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Analysis of visitation frequency through particle tracking method based on LES and model experiment

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Abstract As ventilation efficiency in a room is not always uniformly distributed, an index for measuring ventilation efficiency at a concerned point or in a concerned local domain is required. Local ventilation efficiency is often represented by the rate of the averaged concentration of the local domain to that of exhausted air from the room. From the age theory of air, it is well known that the averaged concentration in a room corresponds to the mean staying time of contaminant. Evaluating the domain-averaged concentration (C_{domain}) means evaluating the average staying time of the contaminant in the domain. It can be only one part of the whole room and can be considered as an occupied zone. Visitation frequency (VF) and the average staying time of the contaminant for one visitation in the local domain (T_p) are introduced to analyze the average staying time of the contaminant in the local domain. The value of VF is strongly affected by the position of the local domain in the room; that is, the position of the local domain in the whole flow field of the room. T_p represents the property of the flow pattern in the local domain. As the indication of VF and T_p represent the mechanism for forming the domain-averaged concentration, they are deeply related to local purging flow rate, which represents the airflow rate for defining the domain-averaged concentration. As VF and T_p are related to the contaminant transportation property, it is effective to analyze them by particle tracking method. A CFD method of large eddy simulation (LES) was thereby carried out in this study. The prediction result by LES is also validated by a precise model experiment. In this paper, the detailed analysis of VF and T_p is carried out on the basis of the particle tracking method utilizing the LES result in order to clarify the mechanism of the domain-averaged concentration. The analyzed room has one supply inlet and one exhaust outlet. A clear re-circulating flow, generated by the forced ventilation, is observed in the room. The value of VF is examined with three types of local domains in the room model. In the room model, VF shows a value of 5.70 when the local domain occupies half of the room. It becomes smaller when the size of the local domain is reduced.

Key words: Ventilation efficiency; Visitation frequency; Local purging flow rate; Model experiment.

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Practical Implications

In recent years, numerical simulation of airflow, temperature, and contaminant distribution field is used in the design of room air-conditioning or of indoor air quality. It is effective in analyzing the structure of the contaminant distribution field and can be used to design a precise controlling method. The averaged concentration in the local domain is the important controlling parameter in the local ventilation design. To analyze and evaluate the domain-averaged concentration, the contaminant distribution field is analyzed and assessed in this study with new concepts, which are visitation frequency and the average particle staying time in the domain, derived from the numerical simulation technique.

Introduction

In order to evaluate the ventilation efficiency at a concerned point or in a concerned local domain, several methods have already been proposed, such as the age theory (Sandberg, 1983) and six indices (SVE1–6), for measuring the ventilation efficiency in a room (Kato and Murakami, 1988, 1992). One of the indices of the SVE concept is the residual lifetime of air (SVE1), which corresponds to the spatial amount (i.e. average concentration) of point-source contaminant in a room. The value of SVE1 expresses the average staying time of the contaminant, the time needed for the contaminant to be exhausted from the room after it was generated.

In this paper, in order to evaluate the mechanism of the local domain-averaged concentration, visitation frequency (VF) (Csanady, 1983) and the average staying time of the contaminant for one visitation in the local domain (T_p) are introduced. The value of (VF × T_p) represents the residual lifetime of air in the local domain. As shown in Table 1, VF and T_p are strongly related to the concept of SVE1, which is based on the same concept of purging flow rate (PFR) (Sandberg, 1992). As PFR is basically applied in the entire room, local purging flow rate (L-PFR) is applied in the local domain. L-PFR is defined by the contaminant generation rate (q_p) at domain 'p' and the average concentration in that domain.

As VF and T_p are related to the contaminant transportation property, it is necessary to use a particle tracking method for detailed analysis. Large eddy simulation (LES), which enables us to use the particle tracking method, is carried out in this research. The concept of LES is to treat or solve directly the large eddies of flows more exactly than the small eddies, which are then to be modeled (Smagorinsky, 1963). The particle tracking analysis is then conducted with the results of the LES and the structure of ventilation efficiency in the local domain is investigated with the calculation of VF and T_p

In this research, the values of VF, T_p and L-PFR are examined by setting up three types of local domains in the room model. Then, under different sizes and different relative positions of the local domains, the properties of VF, T_p and L-PFR are analyzed.

Table 1 Concept of SVE1 and PFR

Whole room

$SVE1(p) = C_{room}(p)/Cs = (Q/V_{room}) \times Tr(p)$ (1)

$C_{room}(p) = \int_{room} C_x(p,x)dx / V_{room}$ (2)

$C_s = q_p/Q$ (3)

$PFR = q_p / C_{room}(p) = V_{room}/T_r(p)$ (4)

In Equations 1–4, SVE1(p) is the scale for ventilation efficiency 1 at position p, non-dimensionalized room-averaged concentration;
$C_x(p, x)$ is the contaminant concentration at x, with the contaminant generation at source point p (kg/m^3);
$C_{room}(p)$ is the room-averaged concentration with the point source p(kg/m^3);
PFR is the purging flow rate (m^3/sec);
q_p is the generation of the contaminant (kg/sec);
Q is the airflow rate of ventilation (m^3/sec);
C_s is the representative concentration;
V_{room} is the volume of the room (m^3);
T_r (p) is the mean staying time of contaminant (residual lifetime of air at point p) (sec)

$SVE1(p) = (q_p/PFR) \times (Q/q_p) = Q/PFR = (Q/V_{room}) \times T_r(p)$ (5)

Equation 5 shows a reciprocal number of PFR (normalized by airflow rate) in the whole room corresponds to SVE1 in the same whole room

Local domain

$SVE1_{domain}(p) = (C_{domain}(p)/C_s) \times (V_{domain}/V_{room}) = (Q/V_{room}) \times T_{r\ domain}(p)$ (6)

$C_{domain}(p) = \int_{domain} C_x(p,x)dx / V_{domain}$ (7)

$L\text{-}PFR = q_p / C_{domain}(p) = V_{domain}/T_{r\ domain}(p)$ (8)

In Equations 6–8, V_{domain} is the volume of the local domain (m^3);
$T_{r\ domain}$ (p) is the mean staying time of contaminant at the domain ($T_{r\ domain}$ (p) = VF × T_p);
VF is the visitation frequency (–);
T_p is the average staying time of contaminant in the local domain for one visitation (sec)

$SVE1_{domain}(p) = (q_p/L\text{-}PFR) \times (Q/q_p) \times (V_{domain}/V_{room})$
$= (Q/L\text{-}PFR) \times (V_{domain}/V_{room}) = (Q/V_{room}) \times (VF \times T_p)$ (9)

Equation 9 shows that a reciprocal number of L-PFR (normalized by the airflow rate) in the domain corresponds to SVE1

Local domain

As contaminant concentration in a room is not always uniform, it is important to evaluate the amount (averaged concentration) of the contaminant in the local domain, such as an occupied zone or breathing zone. In this paper, 'local domain' represents an occupied zone or breathing zone (not the entire room). The purpose of the research is to analyze how the local domain-averaged concentration is determined using VF and T_p.

