper describes the development both of a numerical model which has aimed at enhancing the knowledge of distribution of ventilation air in two-zone enclosures, and of control strategies for indoor contaminant removal. The model allows the simulation of intra- and inter-zone heat and mass transfer in three-dimensional turbulent flow in forced convection circumstances.

The purpose of this study is to investigate the ventilation effectiveness in the two-zone enclosure and the effects of the variation of locations of door, supply and exhaust on the contaminant removal.

Mathematical Formulations of the Numerical Model

In ventilated enclosures, the airflow is mainly turbulent. There are many kinds of turbulent model. The one employed in this paper is the k-ε two-equation turbulent model.

A narrow region exists near solid surfaces where the turbulent fluctuations must be strongly dampened since, right at the surface, turbulent fluctuations are equal to zero. In this region, the turbulent viscosity is no longer dominant. Thus, the k-ε model, which is applicable only for high-Reynolds turbulent flows, is not valid in this region, and a special treatment is required to describe the flow properties. The wall function method is that most widely used for dealing with this problem.

The principle of the wall function method is to use the momentum flux due to shear stress and the heat flux at solid surfaces to modify the source terms in the conservation equations for the grid nodes near the solid surfaces. Thus, the boundary information of solid surfaces can be transferred into the flow field.

The wall function used in this paper is the universal velocity distribution

$$u^+ = \ln(Ey^+)/\kappa \qquad (1)$$

where κ is von Karman's constant ($\kappa = 0.435$). E is a coefficient reflecting the roughness of the wall. It is equal to 9.0 for a smooth wall. u^+ and y^+ are dimensionless velocity and dimensional distance from the wall respectively. They are defined as

$$y^+ = \frac{y}{\mu}(\tau_s \rho)^{1/2} \qquad (2)$$

$$u^+ = u/(\tau_s/\rho)^{1/2} \qquad (3)$$

The fluxes of momentum to solid surfaces can be expressed by (Launder and Spalding, 1974)

$$\frac{u_p}{\tau_s/\rho} C_\mu^{1/4} k_p^{1/2} = \frac{1}{\kappa} \ln\left[E\, y_p \frac{(C_\mu^{1/2} k_p)^{1/2}}{\nu}\right] \qquad (4)$$

The source terms of variables at the grids near a wall are then corrected by shear stress τ_s. The shear stress reduces the velocity component parallel to the walls. The turbulent energy in the region near the wall is diminished as well. Therefore, the shear stress contributes to the sink term of their conservation equations.

However, when the wall function method is applied, the grid nodes near walls must be sufficiently remote from them to ensure that the turbulent Reynolds number, $(k^{1/2}y/\nu)_p$, is much greater than unity, and that the viscous effects are entirely overwhelmed by those of turbulent viscosity.

Ventilation Effectiveness in a Two-Zone Enclosure

The two-zone enclosure with the dimensions of 10 m long, 4 m wide and 3 m high is considered as showed in Figure 1. A partition is fixed at the middle of the enclosure dividing it into two equal-sized zones. Table 1 shows the dimensions and the locations of the openings of the door, supply, and exhaust. All the dimensions remain unchanged throughout this study.

There is a contaminant source placed near the floor in zone A with a unity emission rate. The contaminant is removed by the ventilation air from zone A, passing the door opening, and then out through the exhaust opening in zone B. The average contaminant in each zone may be an indicator of the ventilation effectiveness for the two-zone enclo-

