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NEW SCALES FOR VENTILATION EFFICIENCY AND THEIR APPLICATION BASED ON NUMERICAL SIMULATION OF ROOM AIRFLOW

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Abstract

This paper outlines new methods for evaluating ventilation efficiency in a room [1]. This evaluation of ventilation efficiency must be based on analysis of the flowfield. New scales for ventilation efficiency (SVE 1, 2, 3) based on the flowfield analysis given by numerical simulation techniques are proposed. These new scales are applied to room models and their effectiveness is confirmed.

Keywords

Ventilation Efficiency, Contaminant Distribution, Numerical Simulation

Introduction

Engineering for indoor climate has advanced greatly during the past ten years in response to increasing demand for high-level control of room air distribution. Thus the velocity-diffusion fields in rooms and their resulting ventilation characteristics have been analyzed very often in various fields of environmental control engineering. A lot of excellent researches concerned with ventilation effectiveness have been presented [2,3,4,5,6,7,8,9].

The analysis of velocity-diffusion fields in rooms has been greatly advanced by the development of techniques for numerical simulation of turbulent flowfields. Numerical simulation of a velocity-diffusion field provides all the information necessary for evaluating ventilation efficiency, so the structure of ventilation efficiency can be clarified very easily using the results of numerical simulation. These new scales for ventilation efficiency are thus based on numerical simulation techniques. Applications of the new scales for ventilation efficiency are presented here and their effectiveness is confirmed.

1. Ventilation efficiency determined by flowfield

In a room being ventilated, the characteristics of air change at each point in the room differ in accord with the properties of the flowfields. Furthermore, the mechanisms for supplying fresh air to each point and exhausting contaminant from each point are also different. The manner and efficiency with which air is replaced at each point in a room is called "ventilation effectiveness". However, there exist various types of definitions of ventilation effectiveness since the concept has not yet been clearly established. The meaning of "ventilation effectiveness" ranges from the ventilation efficiency at each point of a room to expressing the ventilation characteristics of an entire room. No matter how this expression is defined, however, "ventilation effectiveness" cannot be determined by factors other than the flowfield in a room. In this context, the flowfield provides the most fundamental information required for analyzing the structure of ventilation efficiency in a room.

However, to our regret, we often find studies on ventilation effectiveness that are not based on detailed analysis of the flowfield. Although a flowfield includes all the information on the distribution characteristics of the ventilation in a room, it is very difficult to intuitively comprehend the ventilation efficiency on the basis of the velocity field itself. This is the reason why many analyses of ventilation efficiency in the past did not employ detailed analyses of velocity fields. Flowfields in rooms are neither uniformly and perfectly mixed nor flow in one direction only from supply to exhaust (i.e. piston flow or plug flow), but rather are much more complicated. The characteristics of ventilation efficiency of perfectly mixed or unidirectional flowfields can be understood intuitively, but the flowfields to which such a simple model is applicable are very, very few.

For clarifying the structure of a flowfield in a room, three-dimensional analysis is necessary. However, conducting such a detailed analysis by means of the experimental method is very difficult and tedious. Before the development of the technique of numerical simulation, 3D analysis of the flowfield was usually omitted even when a structural analysis of the ventilation characteristics of a room was required.

2. Ventilation efficiency estimated by diffusion field

Although the ventilation structure is characterized by the velocity field, it is difficult to use the velocity value characterizing the flowfield as a tool to evaluate the ventilation efficiency directly. From the standpoint of assessing an indoor environment, it would be simplest and most fundamental to evaluate the ventilation effectiveness by means of the air quality at the point in question. In other words, the easiest way to evaluate the ventilation effectiveness would be based on the contaminant concentration at each point in a room. Thus, the characteristics of the ventilation efficiency in a room are clarified most directly by the characteristics of the contaminant concentration distribution in the room with various source positions.

The mechanism for evaluating ventilation efficiency by means of flowfield and contaminant distribution is illustrated in Fig.1.

The analysis and evaluation of ventilation efficiency should be based on the analyses of the flowfields and the resultant contaminant diffusion fields. The technique of numerical simulation allows precise and detailed analysis of the flowfield and contaminant diffusion field far more simply than by experiment. This technique has become the most effective means by which to study the characteristics of ventilation efficiency in a room. This paper presents the concept and the method for evaluating ventilation efficiency in a room based on the spatial distribution characteristics of

