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NEW VENTILATION EFFICIENCY SCALES BASED ON SPATIAL DISTRIBUTION OF CONTAMINANT CONCENTRATION AIDED BY NUMERICAL SIMULATION

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ABSTRACT

Three new scales for measuring ventilation efficiency in a room are defined in order to evaluate the distributions of "ventilation effectiveness" at each point in a room. They are calculated based on the distributions of contaminant concentration in a room,

1. SVE1 (**Scale for Ventilation Efficiency** 1): the spatial average of contaminant concentration in a room where contaminants are generated at a single-point source. It is a function of position, because the averaged value differs according to the location of each source point. This value is defined as a representative of spatial distribution.
2. SVE2: the mean radius of contaminant diffusion in a room. It is defined as the standard deviation of contaminant distribution. It is also a function of position and is defined as another representative of spatial distribution.
3. SVE3: the concentration at a given point in a room, where the contaminant is uniformly generated throughout the room.

SVE1 and SVE2 for one point are calculated from the distribution of contaminant concentration where the contaminant source is located at the point in question. Therefore, SVE1 and SVE2 for all points are obtained by changing the position of the source point to include the entire space. In order to confirm the usefulness of these new scales, the characteristics of ventilation efficiency in an actual conventional flow type of clean room are analyzed by these scales, which are given by calculating the results of three-dimensional numerical simulation of flow and diffusion field based on the k-ε two-equation model.

INTRODUCTION

The major object of ventilation in a room is to replace contaminated air with fresh clean air as quickly as possible. The air exchange rate has been widely used as an overly simple measure of the efficiency of this process. However, while the air exchange rate does explain the overall ventilation effectiveness in a room, it does not represent the ventilation efficiency at each point. If the air exchange rates at each point are conceived imaginatively, their values are sure to be influenced greatly by the airflow pattern. The efficiency of contaminant exhaust and the movement of fresh air to the point in question differ according to the position of the point within the flow field (cf. Figure 2). As there are many fields of high technology in which strict contamination control is required, clean rooms are now in wide use. In order to achieve stringent control of the environment, it seems requisite to deal with the velocity and diffusion field distributions within the room rather than with the overall ventilation effectiveness as before and also to clarify the ventilation efficiency at each point within a room.

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In this study, in order to evaluate the ventilation efficiency at each point within a room, three new scales are defined. Their usefulness is examined by calculating the values of the three scales for all points within a conventional flow type of clean room in actual use.

METHODS IN PRESENT USE FOR ASSESSING VENTILATION EFFICIENCY

There are many varieties of methods or concepts for designing ventilation, for example, (1) air exchange rate; (2) effective method of exhausting contaminants with least dispersion; and (3) effective method of supplying fresh air to the required area with least contamination. The latter two require methods for predicting and controlling the velocity and diffusion fields in a room. The new concept of ventilation efficiency to be proposed here also requires evaluation of the velocity and contaminant distribution fields. Much research has already been carried out in this area. Three approaches have been used: (1) multicell air diffusion theory (e.g., Skaret and Mathisen 1983); (2) age distribution theory (e.g., Chen 1969; Sandberg and Sjoeberg 1983); and (3) numerical and experimental study of flow and diffusion fields (Murakami, et al. 1983; Ishizu and Kaneki 1984; Murakami and Kato 1986; Kato and Murakami 1986).

The former two approaches, multicell air diffusion theory and age distribution theory, are very useful in comprehending overall ventilation effectiveness in a room. However, those theories do not deal directly with the spatial distributions of velocity and contaminant. Such methods thus have both merits and demerits. It is convenient to be able to evaluate ventilation efficiency without measuring or analyzing the flow field, ~~because the measurement or analysis of the three-dimensional airflow in a room is very~~ tedious work. However, the most fundamental and most important procedure, analyzing precisely the characteristics of the flow field and the spatial distribution of the contaminant, remains to be clarified.

At present, the development of an anemometer that can discern the components of turbulent flow (Murakami and Komine 1980) and also the development of numerical simulation for turbulent flow enable us to precisely analyze the flow field in a room (Murakami, et al. 1987). Therefore, it has become possible to analyze the contaminant diffusion field with consideration for details of the airflow pattern. In analysis of contaminant diffusion, spatial distributions of contaminant concentration are very useful for designing room ventilation systems, especially for cases in which the contaminant source point is previously determined. From examining such a spatial distribution of contaminant concentration, one can know which area is dangerous because of highly contaminated air and what air exchange rate is needed in even the most contaminated area for a given air quality standard to be satisfied.

The spatial distributions of contaminant concentration give the most fundamental and direct information on ventilation efficiency: (1) the concentration near the contaminant source tells us whether or not the ventilation near that area is sufficient, and (2) the distribution pattern of concentration in the room tells us where the contaminants remain unexhausted and where the contaminants are exhausted smoothly.

However, the analysis of the spatial distribution pattern of contaminant concentration possesses the following defects: (1) Because the distribution is given according to an individual source point, it depends on the position of the contaminant source. (2) There seems to be no decisive and simple index that represents the ventilation efficiency based on the spatial distributions of contaminant. (3) No methods have been proposed to integrate those different distribution patterns for each point in a room.

NEW CONCEPT OF VENTILATION EFFICIENCY

As mentioned above, the spatial distribution of contaminant concentration well reflects the characteristics of the flow field and its ventilation effectiveness. In order to deal with the spatial distribution of contaminant concentration, the airflow in a room is assumed to be in a steady state and the diffusion process of contaminants is also assumed to be stationary. In this case, contaminants are, of cource, generated constantly. The following are required for the new ventilation efficiency scales:

1. The scales must necessarily and sufficiently represent the characteristics of the spatial distribution of contaminant concentration for each contaminant source point.
2. A simple and universal method for quantitatively expressing the distribution pattern of contaminant must be derived.

The contaminant diffusion pattern varies with the different contaminant source points. If the contaminant source point is different, the concentration at the point would be different even though the contaminant generation rate is the same. Therefore, the concentration at one point alone should not be related directly to the universal scale of ventilation efficiency. However, if one wants to relate the spatial distribution of contaminant concentration to the scale of ventilation efficiency, there are at least two methods. The heart of the concept is how to realize the universality of the contaminant source.

1. One solution is the idea of a generalized contaminant source; that is, for evaluating the ventilation efficiency, only one distribution of contaminant concentration for the generalized contaminant generation should be dealt with. The generalization of contaminant source should be realized in this study by the uniform generation of contaminants throughout the room. In this condition, the different contaminant distributions given by different room shapes or different ventilation systems could be compared and assessed on a common evaluation basis, which is the the uniform generation of contaminant throughout the room. And this concentration at each point may be relatable to the scale of the ventilation efficiency at the point. This idea is defined here as **"Scale for Ventilation Efficiency 3,"** as shown later (cf. Figures 15~20).
2. The other solution is to realize the universality of contaminant generation by integrating and synthesizing the distributions given at each source point in the room. If the characteristics of the distribution pattern of the contaminant can be expressed by quantitative parameters, the integration and synthesization of the different distribution patterns can be achieved by obtaining the spatial distribution of those parameters. In this process, the contaminant source point is moved throughout the room and the universality of contaminant generation should be realized. This quantitative parameter, which represents the distribution pattern, may be relatable to the ventilation efficiency at the point. In this study, two types of distribution moments are used for representing the contaminant distribution. By this method, **Scale for Ventilation Efficiency 1** and 2 will be defined later (cf. Figures 9~11, 12~14).

Moment Expansion

Generally, the distribution function can be expanded by the moment series. Thus, the spatial distribution of contaminant concentration can also be expanded by the moment series. The distribution function of contaminant concentration is transformed into the Fourier transformation.

$$C_k(k)=\int_{v(x)} C_x(X) e^{-2i\pi kX}\, dX \tag{1}$$

here, $C_x(X)$ = concentration at : $X(x,y,z)$
$C_k(k)$ = Fourier transformation of $C_x(X)$
i = imaginary unit $\sqrt{-1}$
X = position vector (X,Y,Z)
k = wave number vector (k_x, k_y, k_z)

The right-hand term of Equation 1 leads to Equations 2 and to 3.

$$C_k(k) = \int_{v(x)} C_x(X) \cdot e^{-2i\pi kx\cdot X} \cdot e^{-2i\pi ky\cdot Y} \cdot e^{-2i\pi kz\cdot Z}\, dX \tag{2}$$

$$C_k(k) = \frac{\sum(-2i\pi kx)^l}{l!} \cdot \frac{\sum(-2i\pi ky)^m}{m!} \cdot \frac{\sum(-2i\pi kz)^n}{n!} \cdot \int_{v(x)} X^l \cdot Y^m \cdot Z^n\, C_x(X)\, dX \tag{3}$$

Equation 3 expresses that the Fourier transformation of contaminant distribution, $C_k(k)$, is expanded with the series in which the moments of the contaminant distribution, $\int_{v(x)} X^l \cdot Y^m \cdot Z^n\, C_x(X)\, dX$, are their coefficients. Thus, the moments of the distribution determine the Fourier transformation of the distribution and also determine the distribution itself.

