THE COMPARISON BETWEEN AIR CHANGE EFFICIENCY AND CONTAMINANT REMOVAL EFFECTIVENESS UNDER SOME TYPICAL AIR FLOW CONDITIONS IN THE ROOM VENTILATED MECHANICALLY

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ABSTRACT

There are many indices to evaluate the ventilation characteristics of the ventilated rooms. These indices are classified into air change efficiency and contaminant removal effectiveness. In order to know how to use many indices for a good understanding of the characteristics of the concerned ventilation system, the values of various efficiencies under some typical air flow conditions with isothermal condition are compared.

The local mean age distributions and local contaminant concentrations are measured with tracer gas technique in a scaled model of the room ventilated mechanically. Four typical air flow conditions are made inside the enclosure. Two conditions are of high velocity type, and the other two conditions are of low velocity type. The ceiling based type and the underfloor type are selected as the typical ventilation system.

The distribution of local air change index and local air quality index were investigated. Then the relationship between local air change index and local air quality index was examined. It is turned out that this relationship express a unique and interesting feature for each ventilation type. And it is confirmed that air change efficiency and contaminant removal effectiveness are also important indices to evaluate the quality of ventilation efficiency.

KEYWORDS

Ventilation efficiency, Air exchange efficiency, Contaminant removal effectiveness, Tracer gas, Model experiments

INTRODUCTION

There are many indices to evaluate the ventilation characteristics of a ventilated room. These indices are classified into "air change efficiency" and "contaminant removal effectiveness" (Etheridge and Sandberg 1996; AIVC 1991). Air change efficiency is the name of the indices to evaluate the amount of fresh air distributed in the room. Contaminant removal effectiveness is the name of the indices to evaluate the cleanliness of the air in the case that a specific contaminant source is supposed to be in the room. Though air change efficiency is based on the concept of the age of air, the contaminant concentration can be estimated by this index when the contaminant emission is uniform throughout the room. In other words, it can be said that the difference between these two categories of ventilation efficiency is the difference of way of contaminant emission.

Recently these indices are attracting the attentions of many engineers and researchers in charge of air conditioning and ventilation. However, it is necessary to know how to use the many indices for a good understanding of the characteristics of the concerned ventilation system.

In this paper some representative indices are used to evaluate some typical isothermal air flow conditions in a scaled model room ventilated mechanically in order to investigate the characteristics and make clear what each efficiency evaluates.

VENTILATION INDICES

The following representative indices (Etheridge and Sandberg 1996; AIVC 1991) are selected for the estimation of ventilation efficiency in this paper. Strictly speaking, local mean age of air and room mean age of air is not the efficiency but basic statistics to define the air change efficiency.

air change efficiency

1. local mean age of air τ_p
2. local air change index ε_p
3. room mean age of air $\langle\tau\rangle$

4. air change efficiency ε_a

contaminant removal effectiveness

1. local air quality index ε_p^c
2. contaminant removal effectiveness ε^c

EXPERIMENTAL SETUP

A model enclosure was used to measure the various indices with tracer gas technique. Figure 1 shows the structure of the model. The model is made of wood except for two walls, which are acrylic for visualization of airflow inside the enclosure. This model has two supply opening with a big chamber and four exhaust opening with a small chamber. The steel plates with a thickness of 3 mm having a circular opening were installed onto the supply and exhaust chambers joined to the model enclosure. The diameter of exhaust opening is 15 cm. There are two plates with different diameters of 6 cm and 30 cm for supply openings. Table 1 shows the combinations of supply opening and exhaust opening. The abbreviations in Table 1 mean the position of supply opening and the velocity in supply opening. High velocity in supply opening corresponds to the diameter of 6 cm and low velocity the diameter of 30 cm. As there is no heat source in the enclosure, the airflow in the enclosure is isothermal. The high velocity type was intended to make airflow perfect mixing, and the low velocity type was intend to make airflow low mixing and something like a piston flow.

Using this model two types of experiments were conducted. One is the measurement of air change efficiency and the other is the measurement of contaminant removal effectiveness. The conditions for the former experiment are listed in Table 2 and the conditions for the latter are listed in Table 3.