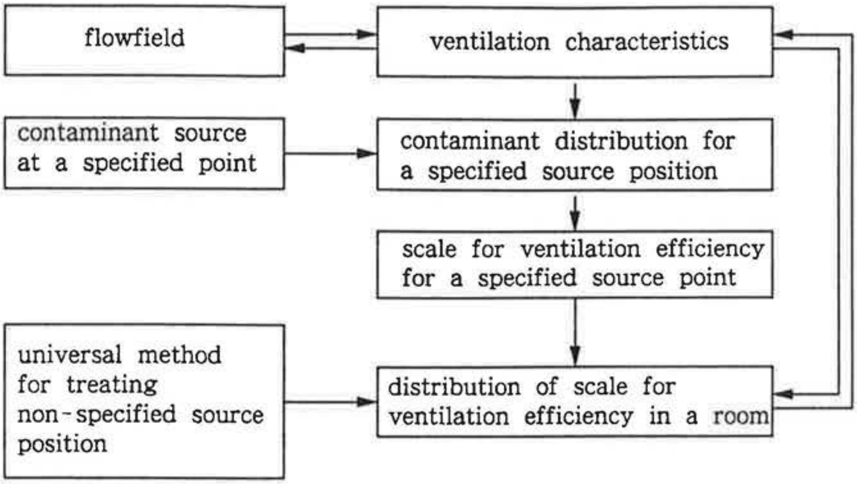


Fig.1 Flowfields, contaminant distribution and ventilation efficiency
(Ventilation characteristics are determined by flowfields and evaluated by contaminant distributions.)

contaminants. Furthermore, the current status of flowfield simulation which constitutes the basis for diffusion field analysis is also reviewed.

3. Basic concepts of new scales for ventilation efficiency based on contaminant distribution

Kato and Murakami have proposed new ventilation efficiency scales based on spatial concentration distributions of contaminant [1]. They have clarified the relationship between the proposed scales and the conventional ones of ventilation efficiency. The fundamental concepts and logic which relate the scales for ventilation efficiency to the characteristics of the contaminant distribution in a room are given below.

Statement 1 : the minimum air change rate is determined on the basis of uniform contaminant concentration given by assuming perfect mixing in a room.

Deduction 1 : it seems most reasonable to define the ventilation efficiency in a room as being based on the contaminant concentration distribution in a room.

Deduction 2 : consequently, the scale for ventilation efficiency should reflect the contaminant concentration distribution in a room.

Sub-statement 1 : the concentration distribution in a room varies extremely according to the source point of contaminant.

Sub-statement 2 : it is often the case that the source point of contaminant cannot be specified beforehand. Even so, it is necessary to predict the ventilation efficiency.

Sub-statement 3: it is preferable that the ventilation efficiency of rooms can be compared with each other even when the various conditions of the rooms (e.g. the ventilation system and/or the shape of the rooms etc.) are different. (In this sense, the air change rate is a very simple and universal scale.)

Sub-statement 4 : The flowfield of a room determines the ventilation characteristics, and flowfields can be compared with each other without considering the position of the contaminant source because contaminant can usually be regarded as passive and with no influence on the flowfield.

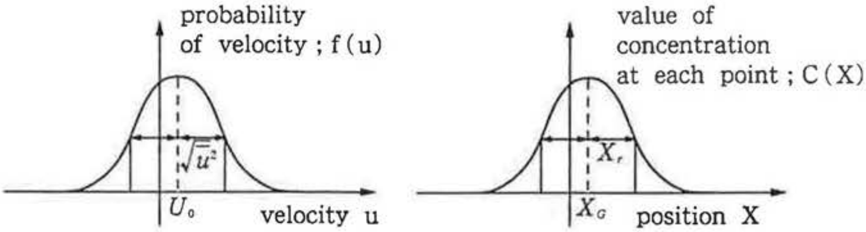
Deduction 3 : When the source point of contaminant cannot be specified beforehand, a universal rule for defining the generation of contaminant is required, because the ventilation efficiency cannot be evaluated without generation of contaminant. It is preferable that the conditions of contaminant generation be treated in an universal manner even when the condition of rooms (e.g. the shape, the system of supply / exhaust etc.) are different.

Deduction 4 : The simplest case in the universal treatment of the generation point of contaminant is to assume that the contaminant is generated precisely at the point where the ventilation efficiency is to be evaluated. In this case, the evaluation of the ventilation efficiency at that point is conducted by evaluating the concentration distribution with the contaminant generation at that point. However, evaluation of the ventilation efficiency of an entire room by this means requires analyses of the innumerable concentration distributions for all source points in a room. This analysis leads to the distributions of SVE 1 and 2 (Scale for Ventilation Efficiency), as will be described later.

Deduction 5 : One universal rule for handling the generation point of contaminant is to assume an "uniform generation" of contaminant throughout a room. This concept leads to SVE 3.

Statement 2 : A new method is required which can analyze and synthesize the numerous concentration distributions given by many contaminant sources. Based on the arguments above, the following proposals for new scales of ventilation efficiency are given.

Proposal 1 : Mathematical analysis of the concentration distribution by moment expansion would be very useful for synthesizing the numerous distributions given for each source point. The characteristics of spatial distribution are represented by moments of low order. The mathematical meaning of moment expansion analysis for diffusion fields is explained by analogy with probability density function of velocity in Fig. 2. The low order moments of the concentration distribution can be used for the ventilation scales. The scale for ventilation efficiency at a certain point can be defined on the basis of the low order moments



zero-th moment	$\int f(u)du = 1$	$\int C(X)dX = C_0$	(1)
first moment	$\int uf(u)du = U_0$ (mean velocity)	$\int \frac{XC(X)}{C_0}dX = X_G$ (the center of gravity)	(2)
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)	(3)

(If the function f(u) can 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) can 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 total amount.)