Visitation frequency

Visitation frequency represents the number of times a particle enters the local domain and passes through it. VF = 1 means that after being generated a particle stays only once in the local domain, in other words, after leaving the local domain, the particle never returns. VF = 2 means that a particle stays in the local domain for the first time, is transported to the outside and then returns again to the local domain, due to the re-circulating flow, for only one more time.

Returning frequency (RF) represents the number of times a particle returns to the local domain except for the generation. If a particle is generated in the local domain, RF is also a useful index to directly represent this return.

The average value of VF for all particles is an important index that indicates how efficient a ventilation system is to purge/remove contaminant particles from the local domain in question. From the viewpoint of the entire flow field in a room, a low value of average VF indicates a good ventilation design for the local domain, because fewer particles of contaminant return to the local domain.

The average VF values are calculated by using Equation 10. Here, the average VF is sometimes cited without the word 'average', when it apparently expresses the average value.

As it is difficult to obtain detailed VF data from a model experiment and calculation using a RANS model, calculation of a particle tracking method based on LES is carried out in order to obtain detailed statistical information of the VF:

$$\mathrm{VF} = 1 + (J_p/M_p) = 1 + (\Delta q_p/q_p), \quad (10)$$

$$\mathrm{RF} = \mathrm{VF} - 1 = (J_p/M_p) = (\Delta q_p/q_p), \quad (11)$$

where J_p is the amount of particles, visiting (returning to) the local domain 'p' per unit time (particle/sec); M_p the amount of particles generated in the local domain (particle/sec); Δq_p the inflow rate of particles into the local domain 'p' per unit time (kg/sec); and q_p the particle-generation rate per unit time (kg/sec).

Average staying time

The average staying time of a particle in the local domain (T_p) represents the average time a particle takes from once coming/or being generated into the local domain to its leaving. Multiplying T_p by VF indicates the total average staying time (lifespan of a contaminant particle) in the local domain (see Appendix A).

Local purging flow rate

Local purging flow rate is an index of ventilation efficiency in a local domain, such as an occupied zone or confined space in a room. It was originally defined as the effective airflow rate to remove/purge contaminants from the local domain. In this paper, L-PFR has been redefined by using the concept of VF and T_p. L-PFR is redefined with the net ventilation rate by which the domain-averaged concentration of the local domain is defined; that is, L-PFR is defined as the local ventilation efficiency. Following this concept, a reciprocal number of SVE1, which evaluates the spatial amount of contaminant in the whole room, corresponds to the PFR for the same whole room. PFR represents the value of the whole room and L-PFR represents the value of only the local domain (see Appendix B).

In this paper, L-PFR is defined by the contaminant generation rate in the local domain and the averaged concentration in it; then, the value of L-PFR can be simply calculated from the concentration simulation based on the scalar transport equation (Davidson and Olsson, 1987).

As L-PFR is related to the contaminant (particle) remaining property in the domain, as represented by VF and T_p a detailed analysis of L-PFR requires information of VF and T_p (cf. Equation 12):

$$\text{L-PFR} = V_{\mathrm{domain}}/(\mathrm{VF} \times T_p) = q_p/C_{\mathrm{domain}} \quad (12)$$

where L-PFR is the local purging flow rate (m^3/sec), V_{domain} the volume of the local domain (m^3), VF the visitation frequency of particles (–), T_p the average staying time of particles in the local domain 'p' (second per staying once), q_p the particles generation rate per unit time (kg/sec), and C_{domain} the local domain-averaged concentration (kg/m^3).

Room model

The room model shown in Figure 1 is used for analyzing VF, T_p and L-PFR. The model is a cavity of dimension 1.5 m (x) : 0.3 m (y) : 1.0 m (z) in which a two-dimensional mean flow field is developed. It is equipped with 0.02-m width inlet and outlet slots.

To examine the properties of VF, T_p and L-PFR indices, three types of local domains are set up inside the room model: (i) 1/2 volume of total space for volume 1, regarded as occupied space; (ii) 1/4 volume of volume 1 for volume 2; (iii) 1/9 volume of volume 1 for volume 3, regarded as breathing space. The width (Y direction) of all three domains is the same and is identical with that of the cavity. Particle generating points are located inside the local domains for all cases. The properties of VF, T_p and L-PFR are then analyzed systematically according to the change of particle generating point. Figures 2 and 3 show the location of particle generating points and the local domain indicated on the mean streamlines, which is calculated by LES. Point 1 is the center position of occupied space [0.75 m (x), 0.15 m (y), 0.25 m (z)], point 2 is set on the floor [0.75 m (x), 0.15 m (y), 0.01 m (z)], point 3 is the center of the cavity [0.75 m (x), 0.15 m (y), 0.5 m (z)], point 4 is set at a supply inlet [0.0 m (x), 0.15 m (y), 0.99 m (z)]. Points 5(1), 5(2), and 5(3) are set near the exhaust outlet [1.5 m (x), 0.15 m (y), 0.01 m (z)], [1.485 m (x), 0.15 m (y), 0.01 m (z)], and [1.47 m (x), 0.15 m (y), 0.01 m (z)], respectively.