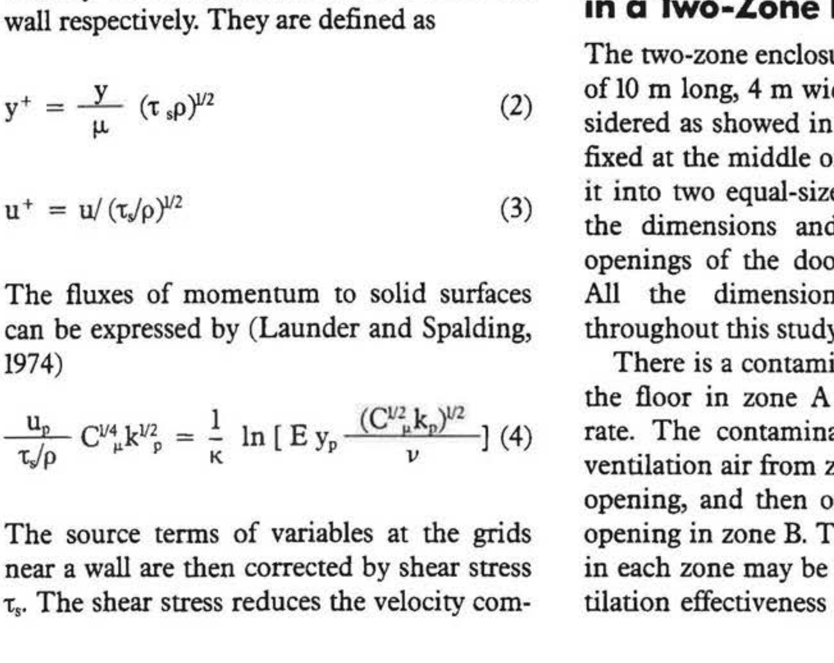


Fig. 1 Configuration of a partitioned enclosure.

Table 1 The dimensions and locations of opening for the basic model.

	door	supply	exhaust	source
dimension				
w/W	0.17	0.083	0.083	-
h/H	0.75	0.083	-	-
l/L	-	-	0.056	-
location				
x/L	0.5	0.0	0.75	0.25
y/W	0.5	0.46	0.875	0.46
z/H	-	0.875	1.0	0.46

sure. It is obvious that the amount of contaminant held in each zone will be affected by the ventilation flow rate and the locations of door, supply and exhaust.

In order to examine the effects of these main parameters on the contaminant removal and air freshness in each zone, a variety of positions for door, supply, and exhaust are computed. The door and supply are moved in the y direction to five different positions, respectively, while the change of exhaust location is in the x direction within zone B, as shown in Table 2. The average contaminants for five different ventilation rates are computed as well. Note: when one parameter changes, the other parameters remain fixed, as those for the basic model presented in Table 1. In cases where the opening position changes, the air velocity at the supply opening is fixed at 1.0m/s; this provides a ventilation rate of 2.5 ach.

Table 2 Changes of opening positions.

door	y_D /W	0.17	0.33	0.50	0.66	0.83
supply	y_I /W	0.13	0.29	0.46	0.63	0.79
exhaust	x_E /L	0.53	0.64	0.75	0.86	0.97

The ceiling, floor and walls are considered to be well insulated, therefore an isothermal airflow could be assumed. The thickness of the partition is assumed to be negligibly small in comparison with the length of the enclosure. It is also assumed that the contaminant source is a point source with an emission rate negligibly small in comparison with the ventilation flow rate.

The ventilation effectiveness can be defined differently according to the purpose of ventilation. In general, it expresses the ability of a system to evacuate indoor contaminants, and therefore is closely related to the freshness of air in the enclosure being ventilated. The concept of air age (Sandberg and Sjoberg, 1983) that reflects the freshness of air is adopted in this study to assess the performance of the ventilation system. The local mean age of the air at an arbitrary point is defined as the time, τ, that has elapsed (on average) since the molecules passing this point entered the enclosure. Thus, the high value of air age at a spot implies a poor air circulation there. There are two methods for determining the local mean age numerically.

(1) Step-up method: at time $t=0$, a fraction of the supply air is labelled with contaminant. The contaminant concentration at each point is computed for each time-step.

(2) Step-down method: fresh air is supplied to an enclosure which is initially filled with a uniform concentration of contaminant. The decay of concentration at each point is computed for each time step (Davidson and Olsson, 1987).

In this study, the Step-down method is adopted, and the local mean age of air is determined in the following form:

$$\tau_p = \frac{1}{c_0} \int_0^{\infty} c_p(\tau)\, d\tau \qquad (5)$$

where c_0 is the initial contaminant concentration of the enclosure, and $c_p(\tau)$ is the local concentration at time τ, which is determined by its own conservation equation.