Fig.2 Moment expansion analysis for probability of velocity fluctuation and contaminant diffusion field

of the concentration distribution, which is given with the contaminant source at the same point.

Proposal 2 : Next we would like to obtain the distribution of the ventilation efficiency scale in a room. This distribution is obtained by calculating the ventilation efficiency scale at every point in a room by moving the source point throughout the room. This requires an immense amount of work. Experimental method cannot be applied, and the huge number of calculations can be done only with the aid of numerical simulation.

Proposal 3 : In case of uniform generation of contaminant in a room, the distribution of contaminant concentration is itself a useful scale for evaluating ventilation efficiency, as will be explained later in detail.

The proposals stated above lead to new concepts for ventilation scales which have many advantages over the previous ones.

Advantage 1 : The moment of zero-th order corresponds to the average concentration of contaminant, namely the mean staying time of the contaminant (the age of contaminant) in a room. Its mathematical definition is shown by Eq. (1) in Fig. 2. It expresses one aspect of the contaminant exhaust capacity of the ventilation system.

Advantage 2 : The moment of first order corresponds to the center of gravity of concentration distribution. Its definition is shown by Eq. 2 in Fig. 2.

Advantage 3 : The second moment corresponds to the diffusion radius of contaminant. It also expresses one aspect of the contaminant exhaust capacity of the ventilation system (cf. Eq. 3 in Fig. 2).

Advantage 4 : The concentration with "uniform generation" in a room corresponds to the time required for fresh air to travel from the supply opening to the given point (the age of the supply air).

4. Scales for ventilation efficiency based on moment expansion analysis of concentration distribution

The ventilation efficiency scales based on moment expansion analysis of concentration distribution of the contaminant and their physical meanings are given below in detail [1].

4.1 Scale for ventilation efficiency 1 and its distribution (SVE 1; average concentration of contaminant, residence time of contaminant)

SVE 1 means the average concentration of contaminant at a given source point in a room. This is expressed as the zero-th moment of the concentration distribution normalized by the perfect mixing concentration in the following equations (cf. Fig. 2).

$$SVE1(X_S) = \frac{C_0(X_S)}{C_S \int_{V(X)} dX} \qquad (4)$$

here,

$$C_S = q/Q \qquad (5)$$

$$C_0(X_S) = \int_{V(X)} C_X(X_S, X)\,dX \qquad (6)$$

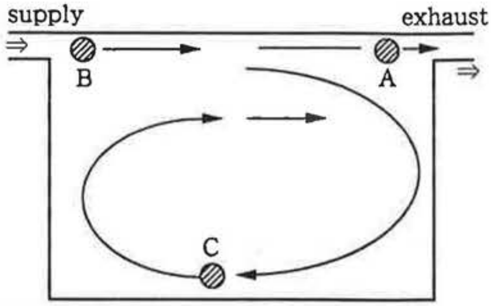
$SVE1(X_S)$ (–) = Scale for Ventilation Efficiency 1 at the position X_s just where the contaminant is generated. SVE1s are defined for each source position. Distribution of SVE1 (X_s) is obtained by scanning the whole space by changing the position of the contaminant source.

$C_X(X_S, X)$(kg/m^3) = the contaminant concentration at X, with the contaminant generation at source point X_S.

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

Q (m^3/s) = airflow rate.

C_S (kg/m^3) = The perfect mixing concentration (equal to the average concentration at exhaust).



SVE1 : spatial average concentration (residence time of contaminant)
2 : mean radius of diffusion
3 : age of supply air

Point A
SVE1 ≪ concentration at exhaust (very small)
2 : very small
3 : rather small (rather young)

Point B
SVE1 ≒ concentration at exhaust (medium)
2 : large
3 : very small (very young)

Point C
SVE1 ≫ concentration at exhaust (very large)
2 : very large
3 : very large (very old)

Fig.3 Change of SVE 1,2 and 3 according to position
(In case of SVE 1 and 2, contaminant is generated at each position A, B, C. In case of SVE 3, contaminant is generated uniformly throughout the room.)

The spatial distribution of SVE 1 can be calculated by scanning source points Xs throughout the space.

SVE 1, the average concentration of contaminant in a room, exactly corresponds to the mean time the contaminant stays in the room, that is, until the contaminant generated is exhausted through the exhaust opening. Namely this means the residence time of the contaminant. A high average concentration of contaminant indicates that much of the contaminant stays in the room in a stationary state. As the contaminant generation is assumed to be constant, the value of the contaminant concentration corresponds to the residence time the contaminant stays in the room. Even if the same amount of contaminant is generated, the average concentration varies greatly according to the source position, as is shown in Fig. 3. The distribution of this scale for various source positions well illustrates how influential the source position is in determining whether the contaminant is exhausted quickly or slowly.