Low Order Moments

In this study, the low order moments of the spatial distribution of contaminant concentration, which are most important, are used for the scales of ventilation efficiency.

(1) zero-th moment (amount of contaminant within the space)

$$C_0 = \int_{V(X)} C(X)\, dX \tag{4}$$

(2) first moment (center of gravity of the contaminant distribution)

$$X_0 = \int_{V(X)} X \cdot C(X) dX \,/\, C_0 \tag{5}$$

(3) second moment (square of standard deviation of the contaminant distribution)

$$X_1^2 = \int_{V(X)} (X-X_0)^2 \cdot C_X(X)\, dX \,/ C_0 \tag{6}$$

The meaning of the moments shown above are explained in Figure 1 by comparing them to those of the probability density function of turbulence velocity fluctuation.

DEFINITION OF VENTILATION EFFICIENCY SCALE AND ITS PHYSICAL MEANING

Scale for Ventilation Efficiency 1 (SVE1)

The first scale for ventilation efficiency (SVE1) is the spatial average of the contaminant concentration, which corresponds to the zero-th moment of the distribution function divided by the room volume. This spatial average of concentration is made dimensionless by dividing by the average concentration at exhaust.

$$SVE1(X_s) = C_0(X_s)/(C_s \int_{V(X)} dX) \tag{7}$$

here, $C_s = q/Q$ (8)

$$C_0(X_s) = \int_{V(X)} C_X (X_s, X) dX \tag{9}$$

$SVE1(X_s)$ (-)= scale for ventilation efficiency 1 at the position of X_s. Distribution of SVE1 (X_s) is obtained by scanning the whole space by changing the position of the contaminant source.

$C_X(X_s, X)$ (kg/m³)= the contaminant concentration at X, with the contaminant generation at source point X_s.

q (kg/s)= generation rate of contaminant.

Q (m³/s)= airflow rate.

C_s (kg/m³)= The representative concentration (equal to the average concentration at exhaust).

SVE1, the spatial average of concentration, expresses the time contaminants stay in a room. In a situation where the contaminant generation and exhaust are stationary, the averaged concentration in the space seems to be exactly proportional to the averaged time the contaminant stays in the room. The meaning of this condition will be easily explained by what follows. Figure 2 shows the variation of SVE1 according to position. If the contaminants are generated near the exhaust, at point C, the contaminants are smoothly exhausted and the spatial average concentration may be expected to be small. However, if the contaminants are generated within the recirculating flow, at point B, the contaminants are likely to stay longer in the room and the spatial average concentration value will increase, in spite of the constant generation and constant exhaust of contaminant. If the contaminants are generated in the supply jet, the contaminants diffuse well. The concentration of contaminant in the room becomes uniform and approaches the value of one.

It should be noted that the concentration of contaminant is dimensionless. And in a situation where the contaminant is mixed with air prior to arrival at the supply jet, the average spatial concentration is equal to 1. The conditions where contaminants are completely mixed with air is the 'standard condition' for the contaminant diffusion field. Therefore, if the value is below 1, it means that the ventilation efficiency in the room is relatively good and that the contaminant is likely to be easily exhausted. If it exceeds 1, it means that the ventilation efficiency is relatively poor and that the contaminant is likely to stay longer in the room.

The SVE1 at one point is calculated from the distribution of contaminant concentration where the contaminant source is located at the point in question. Figure 8 shows an example of the distribution where contaminants are generated at the center of the room. In this situation, the SVE1 defined at the source point is obtained. The distribution of SVE1 is obtained by scanning the whole space by changing the position of the source point. Figure 9 shows an example of the distribution of SVE1. Here, more than 100 cases of contaminant distributions are simulated.

Scale for Ventilation Efficiency 2 (SVE2)

The second scale for ventilation efficiency (SVE2) is the square root of the second moment of the contaminant concentration.

$$SVE2(X_s)^2 = \int_{v(x)} \{X - X_G(X_s)\}^2 \cdot C_x(X_s, X) dX / C_0(X_s) \tag{10}$$

here, $X_G(X_s) = \int_{v(x)} X \cdot C_x(X_s, X) dX / C_0(X_s)$ (11)

$SVE2(X_s)$ (m)= Scale for Ventilation Efficiency 2 at the position X_s. Distribution of SVE 2 (X_s) is obtained by scanning the whole space by changing the position of the contaminant source.

$X_G(X_s)$ (m)= The center of gravity for the contaminant distribution. As is shown in Equation 11, this term is defined as the first moment of the distribution.

SVE2, the square root of the second moment of the contaminant distribution, expresses the mean radius of contaminant diffusion. In the calculation of the second moment of the concentration, the center of gravity of the concentration distribution is set at the origin of the coordinates. The distribution of SVE2 is obtained by scanning the whole space by changing the position of the source point. Figure 12 shows an example of the distribution of SVE2. Here, more than 100 contaminant distributions are simulated.

Because the concentration distribution is three-dimentional, six components of second moments are obtained; three are normal moments and three are cross-moments. In this study, the resultant radius, which is the square root of the sum of three normal second moments, is used for the mean radius of diffusion.

In the condition where concentration is uniform in a room, that is to say, the standard condition' for the contaminant diffusion field, contaminants thoroughly spread and diffuse into the room. The value of SVE2 become very large. The minimum possible value of SVE2 is, of course, zero. Figure 2 shows the variations of SVE2 according to position. If the contaminants are generated near the exhaust, at point C, the contaminants are exhausted without diffusion. In this case, the value of SVE2 is expected to be small. However, if the contaminants are generated at the supply outlet, the contaminants spread and diffuse throughout the room. The SVE2 is expected to be the largest.

Scale for Ventilation Efficiency 3 (SVE3)

The third scale for ventilation efficiency (SVE3) corresponds to the mean traveling time required by the supplied air mass to reach the point concerned. It is defined as the concentration in the case of uniform contaminant generation throughout a room.

$$SVE3(X) = C_x'(X)/C_s \tag{12}$$

here, $C_s = q/Q$ (13)

SVE3(X)(-)= Scale for Ventilation Efficiency 3 at position X.

$C_x'(X)$ (kg/m^3)= the contaminant concentration in case of uniform contaminant generation throughout a room. The amount of contaminant generation rate is q.

SVE3, the concentration with uniform contaminant generation, is the index that shows how long the fresh clean air travels through the room before it reaches the point in question.

In a situation where the contaminant is generated uniformly and continuously throughout a room, the air mass from a supply outlet is gradually contaminated as it travels in the room by being mixed with the generated contaminants. Its concentration may be regarded as proportional to the time elapsed from when the air mass leaves the supply outlet until it reaches the point. Therefore, in the case of uniform and continuous contaminant generation throughout the room, the concentration at the point corresponds to the mean traveling time of the supplied air mass to the point concerned. It may be noted that there would be many passages from the supply outlet to the point concerned so that the traveling time from the supply to the point would vary according the path taken. All air masses, regardless of the path taken, are mixed at the point concerned and form the mean concentration at the point. From this point of view, the concentration at the point will correspond to the 'mean' travel time of the supply air mass (cf. Appendixes).

CALCULATION METHOD OF THREE SCALES OF VENTILATION EFFICIENCY AND THEIR DISTRIBUTION

Utilization of a super computer is the most effective and almost the only method by which to analyze the large number of spatial distributions of contaminant given for each contaminant source. A super computer makes it possible to simulate those distributions numerically using the turbulence model. Figure 3 illustrates the process of calculating the three scales of ventilation efficiency and their distributions.