The average age in each zone is calculated as

$$\tau = \frac{1}{V} \int_v \tau_p dV \qquad (6)$$

where V represents the volume of a zone.

Numerical Procedure

(1) A $14 \times 14 \times 20$ staggered mesh system is used, i.e., the boundaries of the control volume for scalars are identical with the physical boundaries. For the velocity components u, v and w, the staggered control volumes are employed.

(2) The Hybrid scheme developed by Spalding (1972) is adopted, which is a combination of the central-difference scheme and the upwind scheme.

(3) The SIMPLE algorithm (Patankar and Spalding, 1972) is employed to solve the finite-difference equations. SIMPLE stands for Semi-Implicit Method for Pressure Linked Equations.

(4) In order to ensure the mass continuity at the door opening where the flow properties may change rapidly, an overall correction on the velocity component in the direction perpendicular to the partition (the x direction) is added. The overall correction term serves as a boundary condition for the door opening, which is derived from the mass continuity over the sections parallel to the partition (Jiang, 1990). It can be expressed as

$$\Delta u = \frac{Q_{up} - Q}{\sum_j A_{x,j}} \tag{7}$$

where Δu is the overall velocity correction term which is constant for each control volume in the same section; A_x is the area of control volume in the x direction; Q_{up} and Q represent the upstream airflow rate and the airflow rate across the section before velocity is overall-corrected. The summation is carried out over the whole section perpendicular to the x direction.

(5) The false-time step and the Alternative Direction Implicit (ADI) iterative procedure with under-relaxation are employed.

(6) Convergence of the iteration process is pronounced when the total absolute value of residual sources in the continuity equation is small enough (less than 1% relative error) and when the variation in value of variables between two iterations is small enough (less than 0.1% relative error). The reason for choosing the residual source in the continuity equation as a monitor is that the convergence of the continuity equation in this study is slower than other variables.

Results

The air age in Figure 2 through Figure 5 is normalized by a reference time τ_n, the time needed to replace the air in the enclosure;

$$\tau_n = \frac{\text{the volume of the enclosure}}{\text{the volume flow rate of supply air}} \tag{8}$$

The variation of the average air ages in the two zones with different door locations is presented in Figure 2. The average air age in zone A is much smaller than that in zone B for all cases. In zone A, the average air age is decreased when the door opening is moved from the position y/W = 0.17 northward to y/

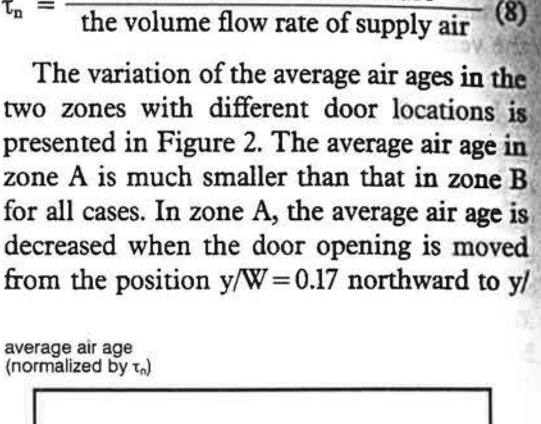


Fig. 2 Variation of average air age with door position.

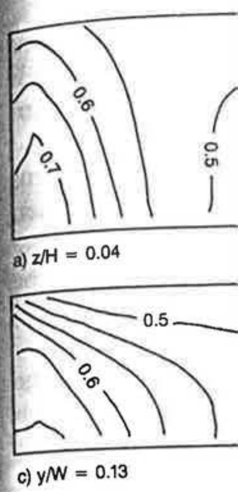
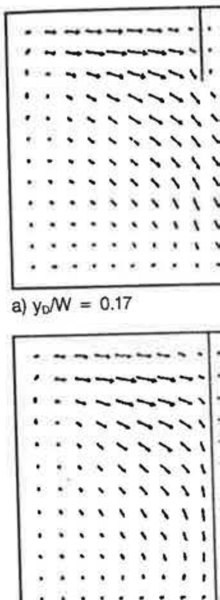