The supply airflow rate in any case was intended to be the same, but it was turned out that the fan performance is gradually decreased. That is the reason why the mean supply airflow rates in tables are not the same. As each measurement of air change efficiency for a certain condition took much longer time than the one of contaminant removal experiment, the rage of supply airflow rate is listed in Table 2.

Local mean age of air was measured by step up and step down method with SF_6. For

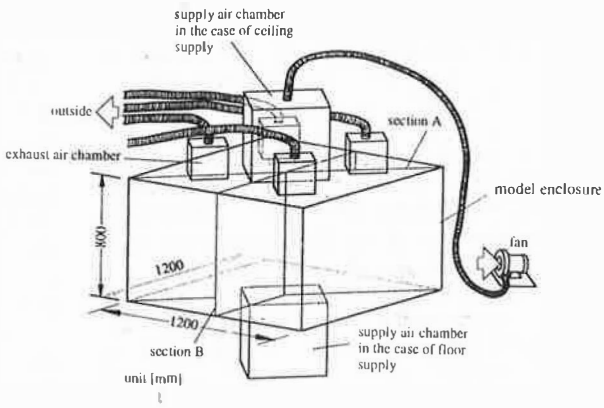


Figure 1 Model of the room mechanically ventilated

Table 1 Types of ventilation

type	supply of air	supply velocity	diameter of supply opening	diameter of exhaust opening
C-H	ceiling	high	30 cm	15 cm
C-L	ceiling	low	6 cm	15 cm
F-H	floor	high	30 cm	15 cm
F-L	floor	low	6 cm	15 cm

Table 2 Conditions for the experiments to measure the air change efficiency

type of ventilation	C-H	C-L	F-H	F-L
measuring time	10 min.	10 min.	10 min	15 min.
generation rate of SF_6	150 cc/min.	150 cc/min	150 cc/min	12.5 cc/min.
supply airflow rate	40.5-45.0 m³/h	45.5-53.0 m³/h	36.6-42.1 m³/h	25.1-28.9 m³/h
mean supply airflow rate	43 m³/h	50 m³/h	38 m³/h	27 m³/h
supply velocity	4.2 m/s	0.12 m/s	3.7 m/s	0.11 m/s

Table 3 Conditions for the experiments to measure the contaminant removal effectiveness

type of ventilation	C-H	C-L	F-H	F-L
measuring time	5 min.	5 min.	5 min.	5 min.
generation rate of SF_6	50 cc/min.	50 cc/min	50 cc/min.	12.5 cc/min.
supply airflow rate	40.2 m³/h	46.3 m³/h	36.6 m³/h	30.1 m³/h
supply velocity	4.0 m/s	0.18 m/s	3.6 m/s	0.12 m/s