To begin with, three-dimensional numerical simulation of room airflows are conducted. Usually airflow in a room is turbulent. Therefore, one should conduct the simulation for a turbulent flow field. In Table 2, turbulence model equations (k-ε two-equation model) are tabulated. Using Equations 1 to 5, the mean (time averaged) turbulent field is obtained. In order to calculate the spatial distributions of contaminant concentration in a room, it is necessary to obtain the distributions of air velocity, U_i and eddy viscosity, they are also calculated from Equations 1 to 5. In this study, numerical simulation is performed by the finite difference method. As Murakami et al. (1987) have confirmed, simulations correspond well to measured results of real airflow in rooms. From the numerical results of airflow simulations, and solving Equation 6 in Table 2 that is a transport equation for contaminant concentration, one can calculate rather easily the spatial distributions of contaminant concentration corresponding to each source point. It has also been confirmed that the correspondence between numerical simulation of the spatial distribution of contaminant concentration and experimental results are good (Murakami et al. 1987).

After the spatial distributions of contaminant are obtained, the three scales of ventilation efficiency and their distributions are calculated by the following processes:

1. SVE1 and SVE2, which are scales for ventilation efficiency at the point of the contaminant source, are to be calculated from the spatial distribution of contaminant concentration.
2. The distributions of SVE1 and SVE2 are obtained by scanning the whole space by changing the position of the source point.
3. The distribution of SVE3 can be obtained by simulating the distribution of contaminant concentration, in this case, the contaminants being generated uniformly throughout the room.

EXAMPLE OF APPLICATIONS

In order to examine the usefulness of these new scales for ventilation efficiency (SVE1, SVE2, and SVE3) , the properties of ventilation efficiency in an actual conventional flow type of clean room are analyzed.

Model Room Used

Three different flow fields (Case 1, Case 2, and Case 3) are analyzed. The geometry of the clean room is shown in Figure 4. In Case 2 and Case 3, some supply outlets or exhaust inlets are closed, and their influence on the ventilation effectiveness is evaluated using the three new scales. The specifications of each supply and exhaust condition are presented in Table 1.

Numerical Simulation of Velocity Distribution

The numerical simulations are based on the k-ε two-equation turbulence model as shown in Table 2. The flow field in the room is divided into mesh systems (26×21×13) and solved by the finite difference method. The boundary conditions used are shown in Table 3. The details of simulation follow Murakami, et al. (1987). The results for velocity distributions are shown in Figures 5, 6 and 7 respectively. The velocity vectors in the vertical sectional planes of X=3.8 m (a), Y=1.8 m (b), and Y=3.4 m (c) are illustrated. Those in the horizontal sectional plane 0.7 m (d) above the floor are also shown. The rising streams are observed at the center of the room and near the wall. It appears that the combination of the supply jets and these rising flows forms large recirculating flows in the room.

Example of Distribution of Contaminant Concentration with Point Source

The new scale for ventilation efficiency (SVE1, SVE2) is obtained by calculating the distribution of contaminant concentration for one source point. The distribution of SVE1, 2 is given by scanning the whole area by changing the source point throughout the room. An example of the spatial distribution of contaminant concentration in Case 1 is shown in Figure 8. In this case, the contaminant source point is located at the center of the room (0.7 m above the floor). The results of the distribution of contaminant concentration are illustrated by nondimensional forms, which are divided by the representative concentration, namely, the value at the exhaust inlets. The contaminants are convected up to the ceiling by the rising streams at the center of the room. The concentration of contaminant becomes very large in these regions.

The Distribution of Scale for Ventilation Efficiency 1 (SVE1)

The distributions of scale for ventilation efficiency (SVE1) for each flow condition are shown in Figures 9, 10, and 11, respectively, which illustrate the distribution of the nondimensional spatial average of the contaminant diffusion. At each case, it is shown that SVE1 takes a higher value (1.5 to 2.0) at the central area of the room and takes a lower value (under 0.5) near the exhaust inlets. For most of the room, SVE1 is higher than 1.0. Although the value of SVE1 has a close relationship to the distance from the exhaust inlets, the supply jet region has little influence on the value of SVE1, and there are few changes in SVE1 in the supply jet region. Comparing the result of Case 3 to the others, in which two supply outlets at the center of the room are closed, it is shown that the ventilation efficiency of Case 3 is rather poorer than that of the others because a higher value of SVE1 is observed in the room. In Case 2, in which the number of the exhaust inlets is reduced, SVE1 takes a relatively smaller value than in the other cases, except for the area near the closed exhaust inlets. It is curious, however, that in the horizontal plane shown here, the airstreams toward the exhaust inlet become strong and the contaminants are rather smoothly exhausted. In this way, SVE1 represents well the change of ventilation efficiency corresponding to the change of ventilation systems.

The Distribution of Scale for Ventilation Efficiency 2 (SVE2)

The distributions of scale for ventilation efficiency (SVE2) for each flow condition are shown in Figures 12, 13, and 14, which illustrate the distributions of the mean radius of contaminant diffusion given for each source point throughout the room. The value in these figures represents the mean radius of diffusion. When it has a larger value, it means that the contaminants diffuse more widely. It is shown that the variations of SVE2 in space are relatively smaller than those of SVE1. SVE2 takes a large value (about 2.5 m) at the center of room and takes a small value (about 0.5 m) near the exhaust inlets. In case 3, where two supply outlets are closed, the mean radius of diffusion uniformly takes a higher value (2.5 m) in most regions of the room.

The Distribution of Scale for Ventilation Efficiency 3 (SVE3)

The distributions of scale for ventilation efficiency (SVE3) are shown in Figures 15, 16, and 17, which illustrate the distribution of the mean travel time for supply air mass. The values in these figures represent the nondimensional contaminant concentration in the case of the contaminants being uniformly generated throughout the room. The higher value of SVE3 means that fresh air from the supply outlet takes a longer time to reach the point, so the chance of being contaminated becomes higher. Figures 15, 16, and 17 show the distributions of SVE3 at the horizontal section (at 0.7 m above the floor), which is the same section where the distributions of SVE1 and SVE2 are shown. The values of SVE3 are small at the supply jet regions and are large at the corners of the room, but the values just under the supply outlets seem to be rather high in spite of the fresh air being supplied directly. This result shows that the supply jet is likely to induce the air and contaminants surrounding it. The distributions of SVE3 in other vertical planes in Case 1 are shown in Figure 18-(a),(b), whose section is located at the center of the room. The value of SVE3 is high near the ceiling. This result means that it takes a relatively longer time for supply air to reach the area near the ceiling. The distributions of SVE3 near the ceiling in each case are shown in Figures 18 (c), 19, and 20. The value of SVE3 is uniformly high around the supply outlets. Although these values are about 1.0 in Case 1, they are more than 1.2 in Case 3 where two supply outlets are closed. In Case 2, where two exhaust inlets are closed, these values are more than 1.5. These results show that reduction of supply outlets or exhaust inlets makes ventilation efficiency worse. It takes much longer travel time for fresh air to reach the circumference of supply outlets.

CONCLUSIONS

In order to evaluate the ventilation effectiveness in a room by numerical simulation, new scales for ventilation efficiency (SVE1, SVE2, and SVE3) are proposed. Their physical meanings and the method of calculation of their scales are explained. The new scales for ventilation efficiency proposed in this paper are:

1. SVE1 (Scale for Ventilation Efficiency 1), a spatial average of contaminant concentration in a room. Its value is defined at the point where the contaminant is generated as a point source. The distribution of SVE1 is given by changing the source point throughout the room.
2. SVE2 : a mean radius of diffusion contaminant dispersion in a room. It is also defined at the point where the contaminant is generated, and its distribution is also given by the same means as SVE1.
3. SVE3 : a concentration value of each point in a room, where the contaminant is uniformly generated throughout the room.

In order to confirm the usefulness of these new scales for ventilation efficiency, the characteristics of ventilation effectiveness in a conventional flow type of clean room are analyzed using these new scales. The results are as follows. (1) First and second new scales represent well the difference of ventilation efficiency that is caused by changing the number of the exhaust inlets and the supply outlets in the same room. (2) These new scales represent well the influence of the position of the contaminant source on the cleanliness of the room air. (3) The third new scale represents well the mean travel time of clean air from the supply outlet. It is easy to know which position in the room is far from or close to the supply outlet from the viewpoint of airflow passage.