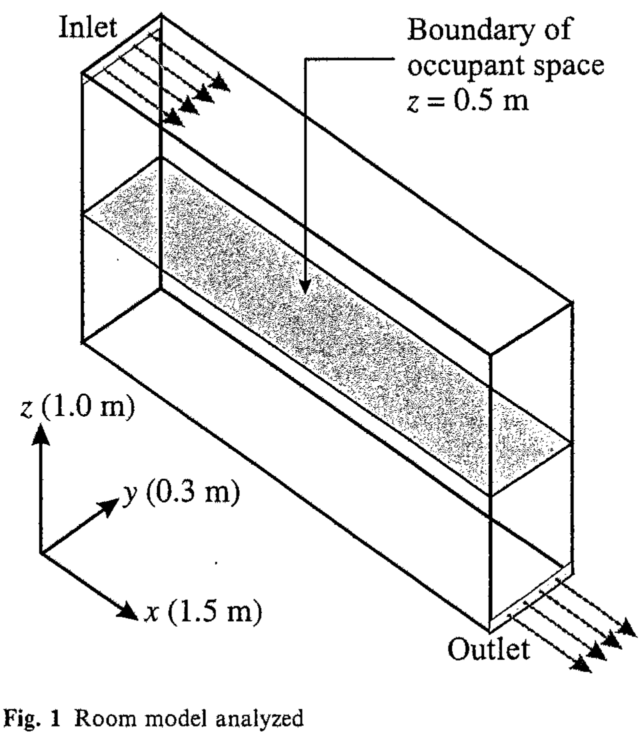

Fig. 1 Room model analyzed

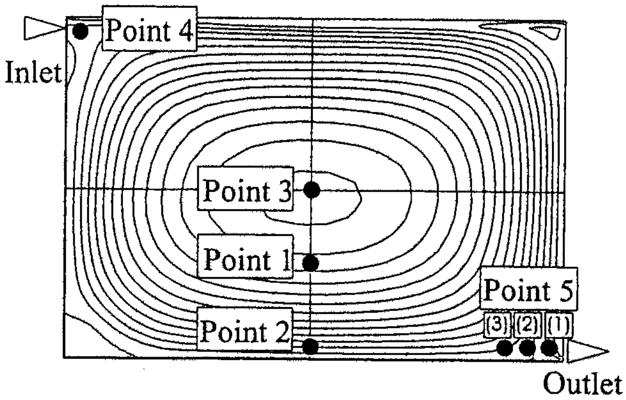

Fig. 2 Mean streamlines and particle generating points

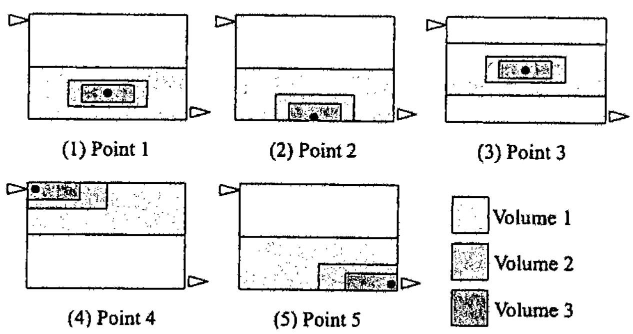

Fig. 3 Local domains for VF evaluation

Model experiment

Model

Large eddy simulation enables us to analyze VF, T_p and L-PFR in detail, as it is able to trace the movement of a particle. LES is based on a model equation of turbulent flow; it is necessary to confirm the correspondence of flow field between the calculation results and the experimental results. In order to validate the results of LES, a model experiment was carried out. A model was composed of a cavity of dimension $(x) : (y) : (z) = 1.5$ m : 0.7 m : 1.0 m, equipped with 0.02-m width inlet and outlet slots (Figure 4). This cavity is divided into three thinner cavities, separated by glass. The center working cavity [0.3 m (y) width, corresponding to the room model as shown in Figure 1], is the one where the measurements were performed, and the other two cavities [0.2 m (y) width], which are called Guard cavities, are the ones where the same flow pattern as in the working cavity was reproduced. The four boundaries (ceiling, floor, right, and left walls) consist of a water-cooling aluminum heat exchanger to control the wall surface temperature (Blay et al., 1992).

Experimental condition

Air inlet velocity (U_{in}) is set at 3 m/sec. Inlet air and all the walls are controlled in isothermal condition (25°C). The supply inlet slot (0.02 m) is positioned along the ceiling and the exhaust outlet slot (0.02 m) is set along the floor on the other sidewall.

Figures 5 and 6 show the longitudinal discharge velocity profile in the horizontal direction (Y) along the inlet slot and the transversal jet velocity profiles, which are measured near the slot at $Y = 150$, 300, 350 mm, respectively. Figure 7 shows the longitudinal discharge velocity profiles in the Y direction below the ceiling ($Z = 950$ mm) and above the floor ($Z = 50$ mm); both are at the same X coordinate (750 mm). As shown in Figures 5–7, a good two-dimensional mean flow was obtained in the cavity.