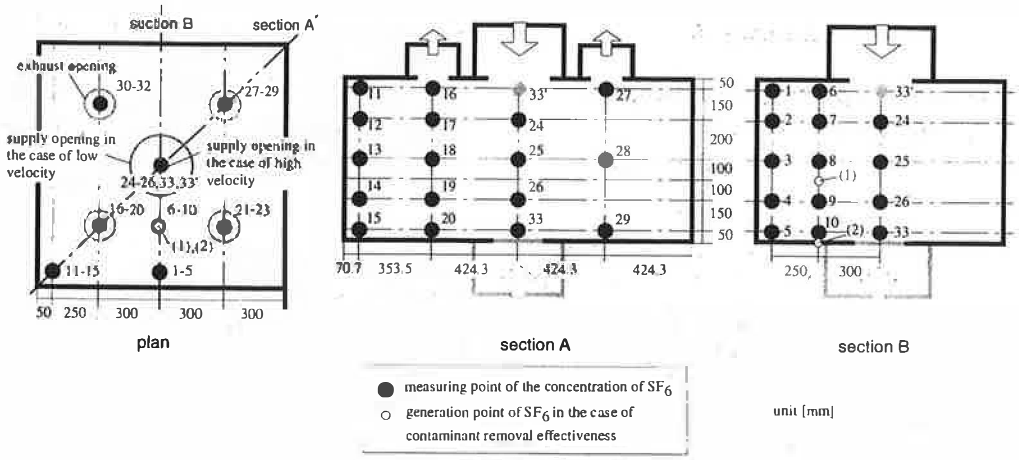


Figure 2 Measuring point and generation point of SF_6

one point in the enclosure, a set of step up and down was conducted. The points where the change of SF_6 concentration was measured were shown in Figure 2. When stepping up the concentration in the enclosure, the SF_6 gas was emitted in the supply hose near the fan. The local air change index was calculated from the local mean age of air. After a series of measurements of local air change efficiency, the SF_6 concentration of the exhausted air in each exhaust hose was measured sequentially to calculate the room mean age of air and the air change efficiency.

Local air quality index and contaminant removal effectiveness were calculated from the equilibrium concentration at measuring points with the constant generation of SF_6 gas at the point of (1) or (2) in Figure 2. The gas generation points are located in the plane of section B.

For all the measurement of SF_6 concentration real time gas monitor (model 1311 by B & K) was used.

Before these measurements, the airflow patterns were visualized with smoke injected into supply air and laser light sheet projected from the side of the enclosure.

CALCULATION OF INDICES

The indices listed above are calculated from the measured concentration. The equations to calculate them are as follows.

In the case of step up method local mean age of air τ_p can be calculated by,

$$\tau_p = \int_0^\infty \left(1 - \frac{C_p(t)}{C_s}\right) dt \qquad (1)$$

where $C_p(t)$= concentration at time t and point p,
C_s= concentration of supply air.

In the case of step down method τ_p can be given by the next equation:

$$\tau_p = \int_0^\infty \frac{C_p(t)}{C_p(0)} dt \qquad (2)$$

where $C_p(0)$= the initial concentration at point p.

Local air change index ε_p can be obtained by,

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \qquad (3)$$

where τ_n= the nominal time constant. This constant is the volume of the enclosure V divided by the ventilation flow rate Q:

$$\tau_n = \frac{V}{Q}. \qquad (4)$$

Room mean age of air $\langle\tau\rangle$ is derived from equation (5) in the case of step up method:

$$\langle\tau\rangle = \frac{\int_0^\infty t\{QC_s - (Q_1C_{e1}(t) + Q_2C_{e2}(t) + Q_3C_{e3}(t) + Q_4C_{e4}(t))\}dt}{\int_0^\infty \{QC_s - (Q_1C_{e1}(t) + Q_2C_{e2}(t) + Q_3C_{e3}(t) + Q_4C_{e4}(t))\}dt}. \qquad (5)$$

where Q_1, Q_2, Q_3, Q_4= airflow rate of each exhaust opening

C_{e1}, C_{e2}, C_{e3}, C_{e4}= concentration of the air in each exhaust opening

As for the step down method, the next equation can be applied:

$$\langle\tau\rangle = \frac{\int_0^\infty t(Q_1C_{e1}(t)+Q_2C_{e2}(t)+Q_3C_{e3}(t)+Q_4C_{e4}(t))dt}{\int_0^\infty (Q_1C_{e1}(t)+Q_2C_{e2}(t)+Q_3C_{e3}(t)+Q_4C_{e4}(t))dt} \quad (6)$$

Air change efficiency ε_a is calculated by,

$$\varepsilon_a = \frac{\tau_n}{\tau_r} \quad (7)$$

where τ_r= the average time of replacement of the air. τ_r is twice the room mean age of air :

$$\tau_r = 2\langle\tau\rangle . \quad (8)$$

So far as contaminant removal effectiveness, the local air quality index ε_p^c can be expressed by,

$$\varepsilon_p^c = \frac{C_e}{C_p} . \quad (9)$$

where C_e= the exhaust concentration,
C_p= the equilibrium concentration at point p.