NOMENCLATURE

C_D, C_1, C_2 = empirical constants in turbulence model (*cf.* Table 2)
C = contaminant concentration
C_0 = zero-th moment of contaminant distribution (amount of contaminant within space)
C_s = representative concentration defined by that of exhaust outlet (ratio of contaminant generation rate to air supply volume rate)
C_x = contaminant distribution function
C_k = Fourier transformation of C_x
i = the imaginary unit, $\sqrt{-1}$
k = turbulence kinetic energy
k_0 = boundary value for k of inflow
k = wave number vector
l = length scale of turbulence
l_0 = boundary value for l of inflow
L_0 = representative length defined by width of supply outlet
P = mean pressure
q = production rate of contaminant
Q = airflow rate
R_0 = Reynolds number, $R_0=U_0L_0/\nu$
R_{0t} = turbulent Reynolds number, $R_{0t}=U_0L_0/\nu_t$
SVE1 = scale for ventilation efficiency 1 (cf.Equation 7)
SVE2 = scale for ventilation efficiency 2 (cf.Equation 10)
SVE3 = scale for ventilation efficiency 3 (cf.Equation 12)
U,V,W = X, Y, Z components of velocity vector
U_i, U_j = components of velocity vector
U_0 = representative velocity defined by inflow air velocity
X = position vector
X_0 = position of center of gravity
X_R = mean radius of diffusion
κ = von Karman constant, 0.4
ρ = fluid density
π = the ratio of the circumference to its diameter
ν = molecular kinematic viscosity
ν_t = eddy kinematic viscosity
$\sigma_1, \sigma_2, \sigma_3$ = turbulence Prandtl/Schmidt number of k, ε, C (*cf.* Table 2)

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APPENDIX

The Scale for Ventilation Efficiency 3 is related to the travel time of supply air by a transport equation as follows. If the airflow in a room may be assumed to be laminar, the distribution of the travel time of a marker that has no inertia is Expressed as equation A-1 (Matsumoto et al. 1985).

$$\partial TU_i / \partial X_i = T_P \qquad \text{(A-1)}$$

T (s)= marker's travel time from supply
U_i (m/s)= flow velocity (i=X,Y,Z)
T_P (-)= generation term (=1)

Airflow in a room is usually turbulent. Reynolds average operation for Equation A-1 leads to Equation A-2.

$$\partial \langle T\rangle\langle U_i\rangle / \partial X_i = -\partial \overline{\langle T'U_i'\rangle} / \partial X_i + T_P \qquad \text{(A-2)}$$

$\langle\ \rangle$ = ensemble average operation.
$'$ = fluctuating value.
$\langle T\rangle$ = ensemble average of T.
$\langle U_i\rangle$ = ensemble average of U_i.
T' = fluctuating component of T ($=T-\langle T\rangle$)
U_i' = fluctuating component of U_i ($=U_i-\langle U_i\rangle$)

In Equation A-2, if one approximates the correlation between fluctuating time and velocity using the gradient transport hypothesis, A-2 leads to A-3.

$$\partial \langle T\rangle\langle U_i\rangle / \partial X_i = \partial / \partial X_i \{ (\nu_t / \sigma_t) \partial T / \partial X_i \} + T_P \qquad \text{(A-3)}$$

ν_t = turbulence eddy viscosity
σ_t = turbulence Schmidt number of T (~1.0)

Equation A-3 is the same as the transport equation of scalar quantity at the turbulence flow field.

TABLE 1

Specifications of Model Clean Rooms

Room type	Number of supplies	Number of exhausts	Supply* velocity rate(m/s)	Airflow rate (m^3/s)	Generation rate of contaminant (m^3/s)	Remarks
Case 1	6	4	1.0	2.46	2.46	Basic type
Case 2	6	2	1.0	2.46	2.46	Closing two exhausts at diagonal position
Case 3	4	4	1.0	1.64	1.64	Closing two supplies on the center of room

* Supply outlets 0.64×0.64 m^2 , exhaust inlets 0.54×0.54 m^2

TABLE 2

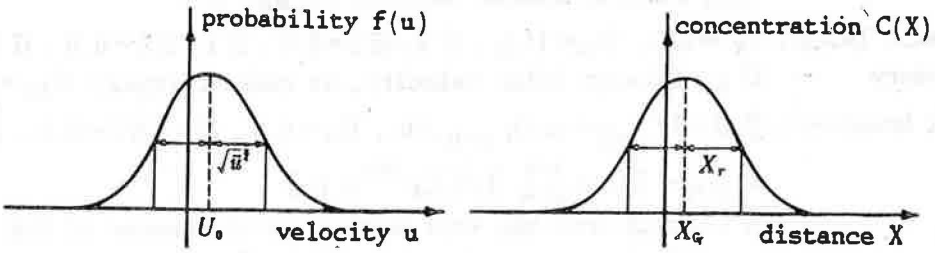
Two-Equations Model (Three-Dimensional)

$\frac{\partial U_i}{\partial X_i} = 0$	(1) Continuity equation
$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial X_j} = -\frac{\partial}{\partial X_i}\left(\frac{P}{\rho} + \frac{2}{3}k\right) + \frac{\partial}{\partial X_j}\left(\nu_t\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right)$	(2) Momentum equation
$\frac{\partial k}{\partial t} + \frac{\partial k U_j}{\partial X_j} = \frac{\partial}{\partial X_j}\left(\frac{\nu_t}{\sigma_1}\frac{\partial k}{\partial X_j}\right) + \nu_t S - \varepsilon$	(3) Transport equation for k
$\frac{\partial \varepsilon}{\partial t} + \frac{\partial \varepsilon U_j}{\partial X_j} = \frac{\partial}{\partial X_j}\left(\frac{\nu_t}{\sigma_2}\frac{\partial \varepsilon}{\partial X_j}\right) + C_1\frac{\varepsilon}{k}\nu_t S - C_2\frac{\varepsilon^2}{k}$	(4) Transport equation for ε
$\nu_t = k^{1/2} l = \left(C_0\frac{k^2}{\varepsilon}\right)$	(5) Equation for deciding ν_t
$\frac{\partial C}{\partial t} + \frac{\partial C U_j}{\partial X_j} = \frac{\partial}{\partial X_j}\left(\frac{\nu_t}{\sigma_3}\frac{\partial C}{\partial X_j}\right)$	(6) Concentration equation
here $S = \left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\frac{\partial U_i}{\partial X_j}$. $\sigma_1 = 1.0,\ \sigma_2 = 1.3,\ \sigma_3 = 1.0$ $C_0 = 0.09,\ C_1 = 1.44,\ C_2 = 1.92$	

TABLE 3

Boundary Conditions for Numerical Simulation

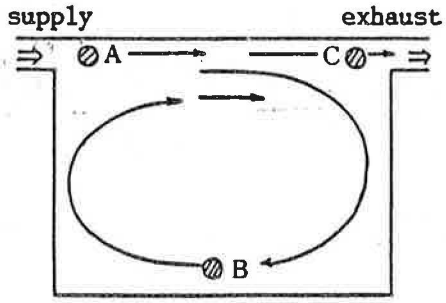
(1) Supply Outlet boundary :	$U_t = 0.0$, $U_n = U_{out}$, $k = 0.005$, $l = 0.33$, $C = 0.0$ suffix t: tangential component, n: normal component U_{out} : Supply outlet velocity, $U_{out} = 1.0$
(2) Exhaust Inlet boundary :	$U_t = 0.0$, $U_n = U_{in}$, $\partial k/\partial Z = 0.0$, $\partial \varepsilon/\partial Z = 0.0$, $\partial C/\partial Z = 0.0$ U_{in}: Exhaust inlet velocity, in case of Type2 : $U_{in} = 1.0$
(3) Wall boundary :	$\partial U/\partial Z_{z=0} = m\,U_{t\,z=h}/h$, $U_n = 0.0$, $\partial k/\partial Z = 0.0$, $\partial C/\partial Z = 0.0$ $\varepsilon_{z=h} = [C_D\,k_{z=h}^{3/2}]/[C_D^{1/4}\,\kappa\,h]$ h : Length from the wall surface to the center of the adjacent cell m : 1/7, Power law of profile $U_t \propto Z^m$ is assumed here. κ : 0.4, von Karman constant



zero-th moment	$\int f(u)du=1$	$\int C(X)dX=C_0$
first moment	$\int uf(u)du=U_0$ (mean velocity)	$\int \frac{XC(X)}{C_0}dX=X_G$ (the center of gravity)
second moment	$\int (u-U_0)^2 f(u)du=\overline{u^2}$ (variance)	$\int (X-X_G)^2\frac{C(X)}{C_0}dX=X_r^2$ (square of mean radius of diffusion)

If the function f(u) could be assumed to be the Gaussian distribution, the probability of finding u(t) between $U_0-\sqrt{\overline{u^2}}$ and $U_0+\sqrt{\overline{u^2}}$ is 68%.
If the concentration distribution C(X) could be assumed to be the Gaussian distribution, the quantity of the contaminant between X_G-X_r and X_G+X_r is 68% of the amount.