4.2 Scale for ventilation efficiency 2 and its distribution (SVE 2; mean radius of contaminant diffusion)

The 2nd moment of the concentration distribution for a given source point means the square of the radius of contaminant diffusion, as is shown in Fig. 2. SVE 2 is defined as the square root of the 2nd moment normalized by the room average concentration (zero-th moment) in the following equations.

$$SVE2(X_S)^2 = \int_{V(X)} \frac{(X - X_G(X_S))^2 \cdot C_X(X_S, X)dX}{C_0(X_S)} \quad (7)$$

here,
$$X_G(X_S) = \int_{V(X)} \frac{X \cdot C_X(X_S, X)dX}{C_0(X_S)} \quad (8)$$

$SVE2(X_S)$(m) = Scale for Ventilation Efficiency 2 at the position X_S. Distribution of SVE2 (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 (8), this value is defined as the first moment of the distribution.

The distribution of SVE 2 is calculated by scanning the source points Xs throughout the space.

SVE 2 possesses a length dimension. It corresponds to the average diffusion distance (the so-called average diffusion radius) of the contaminant. While the room average concentration represents the characteristics of contaminant staying in a room, this represents the scale for the spatial extent of contaminant diffusion in a room. It is desirable that the contaminant generated in a room is exhausted with minimum dispersal in the room. The value of SVE 2 varies greatly according to source position, as is shown in Fig. 3. This scale illustrates well one important characteristic of the source position ; its strong influence on the spatial extent of contaminant diffusion from the source.

4.3 Scale for ventilation efficiency 3 and its distribution (SVE 3; the age of supply air)

The age of supply air at each point in a room can be easily calculated on the basis of concentration at each point if the concentration is uniformly generated in the room. It is defined by the following equations.

$$SVE3 = \frac{C_x'(X)}{C_s} \quad (9)$$

here, $$C_s = \frac{q}{Q} \quad (10)$$

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

$C_x'(X)$ (kg/m³) = the contaminant concentration in case of uniform contaminant generation throughout a room. The contaminant generation rate is q.

The assumption of "uniform generation" is very difficult to realize in actual experiments, but is very easy in numerical simulation. SVE 3 is made possible by the advantage of numerical simulation.

The concept of SVE 3, which is not based on moment expansion of concentration

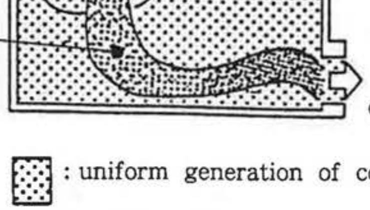


Fig.4 Concentration distribution with uniform generation of contaminant throughout a room

distribution, differs from the former two scales. Whereas SVE 1 and 2 emphasize the exhaust of contaminant, SVE 3 is the age of the supply air itself, equalling the mean time required for the supply air to reach a certain point in a room. It can easily be understood by modeling the room airflow as an assemblage of numerous virtual stream tubes connecting the supply outlet with the exhaust inlet, as is shown in Fig. 5. The virtual stream tubes take various paths with different travelling lengths determined by the turbulent flowfield, including various scales of eddies on the way. Under conditions of uniform generation of contaminant in a room, the contaminant concentration of an air mass travelling along a stream tube increases as the travelling length (the time elapsed from the supply outlet) becomes longer. It may be assumed that various virtual stream tubes may pass through the point P in a room, so the concentration at point P represents the average value of the concentration of each stream tube. Consequently the concentration at each point may be expected to represent the average time required for an air mass to reach that point from the supply outlet. The value of SVE3 varies greatly according to the position concerned as is shown in Fig. 3.

The theoretical foundation for obtaining the age of the supply air from the diffusion equation is presented in detail in the writings of Kato and Murakami [1] and Matsumoto [10].

4.4 Further new scales (SVE 4,5,6) and conceptual relation between the SVEs

Further new scales SVE 4,5 and 6 were recently proposed by S.Kato and S. Murakami and H.Kobayashi. They are described in detail in another paper [11] in this symposium. They are based on a concept different from those of SVE 1,2,3. SVE 4 and 5 means the contribution ratio of a supply opening and that of a exhaust opening respectively. SVE 6 is the residual life time of air in a room. The concept of age and residual life time of air have been familiar in the field of ventilation engineering [2]. The conceptual relation between the SVEs are shown in Fig.5.