Fig. 3 Age contours for



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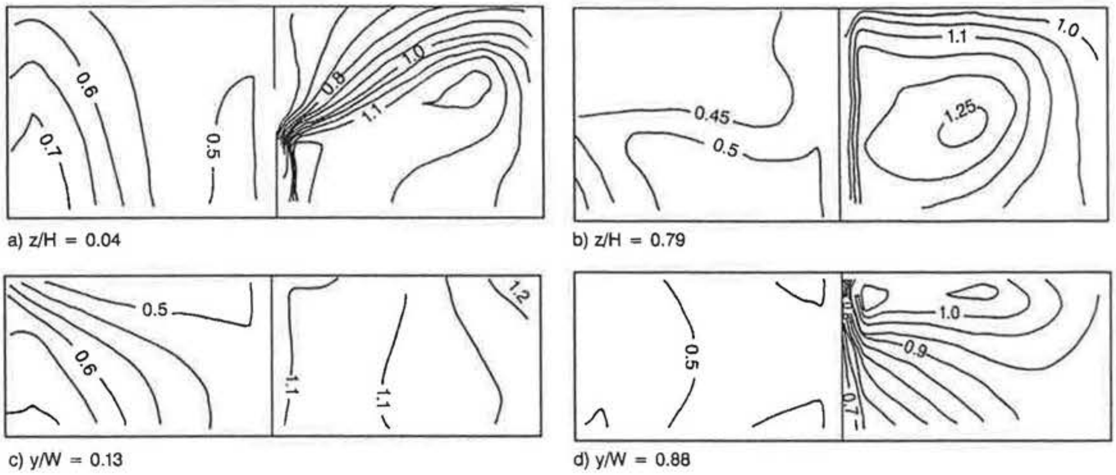
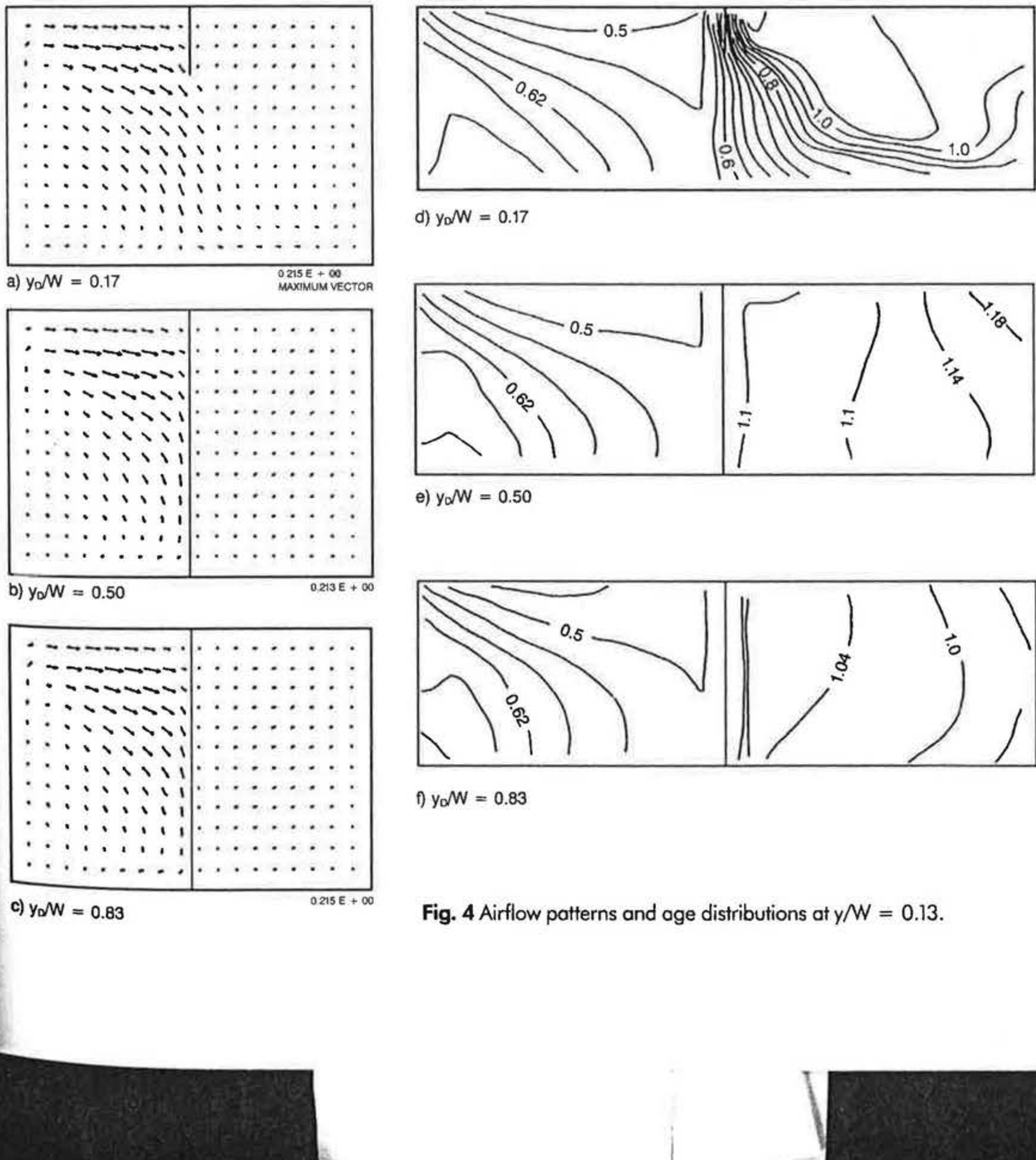