Figure 1 Correspondence of the concentration distribution of contaminant to the probability density function of velocity



- Contaminant source point A
  mean radius of diffusion : large
  spatial average concentration
  ≈ concentration in exhaust
- Contaminant source point B
  mean radius of diffusion : large
  spatial average concentration
  > concentration in exhaust
- Contaminant source point C
  mean radius of diffusion : small
  spatial average concentration
  ≪ concentration in exhaust

Figure 2 Contaminant diffusion field of constant contaminant production

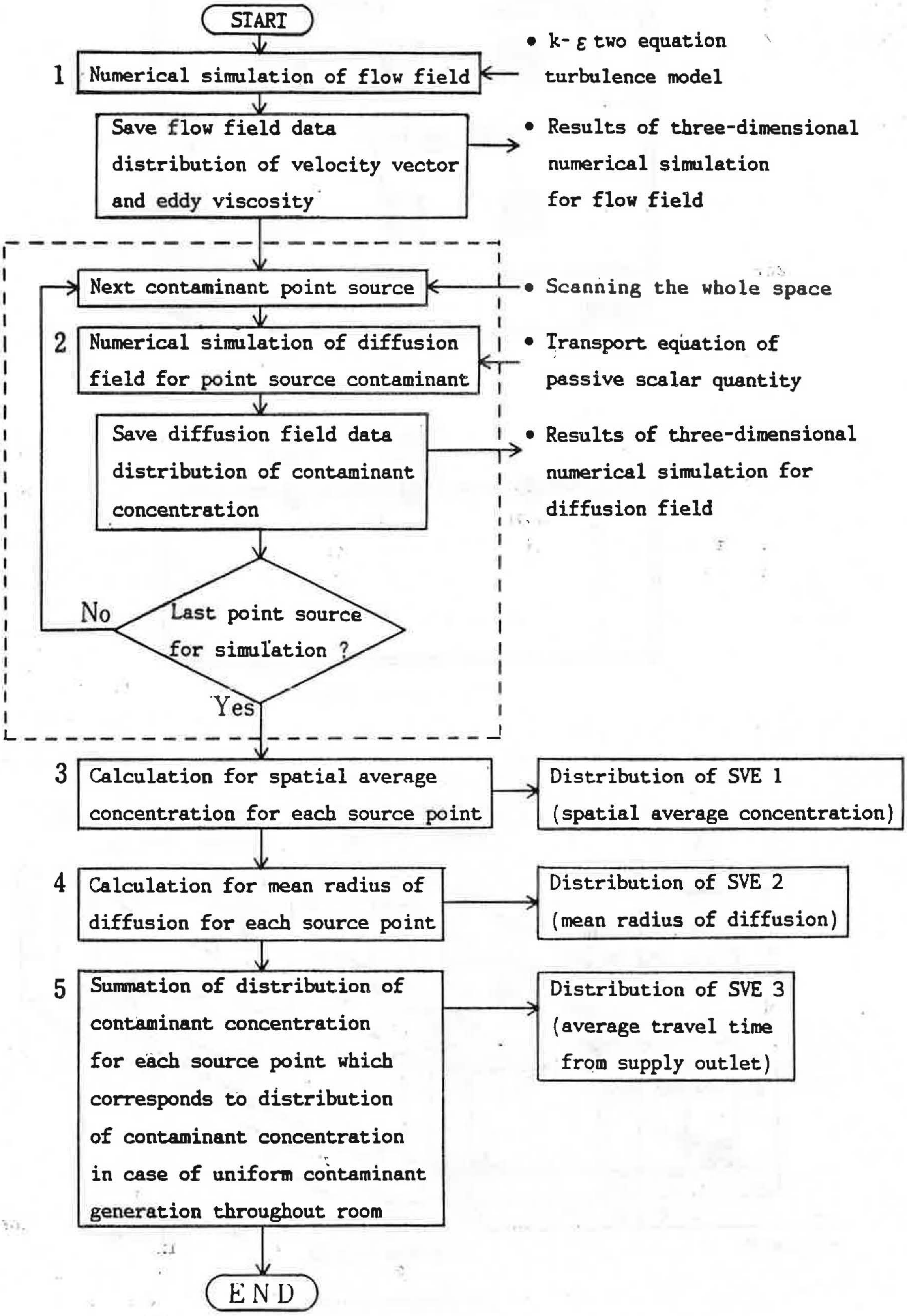
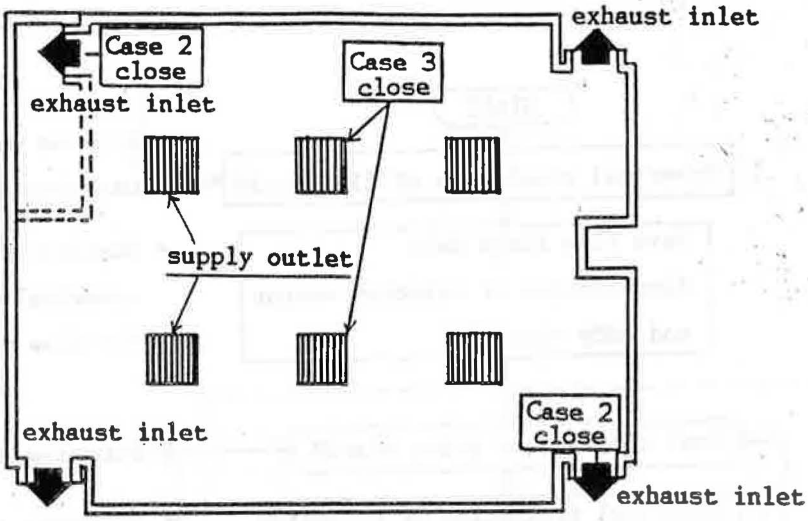
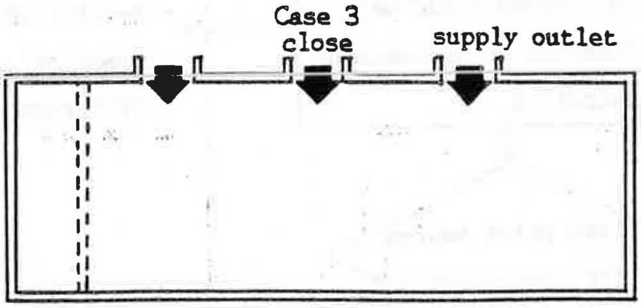


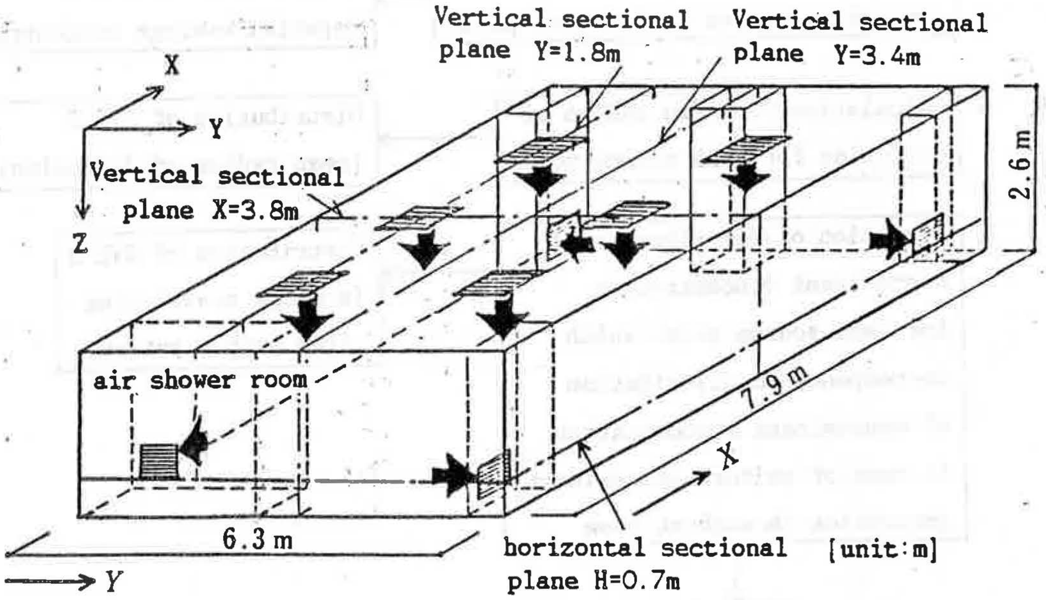
Figure 3 Flow chart of calculation method of scales of ventilation efficiency