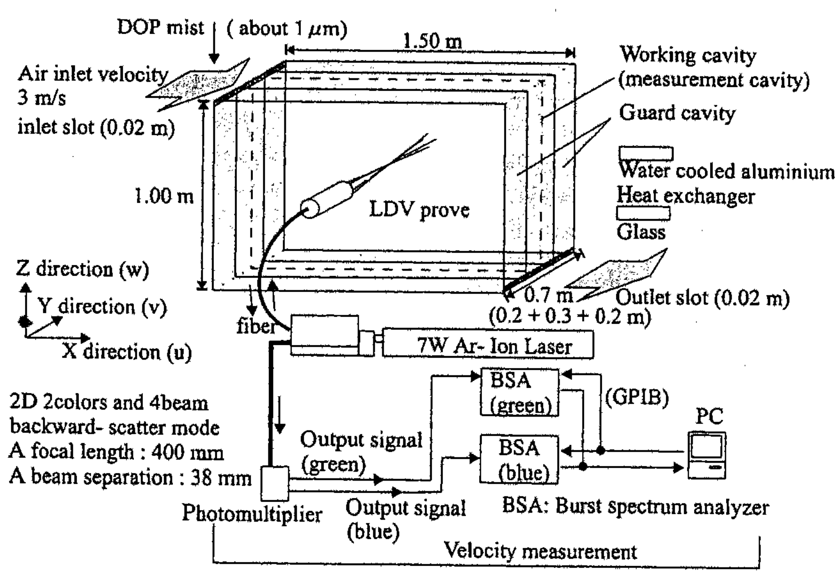

Fig. 4 Experiment model and LDV system

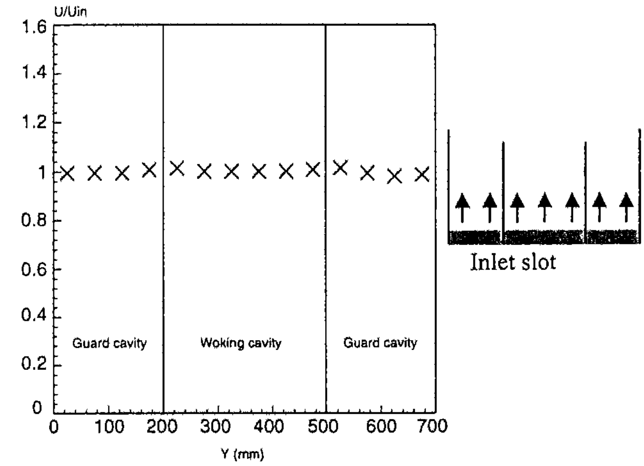

Fig. 5 Horizontal profile of U_{in}

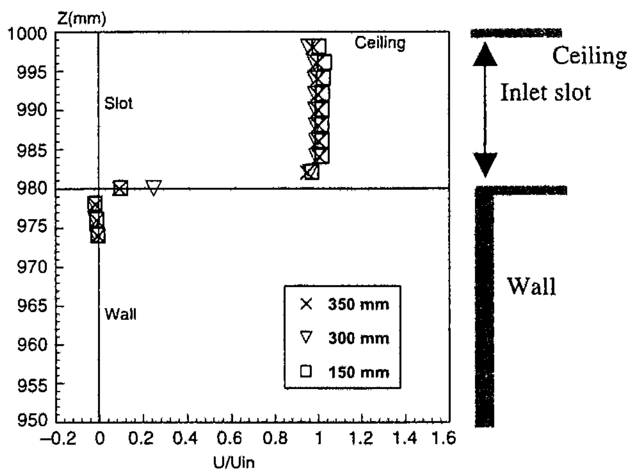

Fig. 6 Vertical profiles of U_{in}

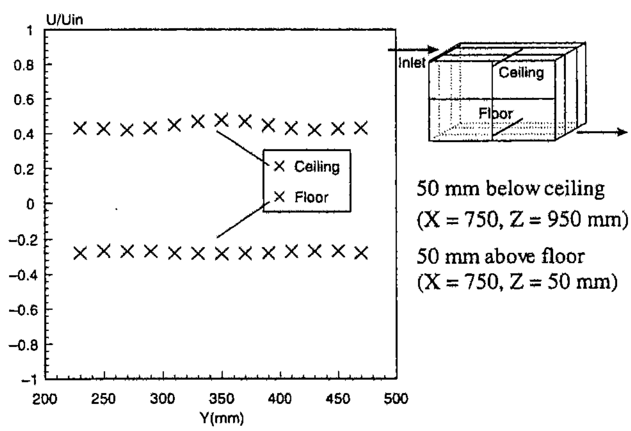

Fig. 7 Horizontal profile of U

Numerical methods and boundary conditions

Large eddy simulation was carried out under the same conditions as in the experimental case, where the sub-grid stress was calculated by the dynamic Smagorinsky model (Germano et al., 1991). A second-order center difference scheme was used for the spatial derivatives. The third-order Runge–Kutta scheme was used for time advancement (Table 2). To analyze the flow field in the boundary layer, the center of the computational cells closest to the wall surface should be at a non-dimensional distance of $y+ < 3$, $y^+ = u^* y_1/\nu$, where y_1 is the distance normal to the wall surface, ν the kinematic viscosity, and $u^* = \sqrt{\tau_w/\rho}$ the friction velocity. Here, ρ is the density and τ_w the wall shear stress. The inequality interval mesh is used for this analysis.

Particle tracking was carried out based on the simulated flow field. Particles were transported by convection of resolvable velocity predicted by LES, whilst the effects of sub-grid scale motion were ignored. One particle is generated per-unit time of 6.67×10^{-4} sec interval, until the total of 75,000 particles were generated. Particle tracking was carried out continuously for 95 sec (nominal time constant of this model room $\tau_n = 25$ sec), in which more than 88% of the total generated particles were exhausted through the exhaust outlet.

The values of VF, T_p and L-PFR vary greatly depending on the position of the particle generating point in the domain. Thus, one of the most representative methods of particle generation would be uniform generation throughout the local domain. However, in order to analyze the subtle difference of VF according to the particle generating points, it is useful to generate at one single-point source as selected here.

Results and discussion

Mean velocity

The comparison of the mean velocity between LES and the model experiment is shown in Figure 8. They are in good agreement. LES is proved to reproduce the experimental flow well.

Using the flow field calculated by LES, particle tracking was carried out. The movements of eight particles from generation to exhaust are as shown in Figure 9.

Table 2 LES boundary condition

SGS model	Dynamic Smagorinsky model
Computational domain	$75L_0(x) \times 15L_0(y) \times 50L_0(z)$, L_0=0.02 m (inlet slot)
Number of grid points	$48(x) \times 23(y) \times 46(z)$
Derivative scheme	Spatial derivatives: a second-order center difference scheme Time advancement: the third-order Runge–Kutta scheme
Inflow boundary	U_{in}: experimental data
Wall boundary	Linear-power law