5. Current status of numerical simulation for turbulent flowfield in a room

Most flowfields in a ventilated room are turbulent. The turbulent flow in a room is composed of various eddies, ranging from large scale to very fine scale. Direct numerical simulation of all such flows, able to analyze even the finest scale of turbulence,

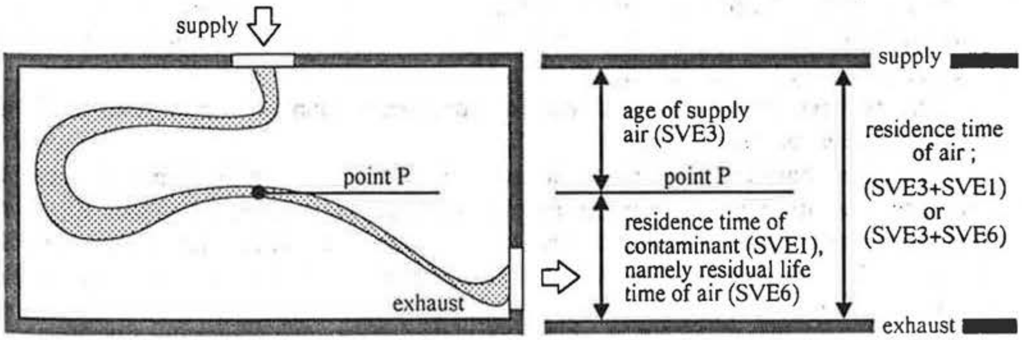


Fig.5 Relation between the SVEs

Table.1 Relative comparison of turbulence models for practical modelling of various flowfields

Turbulence model / wall boundary condition	Standard k−ε / wall function	Low-Re. No. k−ε / non-slip	Standard DSM ASM / wall function	Low-Re. No. DSM ASM / non-slip	LES / wall function	LES / non-slip
1. Simple flows (channel flow, pipe flow, etc) (local equilibrium is valid)	O	O	O	O	O	O
2. Flow with streamline curvature						
1) weak curvature, convection is dominant (usually observed in room)	O	O	O	O	O	O
2) strong curvature (flow around bluff body)	X, Δ	X, Δ	O	O	O	O
3. Jet						
1) normal	O	O	O	O	O	O
2) swirl	X	X	O	O	O	O
4. Impinging flow	X, Δ	X, Δ	O	O	O	O
5. Non − isothermal flow						
1) weak stratification	O	O	O	O	O	O
2) strong stratification	X, Δ	X, Δ	O	O	O	O
6. Convective heat transfer at wall	X, Δ	O	X, Δ	O	X, Δ	O
7. Flowfield with low Reynolds No.	X, Δ	Δ, O	X, Δ	Δ, O	O	O
8. Unsteady flow, unsteady diffusion						
1) highly unsteady	X	X	X	X	O	O
2) vortex shedding	X	Δ	Δ	O	O	O

O : functions well   Δ : insufficiently functional   X : functions poorly

are presently impossible due to computer limitations. However, in analyzing ventilation efficiency, the general purpose can be achieved if the properties of the mean flowfield are given. As the mean velocity field varies in relatively large-scale eddies, the discretization of grids for simulation of the mean flowfield is not required to be so fine. Thus the simulation can be conducted on the basis of mean governing equations ; time average (ensemble average) or spatial average (filtering).

While various turbulence models can be used, selection should be made according to the purpose of the analysis and the accuracy required. The well-known k-ε two-equation model, which is based on eddy viscosity modeling to the Reynolds stress, is widely used for the analysis of mean flowfields [12, 13]. When a flowfield is highly non-isotropic, DSM (Differential Stress Model) [14] or ASM (Algebraic Stress Model) model are applied successfully [15]. For an analysis of unsteady flowfield, LES (Large Eddy Simulation) [16] can be used.

The relative performance of various turbulence models is compared in Table 1 for many types of flowfields.

The flow pattern in a room, where convection is usually dominant, can be predicted by the k- ε model with a certain accuracy. However, when the flowfield features an extremely non-isotropic property, analysis by ASM (or DSM) or LES is effective. LES provides higher estimation accuracy than do the other turbulence models but requires much CPU time.

6. Analysis of flow and diffusion fields in a clean room and examples of evaluating ventilation efficiency

In order to maintain a clean environment in a clean room, the airborne particles generated in the room should be exhausted as fast as possible, with minimum dispersion inside the room. For this purpose, it is important to analyze the flow and diffusion fields in a room and evaluate the ventilation effectiveness. Two case studies are given here using conventional flow type clean rooms. Since a clean room generally has a large air change rate and thus the flowfield is sufficiently turbulent, various turbulence models can be applied easily.

6.1 Case study 1; comparison of contaminant distribution fields and SVEs for various source positions [17]

As shown in the velocity vector field in Fig. 6, the supply jet from the ceiling forms diverging flows near floor level which collide with each other or the side walls and form rising streams. The rising flow surrounding the supply jets reaches the ceiling surface and forms a converging flow directed to the supply outlet. Most flowfields in conventional flow type clean rooms can be modeled by a series of such flow units which consists of a supply jet and the rising streams surrounding it. The same pattern is also shown in Fig. 7. The contaminant distribution fields are compared for various source positions in Fig. 6. The source position is traversed from the area neighboring the exhaust opening or the side wall to the center of the room. Although the flowfield is the same, the contaminant diffusion field changes greatly according to the source position. The values of SVE 1 and 2 are also shown in the Figure. The values of SVE 1 (spatial average concentrations, namely residence time of contaminant) are 0.06, 1.05, 0.76 and 1.50, respectively. When the contaminant is generated near the exhaust opening, SVE 1 becomes extremely small. While it is generated at the center of a room, it takes its largest value. The value of SVE 2 (mean radius of diffusion) becomes greater as the contaminant source is placed farther from the wall.