a) z/H = 0.04
b) z/H = 0.79
c) y/W = 0.13
d) y/W = 0.88

Fig. 3 Age contours for the case with $y_D/W = 0.5$.



a) $y_D/W = 0.17$
b) $y_D/W = 0.50$
c) $y_D/W = 0.83$
d) $y_D/W = 0.17$
e) $y_D/W = 0.50$
f) $y_D/W = 0.83$

Fig. 4 Airflow patterns and age distributions at y/W = 0.13.

W = 0.833. In zone B, the average air age has its largest value when the door is located in the middle of the partition. The average air age decreases as the door opening moves from the central position towards the sidewalls.

Figure 3 illustrates the age distributions in the vertical and horizontal sections for the case with the door at the middle of the partition. The air age in zone A is decreased when the horizontal level rises up or the vertical section moves from south to north. This indicates that the air circulation in the southern part of the zone is not as good as that in the northern part. In zone B, the local age in the lower region is smaller than that in the higher region, since the exhaust opening is located on the ceiling, where the air age is always higher than that in other areas. It is found that, in the region near the southern wall, the air age in zone B is quite uniform.

Figure 4 demonstrates airflow patterns and age distributions at the vertical section of $y/W = 0.13$ when the door is located at $y_D/W = 0.17$, 0.50 and 0.83 respectively. The flow patterns in the upstream zone, zone A, strongly resemble each other, as observed by Haghighat et al. (1990b). As a result, the age distributions in this zone are similar to each other. The local age is increased from ceiling to floor. In the downstream zone, zone B, the average air age in this section for the case with $y_D/W = 0.17$ is lower than those for the other two cases. The reason is that when the