(a) plan

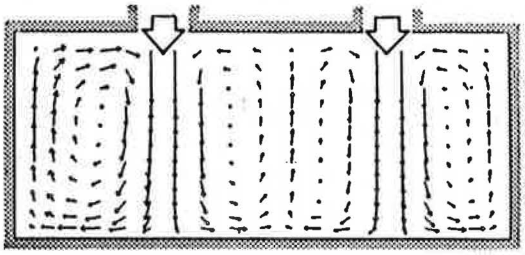


(b) section at Y=3.4m

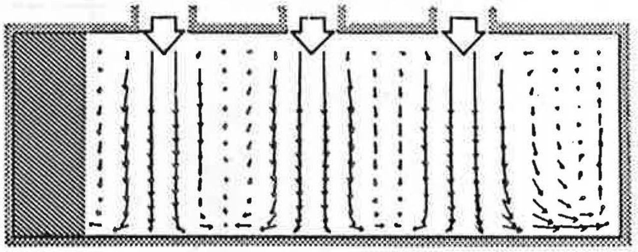


(c) isometric perspective

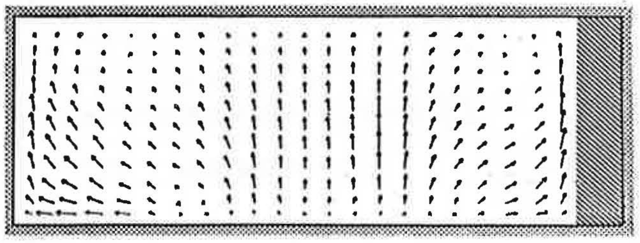
Figure 4 Room model (conventional flow type clean room)



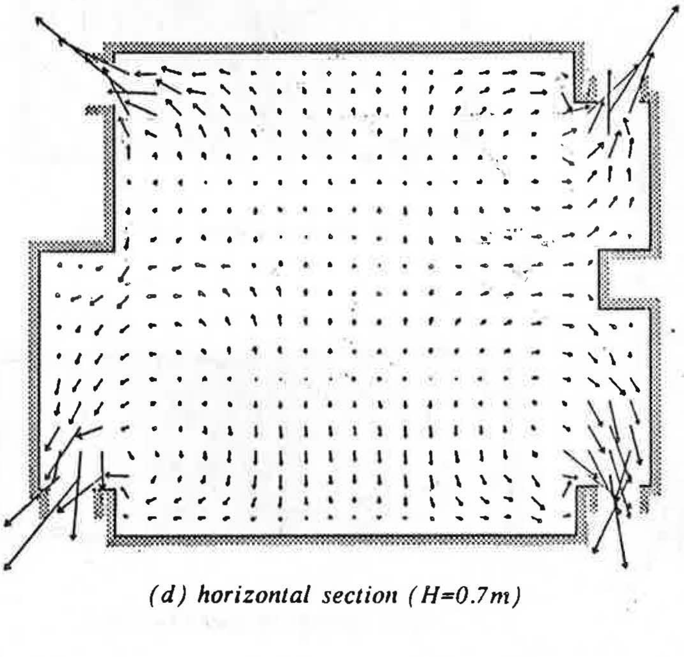
(a) vertical section (X=3.8m)



(b) vertical section (Y=1.8m)

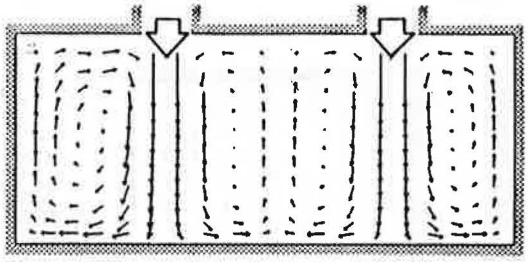


(c) vertical section (Y=3.4m)

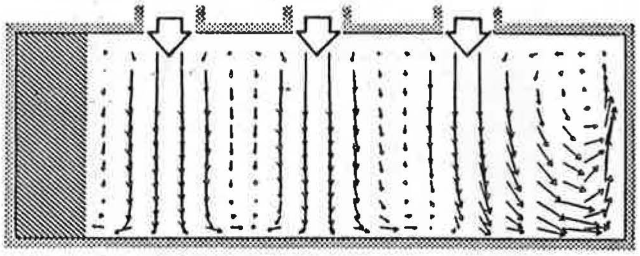


(d) horizontal section (H=0.7m)

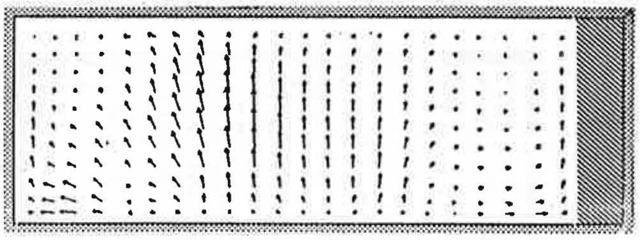
Figure 5 Velocity vectors in Case 1



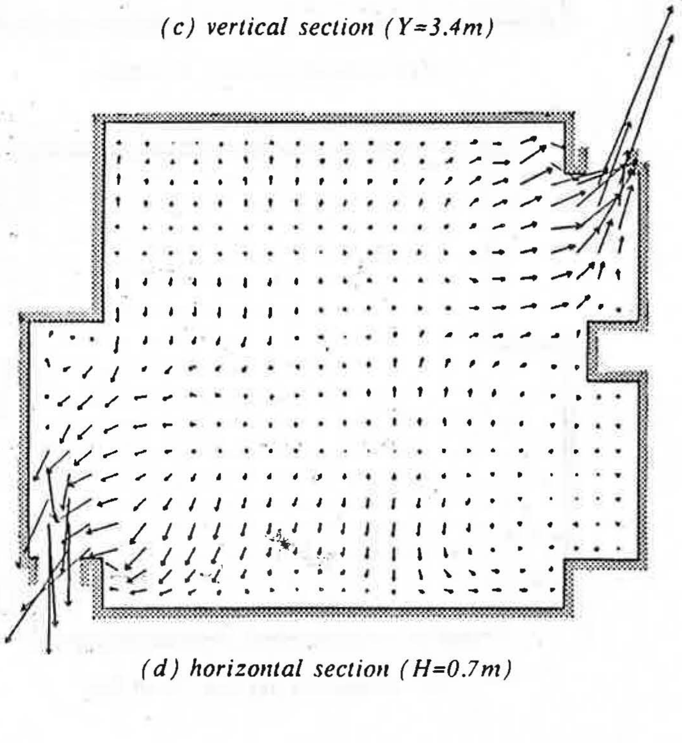
(a) vertical section (X=3.8m)



(b) vertical section (Y=1.8m)

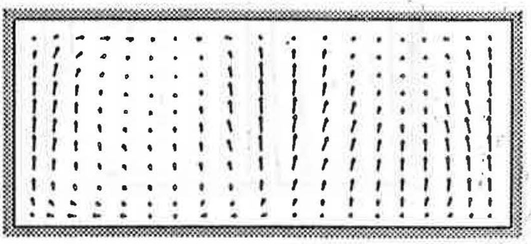


(c) vertical section (Y=3.4m)

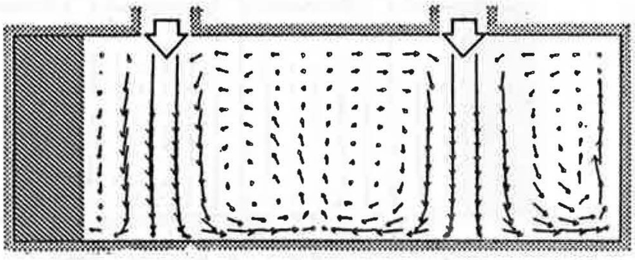


(d) horizontal section (H=0.7m)