Contaminant removal effectiveness ε^c is calculated by the equation (10):

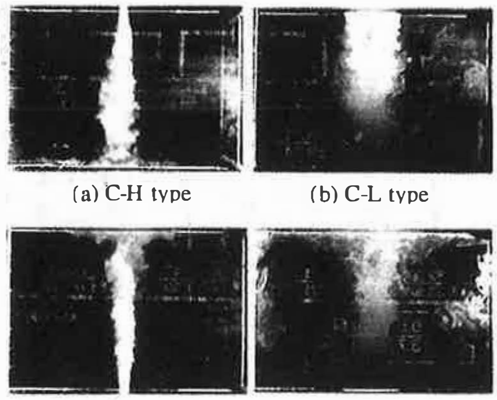
$$\langle\varepsilon^c\rangle = \frac{C_e}{\langle C\rangle} \quad (10)$$

where <C>= the average concentration in the enclosure.

RESULTS AND DISCUSSIONS

Airflow patterns in the enclosure

Figure 3 shows the visualized airflow in the enclosure for each ventilation type. Smoke was injected to supply air and the section A was lit up by laser light sheet. In the cases of high supply velocity (C-H and F-H), supplied air is blown out in the form of jet. It was observed that the air in the enclosure is circulated with high velocity due to the jet. In the cases of low supply velocity (C-L and F-L), the supplied air moves slowly towards the opposite wall with a potential core. It appears that jet is not established in these cases and the mixing inside the enclosure seems weaker than the high velocity cases.



(a) C-H type (b) C-L type

(c) F-H type (d) F-H type

Figure 3 Visualized supply airflow inside enclosure with smoke

The distribution of local mean age of air and local air change index

The distribution of local mean age of air and local air change index of each type is shown in Figure 4. The values above a line is measured by step up method, and the values below a line is measured by step down method. It can be seen that most of the values measured by step up method and the ones measured by step down method are almost the same.

In every figure, the local mean age of air is relatively low and the local air change index is high on the central axis of supply opening. In the cases of high velocity type, these indices in the other area than this axis are relatively equal. This means that the air is quite well mixed beside a small area of supply jet. On the other hand, in the enclosure with low velocity supply the local mean age of air at each point varies with a larger range. This seems to reflect the insufficient mixing and the large distribution of tracer gas concentration.

Though the room mean age of air and the air change efficiency are also written in Figure 4, these values will be investigated later in this paper.