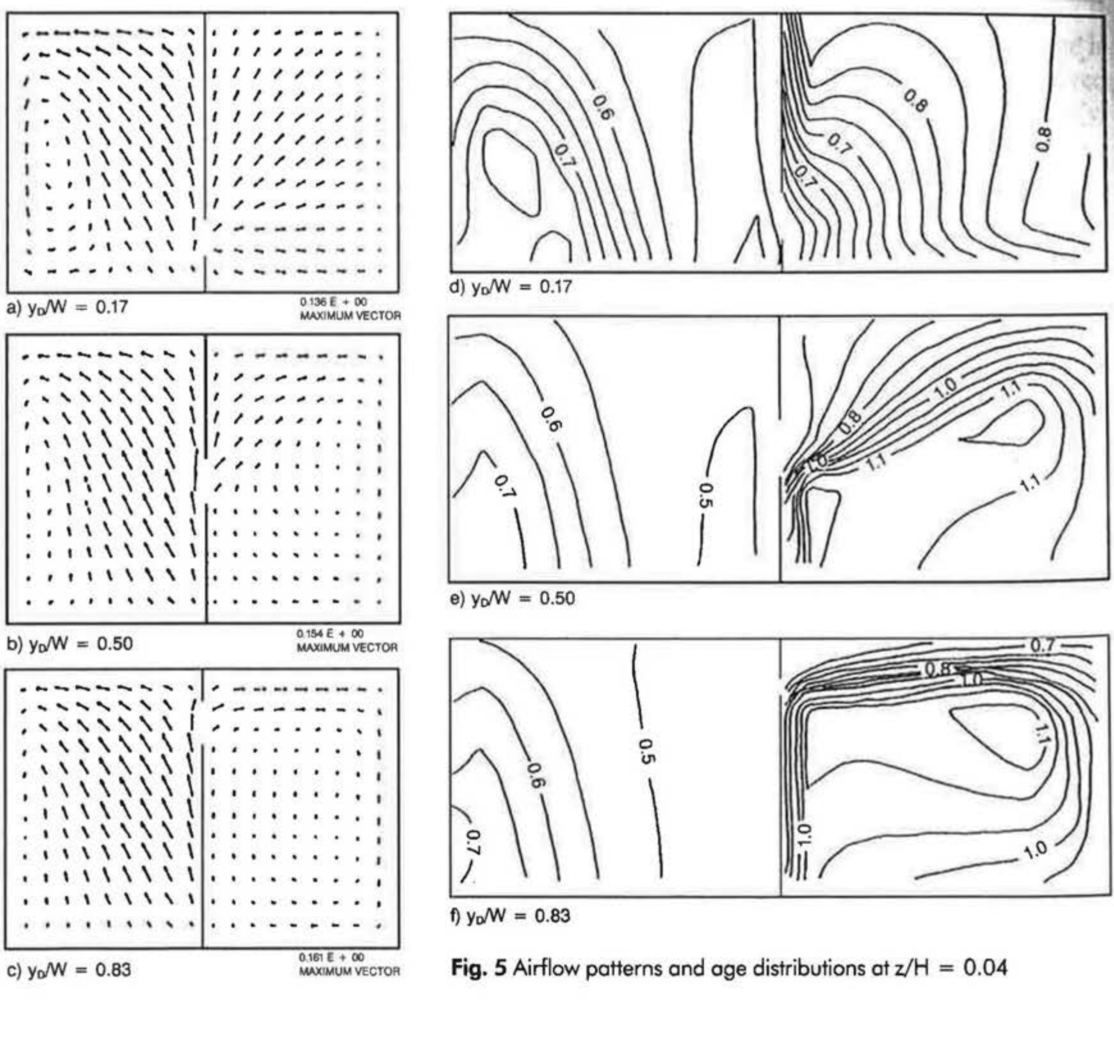
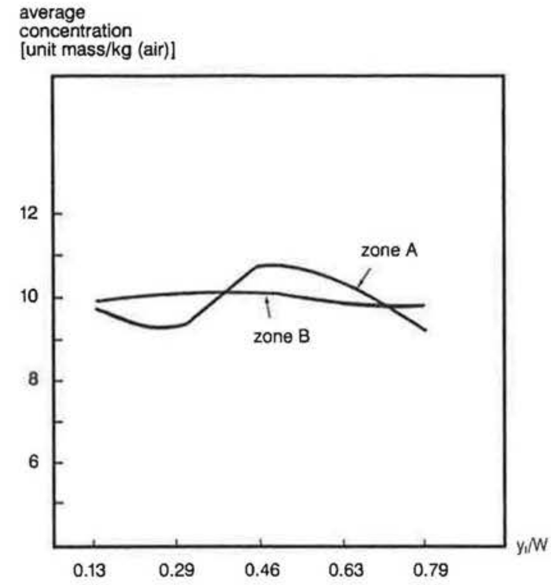


Fig. 5 Airflow patterns and age distributions at $z/H = 0.04$

door is located at $y_D/W = 0.17$, the vertical section, $y/W = 0.13$, crosses the door opening, where the fresh air just enters zone B, without travelling a long way in this zone.