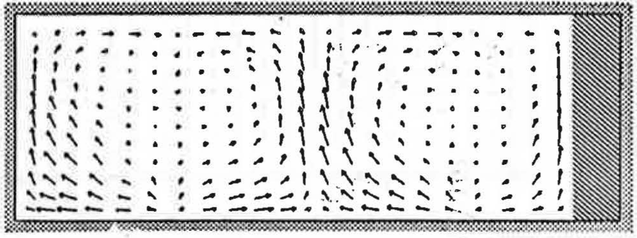
Figure 6 Velocity vectors in Case 2



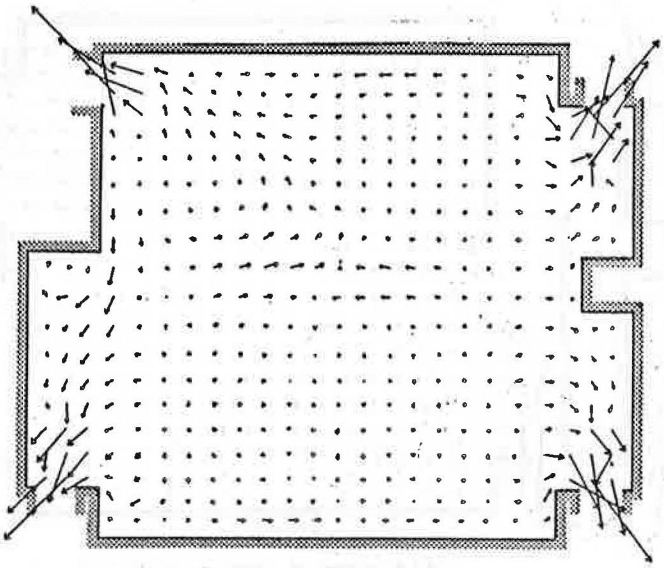
(a) vertical section (X=3.8m)



(b) vertical section (Y=1.8m)

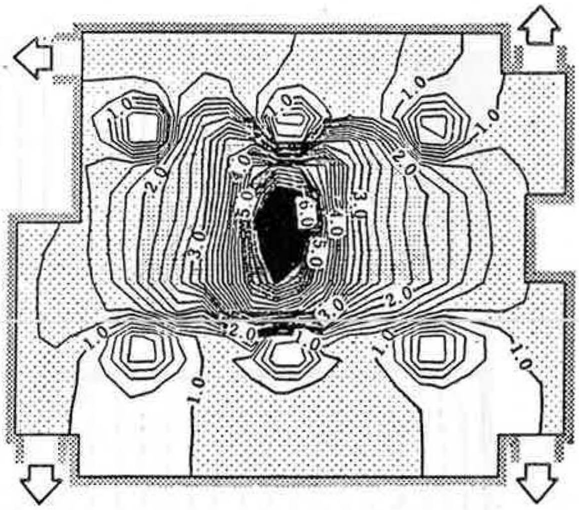


(c) vertical section (Y=3.4m)

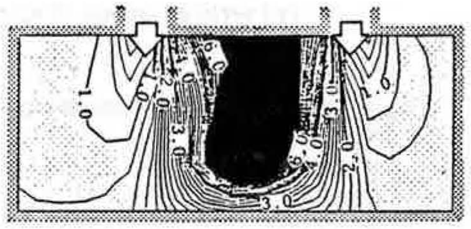


(d) horizontal section (H=0.7m)

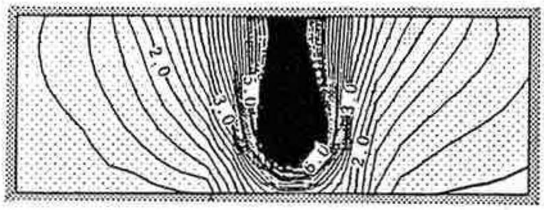
Figure 7 Velocity vectors in Case 3



(a) horizontal section (H=0.7m)



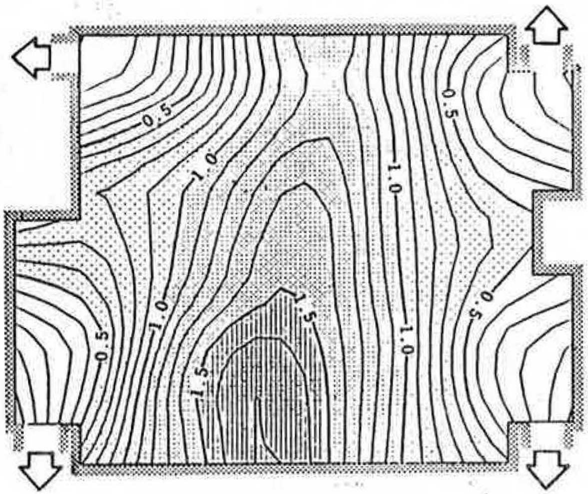
(b) vertical section (X=3.8m)



(c) vertical section (Y=3.4m)

Figure 8 Distribution of contaminant concentration

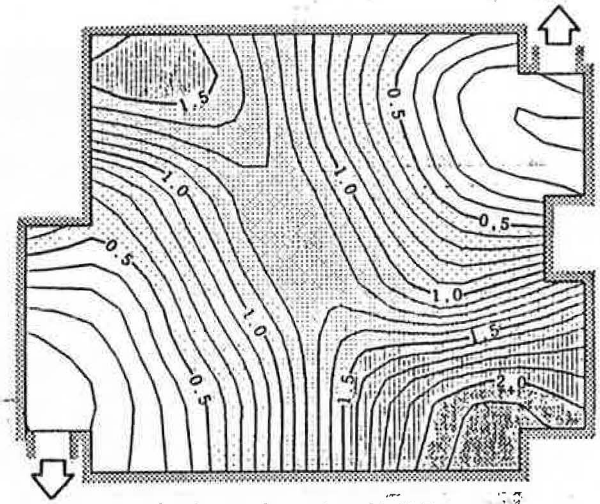
(source point: at the center of room)



horizontal section H=0.7m

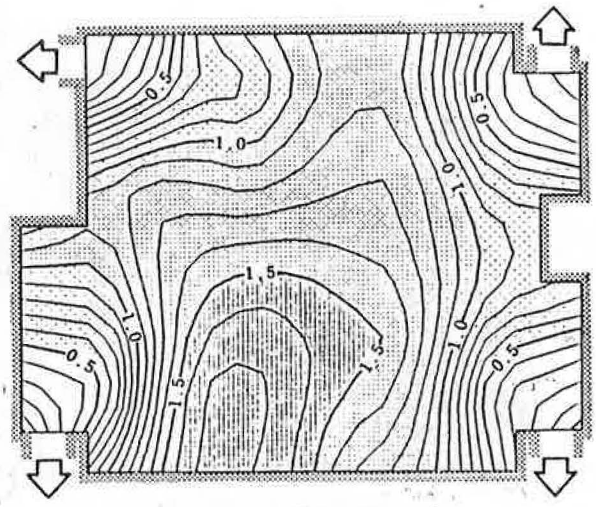
(Distribution of spatial average concentration for each source point)

Figure 9 Distribution of SVE 1 in Case 1



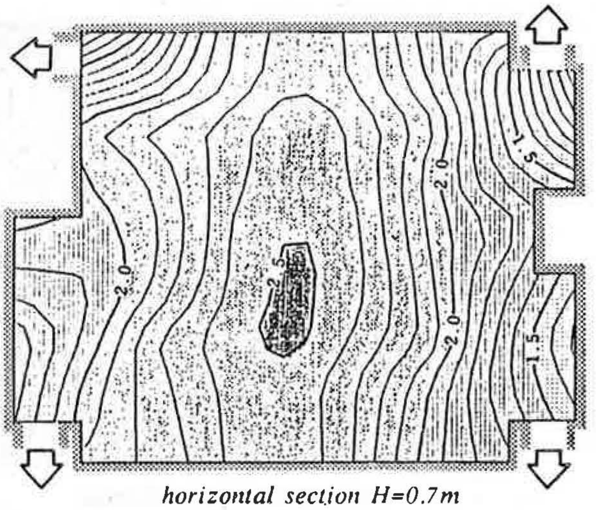
horizontal section H=0.7m

Figure 10 Distribution of SVE 1 in Case 2



horizontal section H=0.7m

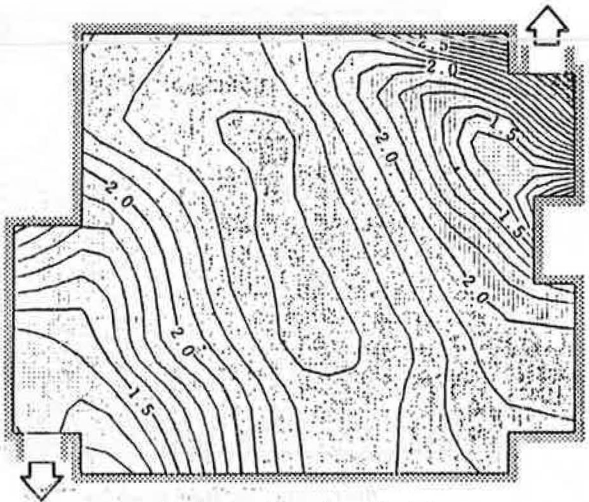
Figure 11 Distribution of SVE 1 in Case 3



horizontal section H=0.7m

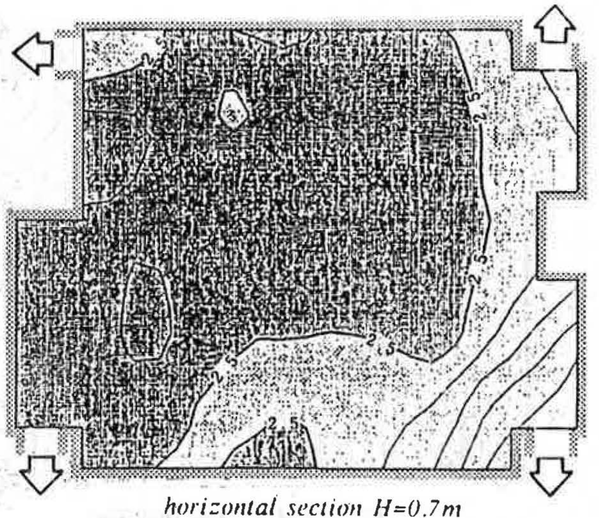
(Distribution of mean radius of diffusion for each source point)