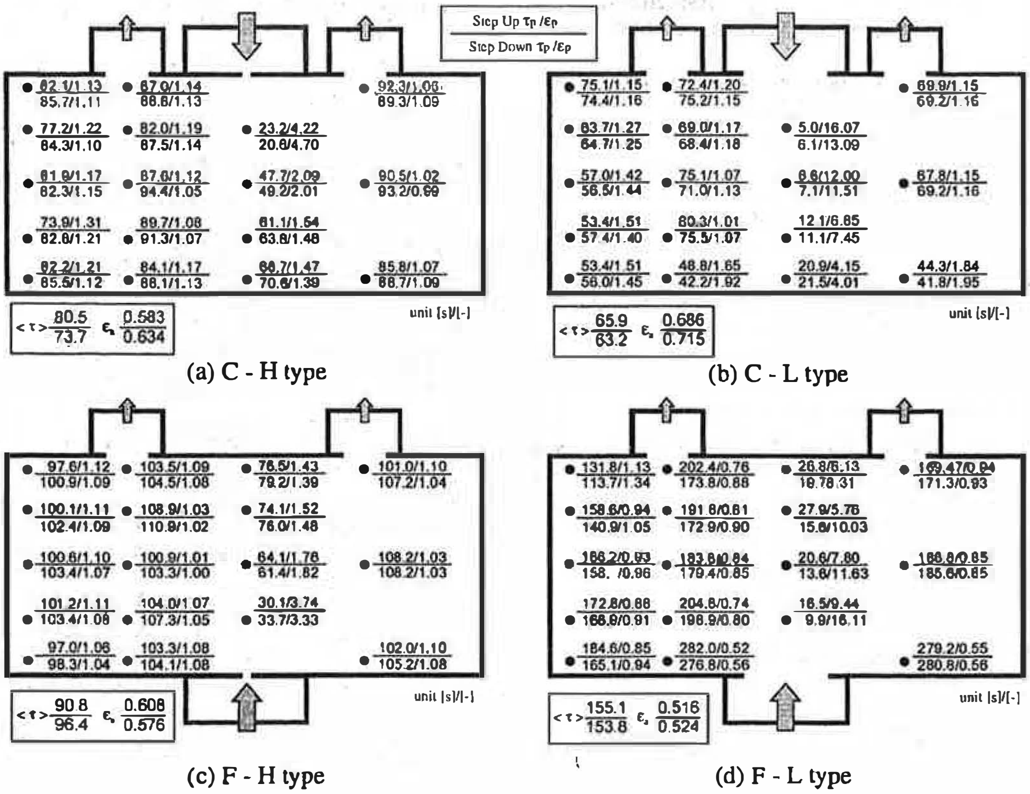


Figure 4 Distribution of local mean age of air and local air change index (section A)

The distribution of local air quality index

Figure 5 show the distribution of local air quality index in section B when SF_6 was generated at point (1). Values of the index are written in the boxes with different gray tones corresponding to the SF_6 concentration at each point, which is proportional to the reciprocal of the index. The local air quality index is lower than unity at every point except for the points on the central axis of supply opening. Comparing the high velocity types (C-H and F-H type) with the low velocity types (C-L and F-L), the high velocity types have larger index value in most ambient zone around the supply airflow. In the case of low velocity type, generated SF_6 is not diffused so rapidly as the high velocity type because of the low velocity in the

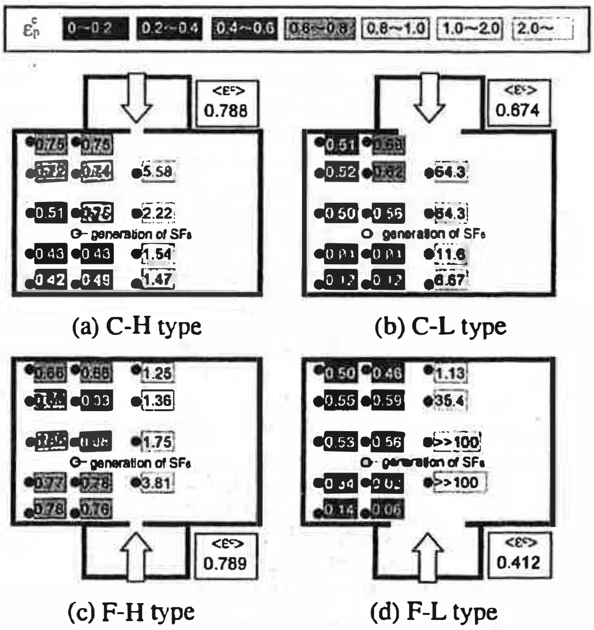


Figure 5 Distribution of local air quality index (section B,the generation point of SF_6: (1))

enclosure, which arise the low value and large unevenness of the local air quality index.

The distribution of local air quality index in the case that the generation point of SF_6 is positioned (2) is shown in Figure 6. For every type of ventilation, the values of the index are larger than those in Figure 5 at most points in the enclosure. This is considered to be brought by the flows along the surface of the enclosure with a high velocity conveying the generated SF_6 to exhaust openings. And it can be seen that the high velocity types have larger values in the ambient area around the supply flow than the low velocity type.

Though the contaminant removal effectiveness is also written in Figure 5 and 6, these values will be investigated later.

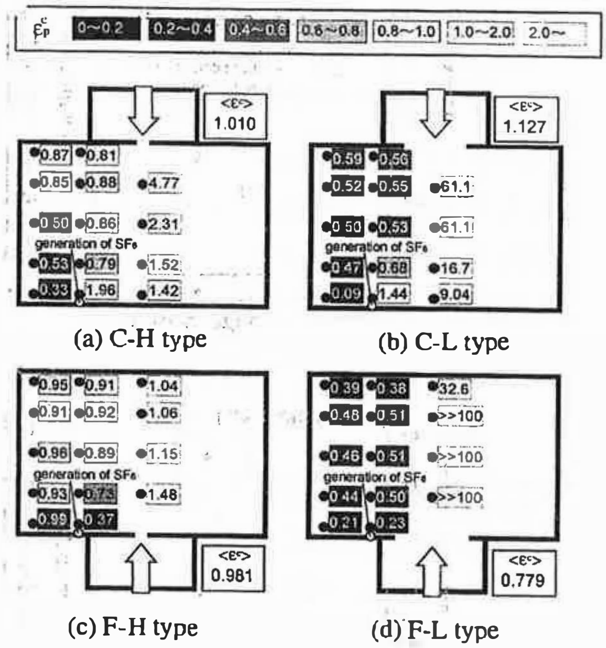


Figure 6 Distribution of local air quality index (section B, the generation point of SF_6: (2))