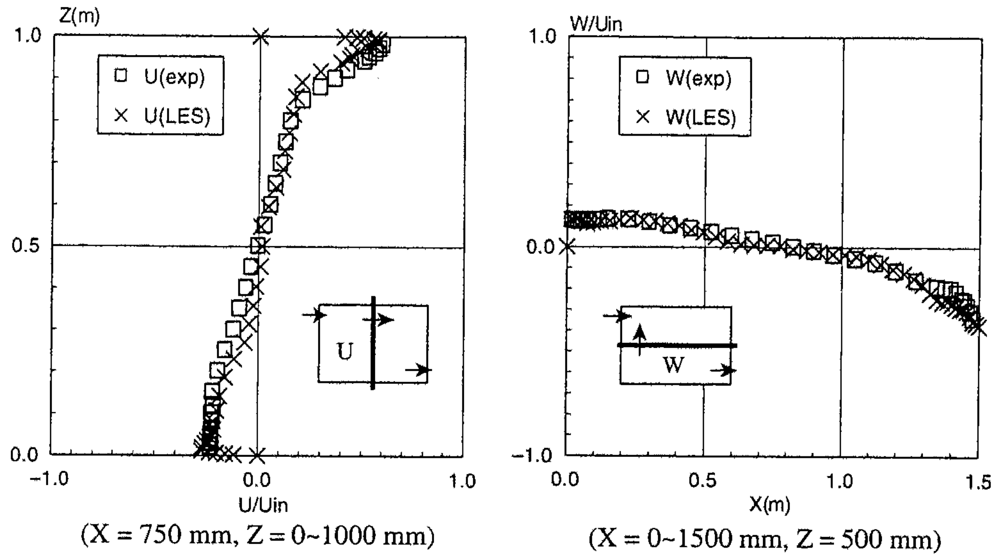

Fig. 8 Comparison between LES and experiment

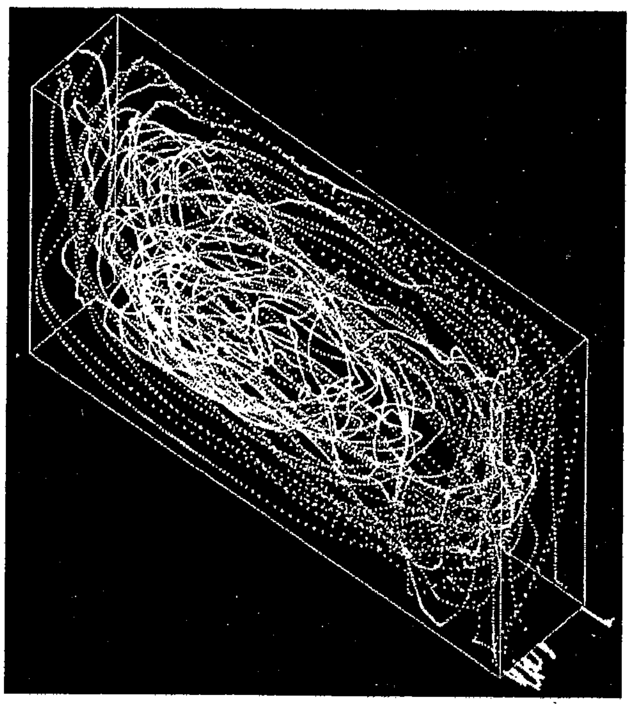

Fig. 9 Movement of eight particles from generation to exhaust

Visitation frequency

In this analysis, T_p is normalized by the nominal time constant ($=\tau_n = Q/V_{room}$), C_{domain} is normalized by the perfect mixing concentration (=representative concentration C_s) and L-PFR is normalized by the airflow rate of ventilation ($=Q$).

Large local domain (*volume 1*). Figure 10 shows the probability distribution of VF at each local domain (volumes 1–3).

In the case of volume 1, in which the generating points are located at points 1–3 [Figure 10(1), (4), (7)], the maximum probability value of VF (mode) exists at VF = 2. The probability of higher VF then decreases gradually.

This can be explained from the clockwise re-circulating flow in the room. After being generated in the domain (VF = 1), the particles were transported farther from the outlet position and then have to return back to volume 1 (VF = 2) to be exhausted through the outlet that is located in the lower-right part of the room.

As shown in Figure 10(7), in the case of generating point 3 (located at the center of the room model), the mode value (VF = 2) becomes the lowest one, compared to other generating point cases. In this case, the tail of the VF distribution (VF probability) becomes the longest. It means that the average VF value becomes the highest.

In the case of generating points 4 (located near the supply inlet) and 5(1) (located very near the exhaust outlet), the mode exists at VF = 1. The amount of particles (probability distribution) is decreasing exponentially.

In the case of generating point 5(1), 86% of the particles are directly exhausted after being generated, as its location is nearest to the exhaust outlet, compared to the other generating points.

In the case of generating point 3, the standard deviation and median value become the highest values, 5.59 and 6.68, respectively.

In the case of generating point 4, the probability at its mode becomes higher than those of generating points 1 and 2. Thirty-four per cent of the particles generated at point 4 are exhausted directly. Point 4 is located on the mean streamline that is connecting the