These scales are thus confirmed to be very effective for comparing the ventilation characteristics with various source positions.

6.2 Case study 2; comparison of ventilation efficiency for 2 types of supply-exhaust system [18]

Fig. 7 compares the flow and diffusion fields in two types of turbulent-flow clean rooms : a room with a conventional supply-exhaust system and one with a supply/exhaust locally-balanced type ventilation system. The supply/exhaust locally-balanced type ventilation system provides an exhaust inlet for each local airflow unit, 9 in total, as is shown in Fig. 7. This arrangement of exhaust openings exhausts the contaminant generated in each flow unit with minimum dispersion into other units [17]. The contaminant diffusion area is reduced significantly (or sometimes dramatically) in the supply/exhaust locally-balanced type ventilation system when compared to the conventional supply-exhaust system, as is shown in Fig. 7.

The values of SVE 1 and SVE 2 for the source position at the center of the

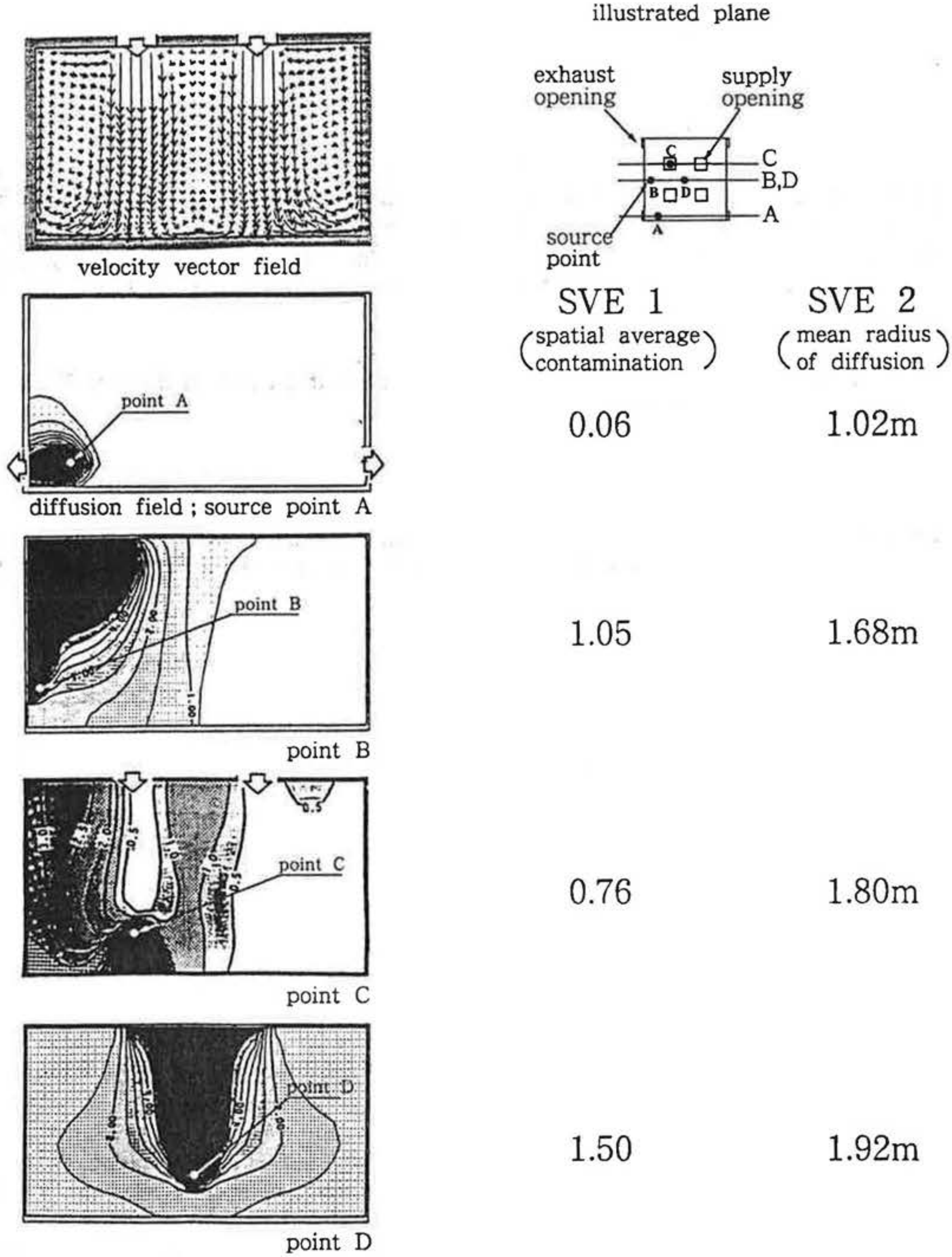


Fig.6 Comparison of contaminant distribution and values of SVEs for various source positions