The relationship between the local air change index and local air quality index

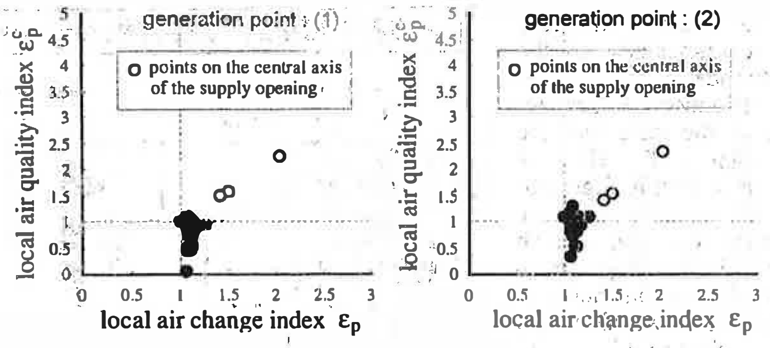
Figure 7 shows the relationship between the local air change index and the local air quality index. For both indices, 1.0 means that the concentration has the same value as that of perfect mixing. The figures on the left row are the case of SF_6 generation point (1) and the ones on the right are of point (2). It should be noted the only data on this area seen in the figure are plotted. The data of the points on the central axis of the supply opening are plotted with a small circle, and the others are plotted with a black dot. In any case each type has its own unique appearance of the distribution regardless of the generation position of SF_6. There is a tendency that the low velocity type has wider range of the index than the high velocity type. As for two high velocity types, these types have very similar tendency of data with each other.

If the overall quality should be evaluated by these figures, the more marks which is located in the right and upper area in each figure means the better quality of ventilation efficiency. According to this meaning, it seems that C-L type has the best quality of ventilation efficiency among four types of ventilation.

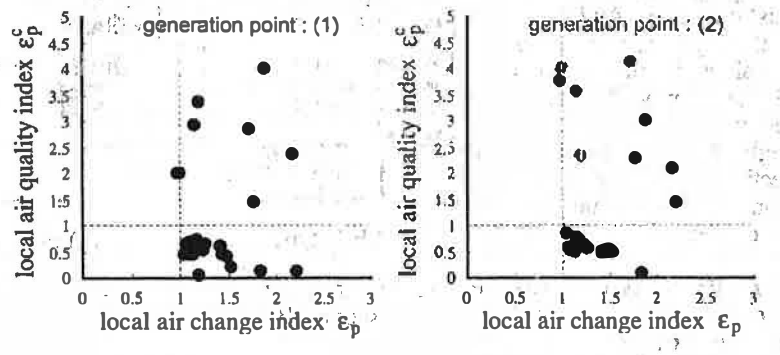
It can be said that this kind of chart is a good way to evaluate the quality and distribution of ventilation efficiency.