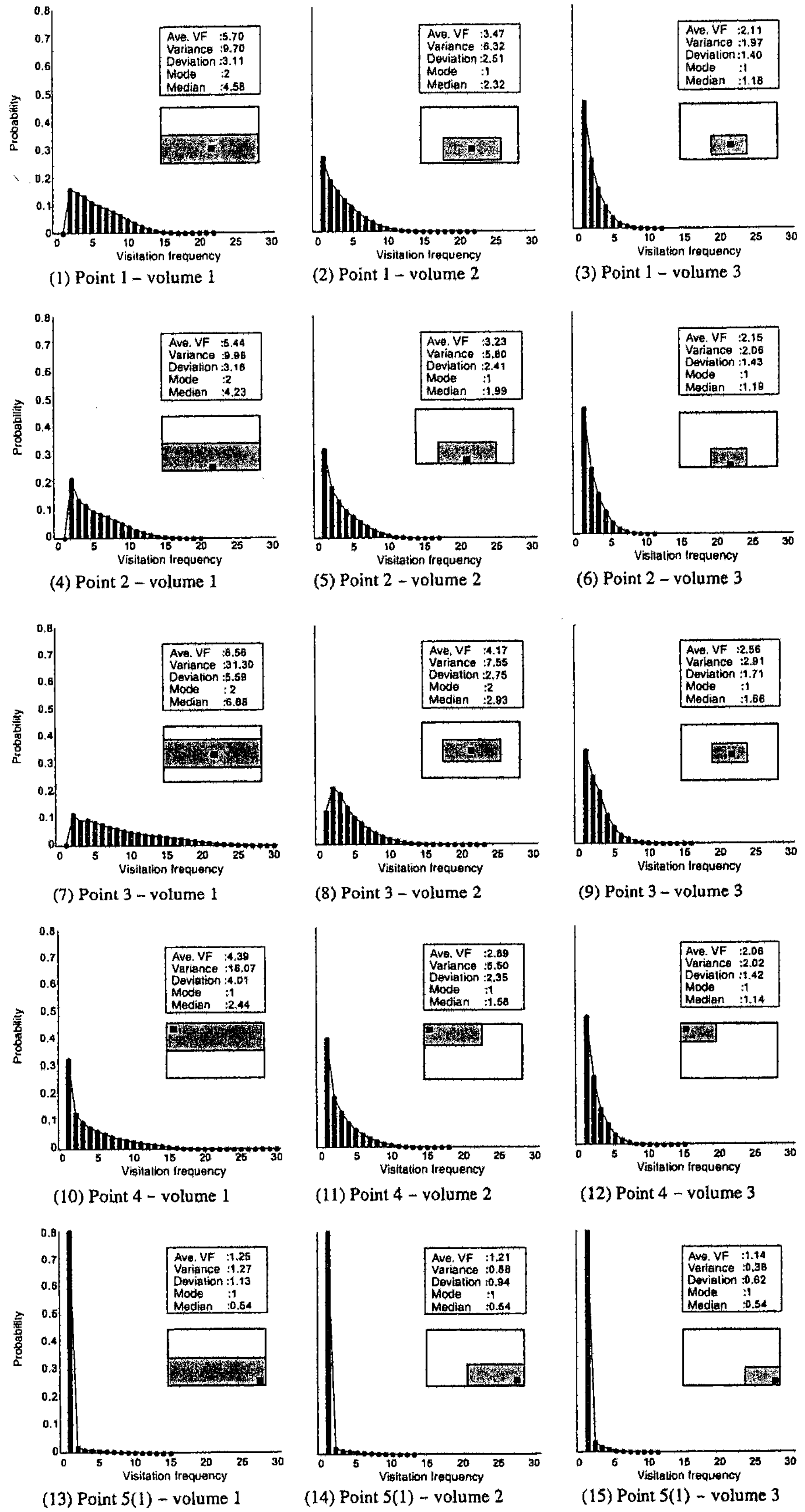

Fig. 10 Probability function of VF

supply inlet and exhaust outlet, and particles generated are transported to the exhaust outlet directly by the mean flow. The remaining 66% of particles have characteristics similar to those of generating points 5(3) and 2, as the relative position to the main flow streamline is the same.

Middle local domain (*volume 2*). In the case of volume 2, the mode of the distribution exists at VF = 1 in all generating points except generating point 3, and the probability of higher VF decreases gradually. Comparing with the case of volume 1, the probability of mode is higher and variance and deviation are smaller.

Small local domain (*volume 3*). In the case of volume 3, the mode of the distribution exists at VF = 1 in all generating points. From the mode position, the probability of higher VF decreases exponentially. In the case of smaller domains (the volume of the local domain = 1/18 of the model room volume), the probability distribution of VF becomes almost the same even though the positions of the domains in the room are different. The only exception is the case of generating point 5.

The value of standard deviation in the cases of the smaller domains (volume 3) becomes smaller than that of larger ones (volume 1). These results suggest that when a local domain becomes smaller to a certain degree, a large flow field structure in the room does not affect its VF characteristics. The VF characteristics of smaller domains depend on their surrounding turbulence characteristics; however, this is independent of the large-scale mean flow structure in the room.

Table 3 The statistical analysis of VF, T_p and L-PFR

	Point 1	Point 2	Point 3	Point 4	Point 5(1)	Point 5(2)	Point 5(3)
(a) Local domain (volume 1)							
VF	5.70	5.44	8.56	4.39	1.25	2.16	3.88
T_p	0.16	0.09	0.12	0.09	0.03	0.08	0.10
C_{domain}	1.79	1.01	2.08	0.83	0.08	0.34	0.74
L-PFR	0.56	0.99	0.48	1.21	13.10	2.94	1.35
(b) Local domain (volume 2)							
VF	3.47	3.23	4.17	2.89	1.21	1.90	3.33
T_p	0.06	0.02	0.06	0.02	0.01	0.01	0.01
C_{domain}	1.85	0.51	2.00	0.45	0.06	0.17	0.36
L-PFR	0.54	1.96	0.50	2.24	15.5	5.96	2.74
(c) Local domain (volume 3)							
VF	2.11	2.15	2.56	2.08	1.14	1.53	2.34
T_p	0.03	0.01	0.03	0.01	0.003	0.01	0.01
C_{domain}	1.33	0.32	1.45	0.33	0.07	0.15	0.26
L-PFR	0.75	3.12	0.69	3.03	13.59	6.84	3.90

T_p is normalized by nominal time constant ($=\tau_n=Q/V_{room}$).
C_{domain} is normalized by perfect mixing concentration (=representative concentration C_s).
L-PFR is normalized by airflow rate of ventilation ($=Q$).

Discussions. Table 3 shows the average value of VF for each case. T_p is normalized by a nominal time constant ($=V/Q = 25$ sec), L-PFR is normalized by supply airflow rate (Q), and C_{domain} is normalized by the mean concentration of the exhaust outlet. Figure 11 shows VF and T_p distribution at each local domain (volumes 1–3). In order to perform a good ventilation design, it is important to reduce the value of VF and T_p.

As shown in Table 3 and Figure 11(1), in the case of volume 1, the average VF becomes the highest at generating point 3 (8.56). This is because volume 1 in the case of generating point 3 has two open boundaries (other boundaries are closed or adjacent to the walls), while volume 1 in cases of other generating points has only one open boundary. Also from Table 3a, the average VF value of point 2 is smaller than that of point 1. This is because point 2 exists on the mean streamline that passes close to the exhaust outlet. In the cases of points 5(1), (2), and (3), where the particle generating points are located near the exhaust outlet, the average VF of point 5(1) almost equals 1. However, in the case of point 5(3), it becomes higher at 3.88, and is almost the same with the cases of points 2 and 4. It means that generating points 5(3), 2, and 4 are located on almost the same mean streamline.

In the case of volume 1 [Table 3a and Figure 11(1)], the average VF of point 3 becomes the highest value, and the average VF is gradually decreased in the order of points 1, 2, 4, then the lowest, point 5. This tendency is almost the same for volume 2 [Table 3b and Figure 11(2)] and volume 3 [Table 3c and Figure 11(3)].

The average particle staying time in the domain for one visitation (T_p)

Large local domain (*volume 1*). Figure 12 shows the probability distribution of T_p at each local domain (volumes 1–3).

As shown in Figure 12(1) and (7), in the case of volume 1 for generating points 1 and 3, the average values of T_p take high values, and the variance and deviation values of T_p also become high. This tendency is similar for the probability distribution of VF [Figure 10(1) and (7)].