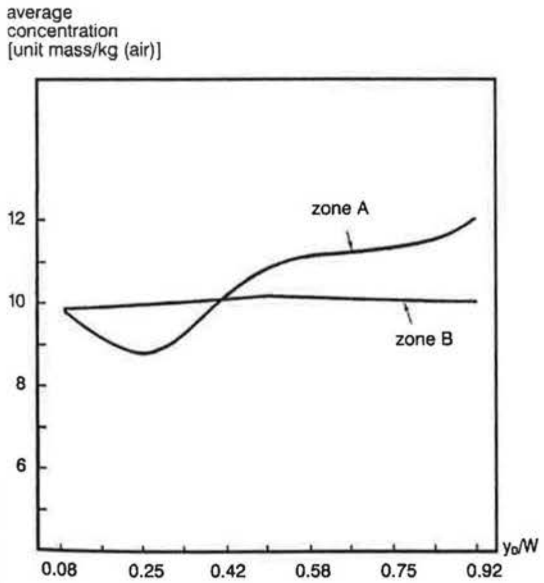
At the horizontal section near the floor, $z/H = 0.04$, as shown in Figure 5, there is an increase in the local age from the partition to the western wall in zone A for the three cases. The average age in zone A in this section rises when the door opening is moved from north to south. This is due to the fact that the exhaust opening is located near the northern wall; thus, for the case with $y_D/W = 0.83$, the air from zone A is sucked into the exhaust with less resistance when the door opening is close to the exhaust. In zone B, the local age increases from the partition to the eastern wall for the case with $y_D/W = 0.17$. In the other two cases, the age in the central areas is higher than in the periphery since the air movement is in a rotation form.

Figures 6, 7 and 8 illustrate the average concentrations in zone A and zone B as a



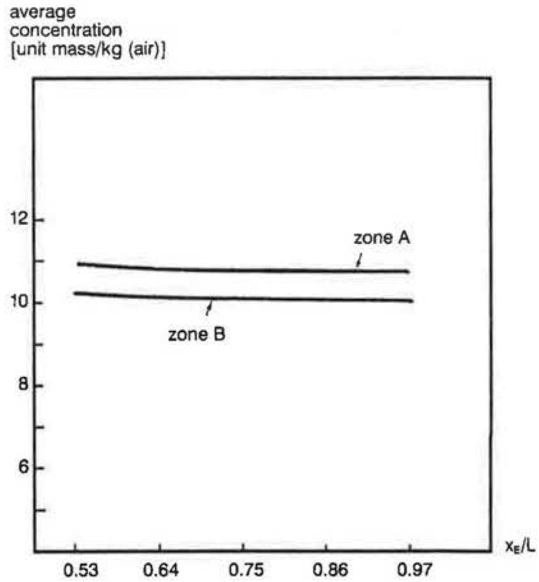
ventilation rate:	2.5 ach		
door location:	$x_D/L = 0.5$	$y_D/W = 0.5$	
supply location:	variable		
exhaust location:	$x_E/L = 0.75$	$y_E/W = 0.88$	$a_E/H = 1.0$

Fig. 7 Variation of average concentration in each zone with supply location.



ventilation rate:	2.5 ach		
door location:	variable		
supply location:	$x_I/L = 0.0$	$y_I/W = 0.46$	$z_I/H = 0.88$
exhaust location:	$x_E/L = 0.75$	$y_E/W = 0.88$	$z_E/H = 1.0$

Fig. 6 Variation of average concentration in each zone with door location.