Figure 12 Distribution of SVE 2 in Case 1



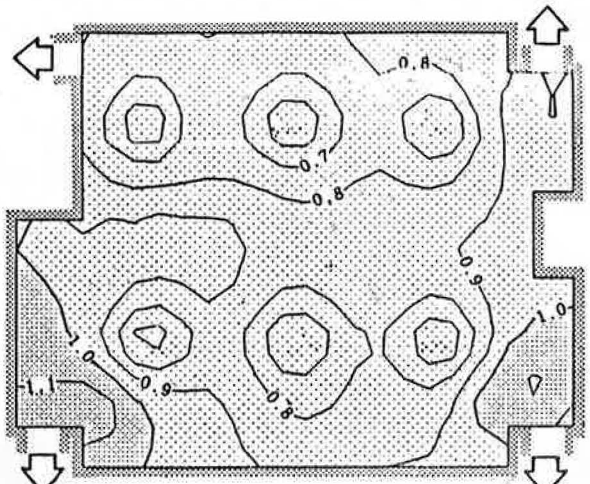
horizontal section H=0.7m

Figure 13 Distribution of SVE 2 in Case 2



horizontal section H=0.7m

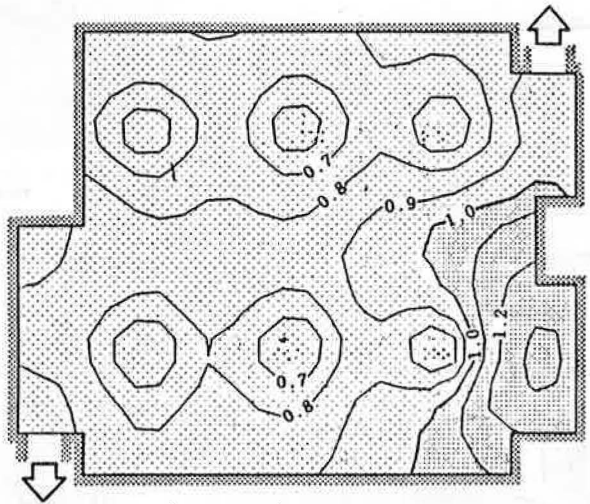
Figure 14 Distribution of SVE 2 in Case 3



horizontal section H=0.7m

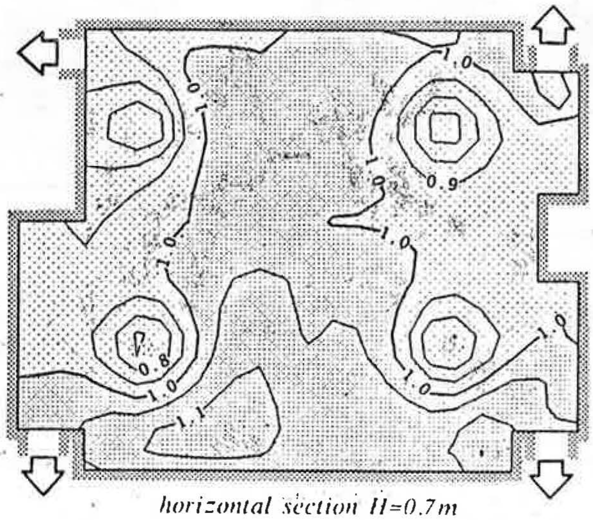
(Distribution of contaminant concentration in case of uniform contaminant production throughout room)

Figure 15 Distribution of SVE 3 in Case 1



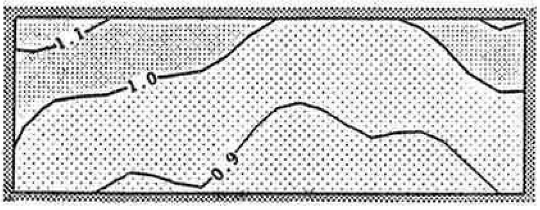
horizontal section H=0.7m

Figure 16 Distribution of SVE 3 in Case 2

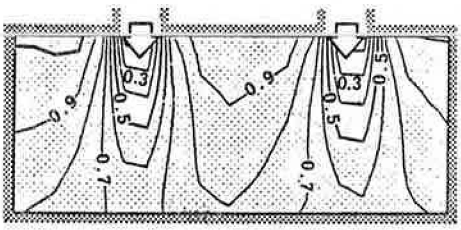


horizontal section H=0.7m

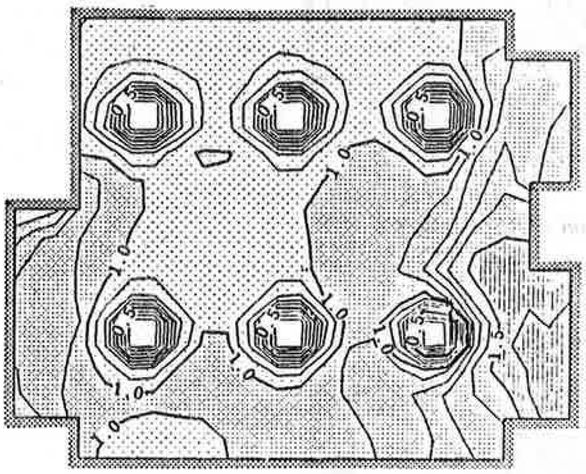
Figure 17 Distribution of SVE 3 in Case 3



(a) vertical section X=3.8m

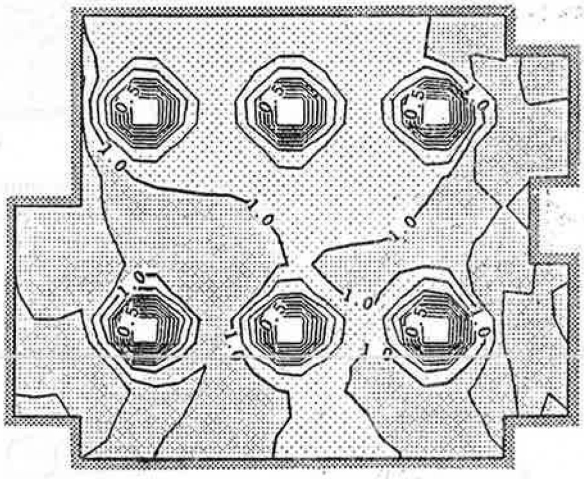


(b) vertical section Y=3.4m



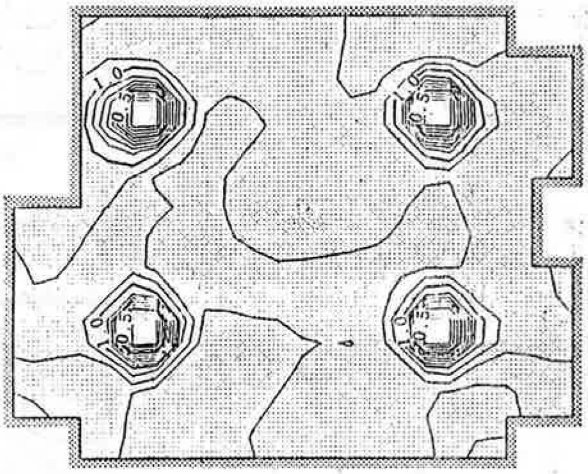
(c) horizontal section H=2.5m

Figure 18 Distribution of SVE 3 in Case 1



horizontal section H=2.5m

Figure 19 Distribution of SVE 3 in Case 2



horizontal section H=2.5m

Figure 20 Distribution of SVE 3 in Case 3