The T_p distributions of volume 1 for points 2 [Figure 12(4)] and 4 [Figure 12(10)] have the same probability distribution. This indicates that both the particle generating points are located on the same streamline, which forms a strong re-circulating flow along the wall.

Middle local domain (*volume 2*). In the case of volume 2 (Figure 12), values for points 1 and 3 become different in magnitude from those of points 2, 4 and

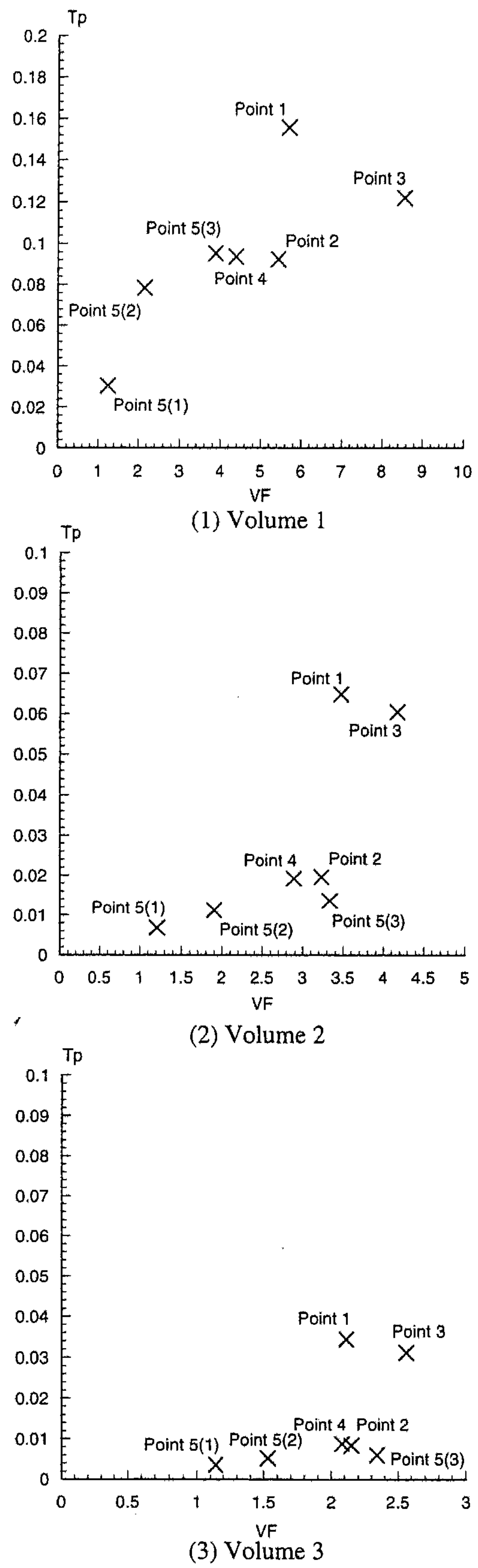

Fig. 11 VF–T_p distribution

5(1). T_p for points 1 and 3 [Figure 12(2), (8)] shows an average T_p of 0.06 (normalized); however, in the case of points 2, 4, and 5(1) [Figure 12(5), (11), and (14)], they are in the range of 0.01–0.02. In the case of volume 2 for generating points 1 and 3, the average and deviation values of T_p become higher, compared with those of other points for the same volume 2.

Small local domain (*volume 3*). The average and deviation value of T_p becomes smaller comparing with volumes 1 and 2.

Discussions

As shown in Table 3a and Figure 11(1), in the case of volume 1 for generating point 1, the average T_p becomes the highest value (0.16), compared with those of other generating points and also other volumes (Table 3b and c). The average T_p of generating points 2, 4, and 5(3) are similar and are about 0.10, as they are located on the same streamline, which forms a strong re-circulating flow along the wall.

As shown in Table 3b and Figure 11(2), in the case of volume 2 for generating points 1 and 3, average T_ps are three to six times higher than other generating points. For volume 3 [Table 3c and Figure 11(3)], the tendency of the average T_p variation is almost similar to that of volume 2, but the absolute values of average T_p are relatively small.

Domain-averaged concentration and local purging flow rate

The ventilation efficiency index for a local domain, C_{domain} is well explained by its VF and T_p Table 3 shows the domain-averaged concentration at each local domain. Here, both L-PFR and C_{domain} are normalized and thereby their product always becomes 1.

Figure 13 shows the L-PFR distribution at each local domain (volumes 1–3). The value of L-PFR in the case of volume 1 for particle generating point 5(1) exceeds the value of 13.0. This is because the generated particles are purged/removed efficiently before diffusing in the room. In the case of points 4, 5(1), (2), and (3), in which the particle generating points are located near the supply inlet or the exhaust outlet, the values of L-PFR reach over 1.0. This means that the regions near the inlet and outlet are ventilated with the same quantity of supply airflow rate.

In this analysis, the smaller the local domain (volume 1 → volume 2 → volume 3), the larger the L-PFR obtained for all the cases. This phenomenon indicates that the product of VF and T_p decreases faster with the decrease of domain volume.