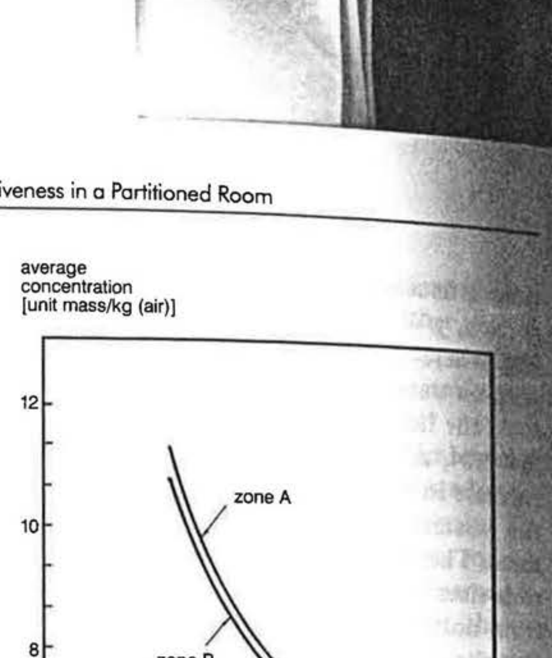


ventilation rate:	2.5 ach		
door location:	$x_D/L = 0.5$	$y_D/W = 0.5$	
supply location:	$x_I/L = 0.0$	$y_I/W = 0.46$	$z_I/H = 0.88$
exhaust location:	variable		

Fig. 8 Variation of average concentration in each zone with exhaust location.

function of the locations of door opening, supply and exhaust respectively. Note that when one parameter varies, the other parameters remain unchanged. In Figure 6, it is observed that the average concentration in zone B remains almost constant when the door position is moved along the partition, or when the inlet position is moved along the western wall. However, the door and inlet positions do affect the average concentration in zone A. It is due to the fact that (1) the inlet location affects the air vortex in zone A, and, therefore, the ability of contaminant removal; (2) although the door location does not affect the airflow pattern in zone A significantly, the relative position between contaminant source and door opening is important for the contaminant removal. The exhaust location moving on the ceiling of zone B does not seem to influence the average concentration in zone A and zone B.

Increasing the ventilation airflow rate results in a rapid decrease of the average concentration in both zones as shown in Figure 9. However, the average concentrations are not inversely proportional to the supply flow rate. When the ventilation rate is higher than 6.0 ach, the decrease of average concentration slows down. For the sake of energy saving, the appropriate ventilation rate needs to be predicted for a new arrangement of a ventilation system.



ventilation rate:	variable		
door location:	$x_D/L = 0.5$	$y_D/W = 0.5$	
supply location:	$x_I/L = 0.0$	$y_I/W = 0.46$	$z_I/H = 0.88$
exhaust location:	$x_E/L = 0.75$	$y_E/W = 0.88$	$z_E/H = 1.0$

Fig. 9 Variation of average concentration in each zone with ventilation rate.

Conclusions

The airflow pattern and the air age distribution in a ventilated partitioned enclosure are predicted by numerical simulation. The effects of door opening positions on the air movement are also investigated. The following conclusions may be drawn from this investigation.

– The average air age in the upstream zone is much lower than the age in the downstream zone (the rate is about 0.6).

– The average air age in Zone A is decreased with the door opening moving from the southern wall towards the northern wall.

– The central position of the door opening results in the highest average age in the downstream zone. When the door opening is moved to either side, the average age in this zone is decreased.

– For such an arrangement of supply and exhaust openings as described in the section of *Ventilation Effectiveness in a Two-Zone Enclosure*, the best location for a door opening in the partition seems to be near the southern wall.

– The average concentration in zone B remains almost constant when the door position is moved along the partition, or when the inlet position is moved along the western wall. In zone A, however, the door and inlet positions do affect the average concentration in this zone.

– The exhaust location moving on the ceiling of zone B does not seem to influence the average concentration in zone A and zone B.

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