Air change efficiency and contaminant removal effectiveness

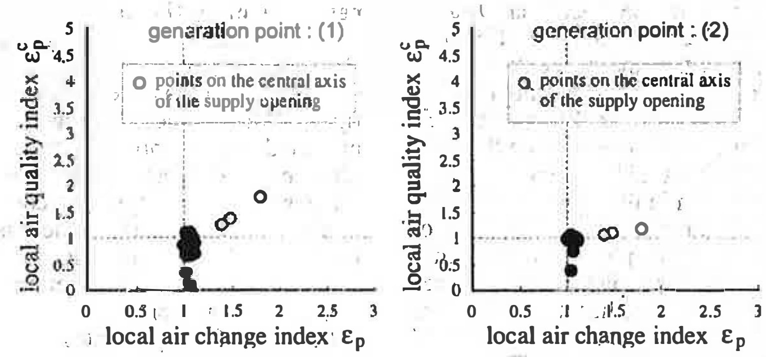
Figure 8 is a bar graph of the air change efficiency, and Figure 9 is that of contaminant removal effectiveness. In every figure, the value for perfect mixing is indicated by a broken line. Air change efficiency suggests that the ventilation efficiency of every type is better than perfect mixing, and the order of them is C-L, C-H, F-H and F-L. This tendency is almost true in the case of contaminant effectiveness with SF_6 generation from point (2) (Figure 9 (b)). When the SF_6 generates from point (1) (Figure 9 (a)), however, the values are lower and the order is a little different. In this case, C-L type does not have so good capacity to remove the contaminant. But it should be noted that the contaminant removal effectiveness was calculated by averaging the concentration of SF_6 weighted by the volume surrounding each measuring point, whichmight lead to some error in this effectiveness. Anyway these indices for overall the enclosure is one of good way to know ventilation quality.



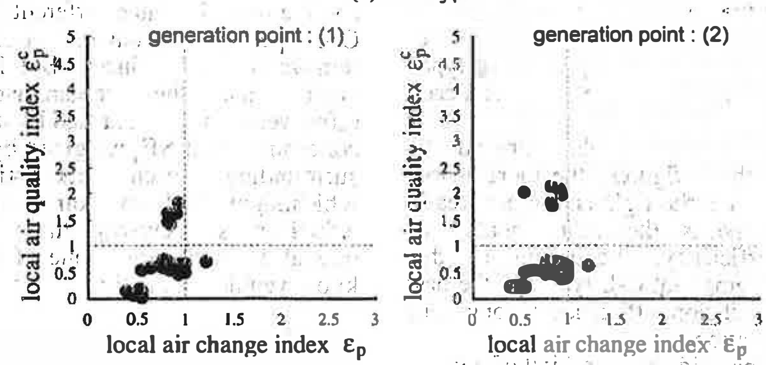
(a) C-H type



(b) C-L type



(c) F-H type



(d) F-L type

Figure 7 Relationship between local air change index and local air quality index

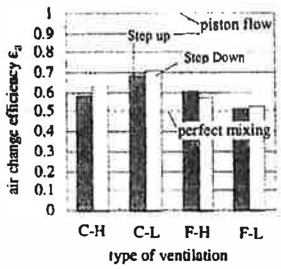
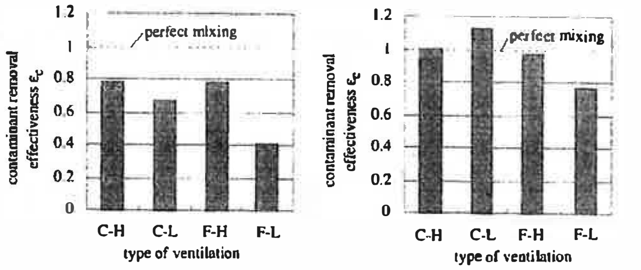


Figure 8 Air change efficiency



(a) SF_6 generation from point (1) (b) SF_6 generation from point (2)

Figure 9 Contaminant removal effectiveness

CONCLUSIONS

Under the airflow condition like C-H or F-H which has a established jet on the central axis of supply opening and high velocity field in the enclosure, local air change index and local air quality index are almost uniform in the ambient area surrounding the jet.

On the other hand, in the case of the low velocity type like C-L or F-L the flow line can be suggested by the distribution of local mean age of air, and local air quality index is distributed nonuniformly depending upon the position of SF_6 generation.

In any case, generation of SF_6 in position (2) causes better effectiveness to remove the contaminant due to the flow along the envelope surface.

A chart to show the relationship between local air change index and local air quality index is very good to know the quality of ventilation efficiency of the concerned ventilation airflow. The low velocity type has a wide distribution of spread marks in this figure.

It is also useful to examine the air change efficiency and the contaminant removal effectiveness to grasp the overall quality of ventilation.

In the future, the authors shall evaluate the displacement flow in the room with heat sources by means of the same indices.

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