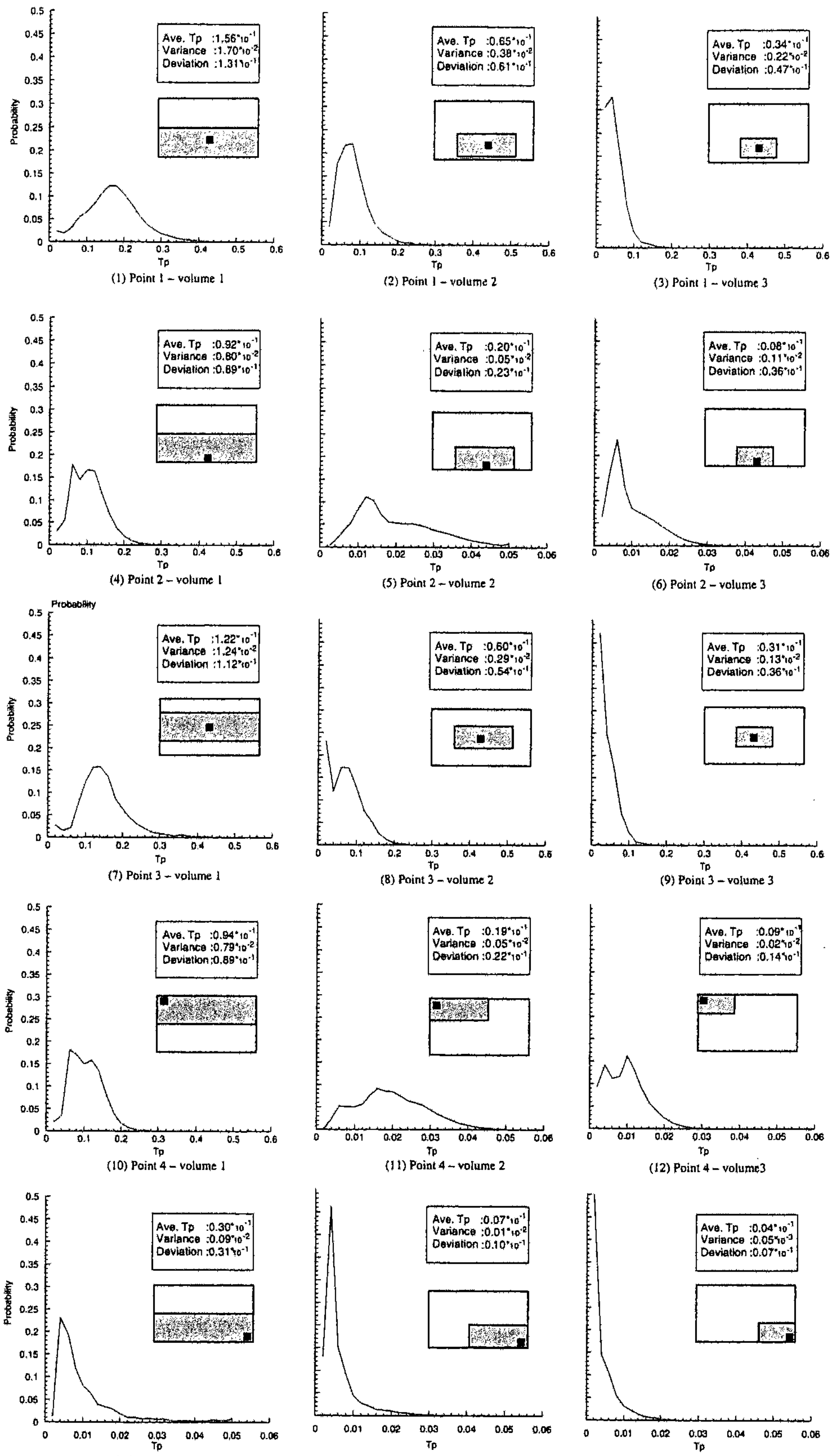

Fig. 12 Probability function of T_p

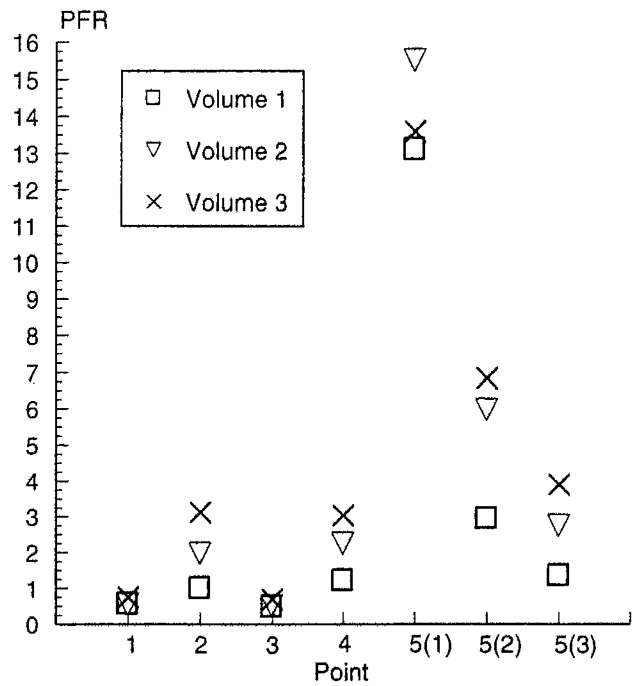

Fig. 13 L-PFR distribution

Concluding remarks

1. A reciprocal number of SVE1 (non-dimensionalized spatial amount of contaminant) that evaluates the spatial amount of contaminant in a whole room corresponds to PFR in the same whole room. L-PFR in a local domain has the same characteristics of SVE1 that is applied in the local domain. L-PFR consists of VF and T_p. They indicate the structure of the ventilation efficiency (C_{domain}) of the local domain.
2. VF and T_p characteristics in the model room were analyzed by a particle tracking method based on LES. The prediction results of flow field by LES agreed well with measurements by the precise model experiment.
3. Using the results of the particle tracking analysis based on LES, under different particle generating points, the changes of the VF property were analyzed systematically. The average value and the standard deviation of VF for generating point 3 that is located at the center of the cavity is the largest compared with other cases. It indicates that the movements of the particles generated at the center of the cavity, which was located in the closed-curve mean streamline, varied widely.
4. T_p in the case of particles generated near the supply inlet, exhaust outlet, and the floor show low values, as these generating points are all located on the same re-circulating flow along the walls. For cases of particles generated at the center of the cavity, the value of T_p becomes high due to the closed-curve mean streamline (diffusive flow field).
5. For L-PFR analysis, the smaller the local domain, the larger the L-PFR obtained for all the cases. For the cases of particles generated near the supply inlet and exhaust outlet, L-PFR values reach more than 1.0.

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Appendix A

Although calculation of a particle tracking method based on large eddy simulation is carried out in order to obtain the statistical detailed information of VF, T_p and L-PFR, they can be estimated using the RANS model calculation also (Davidson and Olsson, 1987). The authors have carried out the calculation of VF, T_p and L-PFR based on the averaged contaminant distribution estimated by the standard k–ϵ model. Details are shown in Ito et al. (2000) and the results are omitted in this paper.

Appendix B

L-PFR was originally defined as the effective airflow rate to remove/purge contaminants from the local domain. Therefore, originally we use equilibrium concentration in the local domain to define L-PFR. In this case, L-PFR cannot be greater than the ventilation flow rate. As shown in Equation 12, in the case of the newly introduced L-PFR concept, L-PFR has the case that exceeds more than the ventilation flow rate because L-PFR shows the ventilation efficiency in the local domain.