(Room model ; 1 size; H 2.7m x L 4.8m x D 4.8m
2 4 supply openings and 4 exhaust openings
3 air change rate ≒ 83 (ACH))

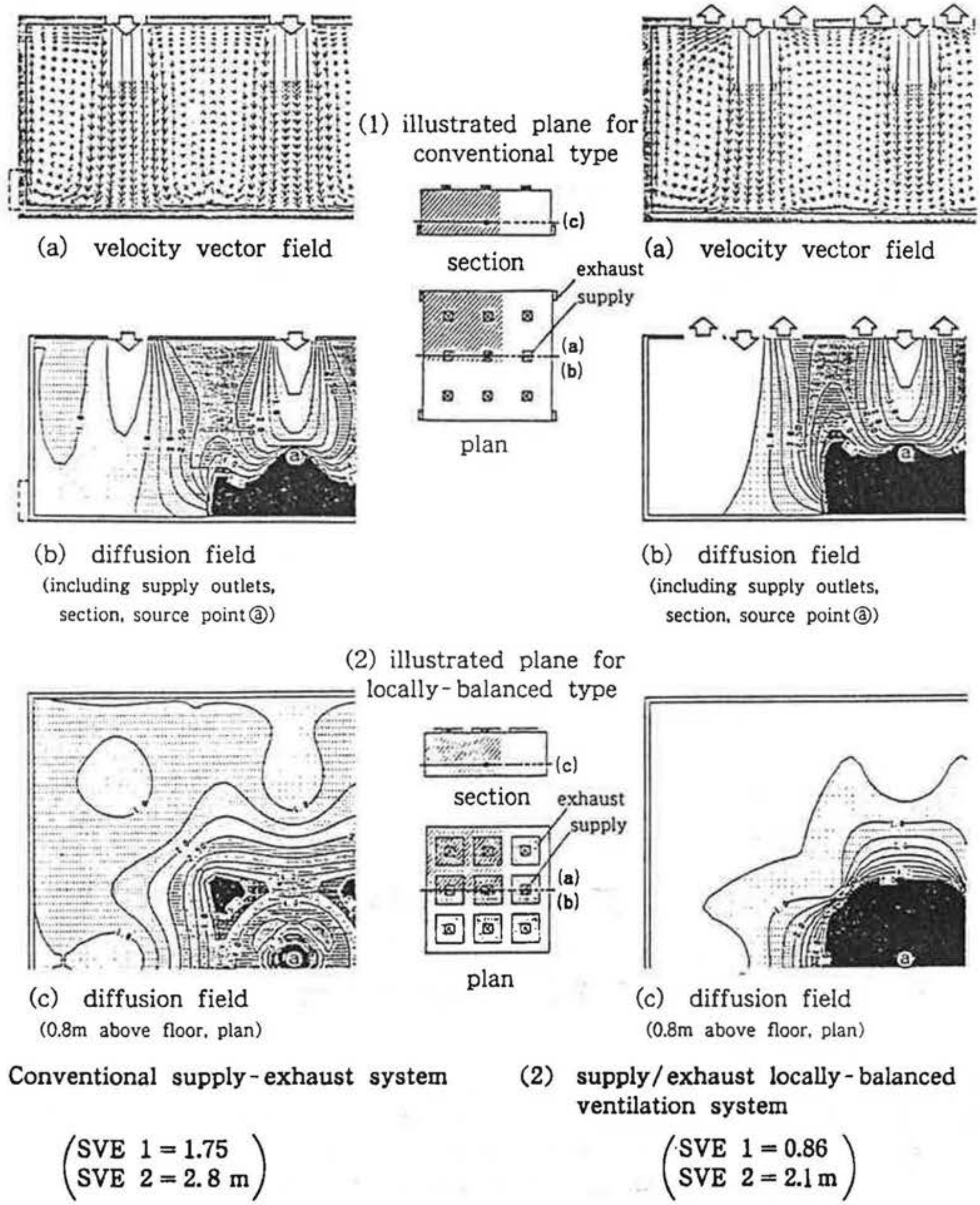
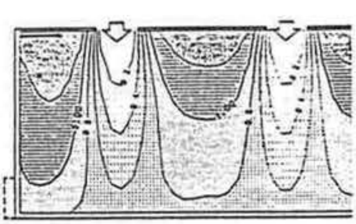
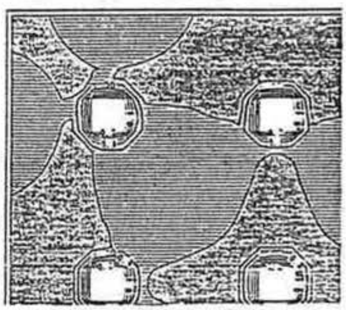


Fig.7 Comparison of contaminant distributions and SVEs for different supply/exhaust systems

(room model ; 1 room size ; H 2.7m x L 7.8m x D 7.8m
2 air change rate ≒ 71 (ACH)
3 9 supply opening
4 exhaust opening; 4 for conventional type and 9 for locally-balanced type)



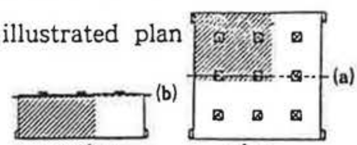
(a) including supply outlets (section)



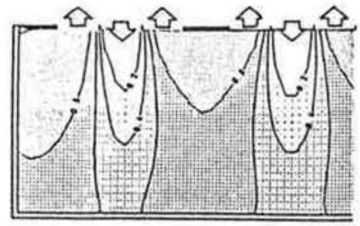
(b) near ceiling (plan)

(1) Contaminant distributions for conventional supply-exhaust system
(source : uniform generation in the whole room)
(average of SVE3 = 0.97)

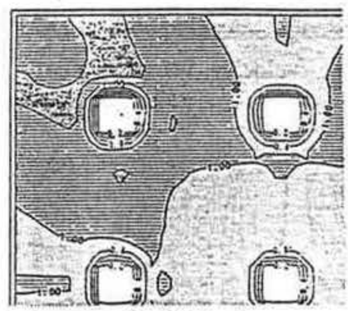
illustrated plan



section plan



(a) including supply outlets (section)

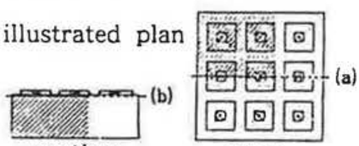


(b) near ceiling (plan)

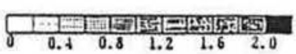
(2) Contaminant distributions for supply/exhaust locally-balanced system

(average of SVE3 = 0.84)

illustrated plan



section plan



Dimensionless concentration

Fig.8 Distribution of SVE 3 for different supply/exhaust systems
(SVE3 : age of supply air)

room are 1.75, and 2.8m with the conventional supply-exhaust system. On the other hand, with the supply/exhaust locally-balanced type ventilation system, SVE 1 is 0.86 and SVE 2 is 2.1m. This indicates that the supply/exhaust locally-balanced type ventilation system exhausts contaminant 2 times faster than the conventional supply-exhaust system. Furthermore, the area of contaminant dispersion in a room is also reduced by 30%. Ventilation efficiency is thus improved significantly with the latter type. SVE 1 and 2 make it possible to compare quantitatively the diffusion and ventilation phenomena of different rooms. These scales are thus confirmed to be very effective in evaluating ventilation systems.

Fig. 8 compares the distribution of SVE 3 (the age of supply air) in both conventional and locally-balanced ventilation systems. In both systems, the age of air in the supply jet region is young (cf. Fig. 8 (a)), while it is old in the region surrounding the supply outlet near the ceiling (cf. Fig. 8 (a), (b)). These figures show the possible travelling routes of supplied air, where the supply jet forms a diverging flow by collision with the floor surface, reaches the ceiling in the form of a rising stream surrounding the jet, and then becomes a converging flow induced by the supply jet near the ceiling. When the respective values of SVE 3 are compared, a region with a value more than 1.2 is observed between the supply outlets near the ceiling in the conventional supply-exhaust system, while the supply/exhaust locally-balanced type shows values smaller than 1.0 in almost all regions. As is well known, the room mean value of SVE 3 represents the average age of the supplied air in a room. The value of the conventional system shows 0.97 and that of the locally-balanced type system 0.84, both representing a value lower than 1.0. The average age of supply air (average of SVE 3) with perfect mixing of air in a room shows 1.0 and that under a plug flow 0.5. The conventional ventilation system is thus evaluated as having ventilation efficiency fairly similar to that of perfect mixing when it is assessed from the standpoint of fresh air distribution, while the ventilation efficiency of the supply/exhaust locally-balanced ventilation system is closer to that of plug flow, although there is good mixing of air in each flow unit.

In Europe and the U.S.A., the evaluation of ventilation efficiency is often based on the age of supply air at present. Although much tedious work is required to obtain by experiment the distribution of the age of supply air in a room, this can be done rather easily and accurately by the numerical simulations presented here. In surveying the experiments for measuring the age of supply air, air leakage in the structure is regarded as critical since that has a serious affect on the accuracy of the measurements. When predicting the age of air, leakage is of great importance, not only in prediction with experimental methods but also with numerical simulation. However, we would like to emphasize that it will not be so difficult to incorporate the effects of leakage in the numerical simulation, in which the boundary conditions including systematic change of these effects can be applied with ease.

7. Conclusion

This paper outlines a study on ventilation characteristics based on analyses of flowfields utilizing numerical simulation. It is emphasized that the ventilation characteristics in a room are determined by the flowfield and can be evaluated by the concentration distribution of contaminant. Presented are scales for ventilation efficiency defined by the characteristics of the spatial distribution of contaminant. Application examples confirm the new scales to be very effective for evaluating ventilation efficiency. The spatial distribution of age of air or residual life time of air in a room, widely known to be a good scale for evaluating ventilation efficiency but difficult to get by measurement, can be obtained easily with the aid of numerical simulation.

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