# EXPERIMENTAL STUDY ON AIR EXCHANGE EFFICIENCY IN HOUSES WITH CENTRAL VENTILATION SYSTEMS



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## ABSTRACT

This paper describes the results we got from the field measurement of air exchange effectiveness (i.e. local mean age of air and local air exchange index). The measurement was carried out on two wooden houses equipped with different kinds of ventilation systems.

The results are as follows:

(1) The value of local mean age of air, based on the definition of AIVC [1] and measured by the step-up tracer-gas method, is twice to five times as large as the value got through the step-down tracer-gas method, because of the infiltration of the houses.

(2) The value of local mean age of air, based on the definition of Sandberg [2], is nearly the same through both the step-up and step-down methods.

(3) The spatial distribution of local mean age of air (TP) and local air exchange efficiency (EP) is very large when a circulating fan is not operating, but when a fan is working the distribution of TP and EP is relatively small.

## KEYWORDS

Air exchange efficiency, Local mean age of air, Air exchange index, Infiltration.

## 1. INTRODUCTION

In the usual ventilation design method, the air exchange rate is calculated on the basis of the pollutants caused by people or combustion and acceptable concentrations of the pollutants must be maintained. But, this method is effective only in the case of the perfect mixing of pollutants. In an actual building, there are both well ventilated places and poorly ventilated places because of the relative position of supply outlets and exhaust inlets.

Formerly in Japan, most of the houses depended on natural ventilation, and mechanical ventilation systems were not installed. But recently, the air-tightness of houses has improved, creating a comfortable indoor environment and saving energy. In an air-tight house the natural ventilation rate decreases, and causes the problems of indoor air pollution and condensation. Therefore, it is necessary to design an efficient mechanical ventilation system and to evaluate ventilation effectiveness.

In this paper, a tracer gas method is used to measure local air exchange efficiency as defined by age of air in an actual full-scale wooden house. Furthermore, the aim of this paper is to evaluate the distribution of the outdoor air quantitatively. In the case of a house, the influence of infiltration must be considered.

In this paper we suggest two kinds of local age of air and three kinds of local mean air exchange efficiency, and evaluate the influence of infiltration according to this suggestion.

The points of this paper are as follows.

(1) The influence of air circulation or lack of it on the index of ventilation efficiency in the room is examined.
(2) The comparison of ventilation efficiency on various levels of air-tightness is examined.
(3) The influence of infiltration on the calculated method of ventilation efficiency is examined.

## 2. DESCRIPTION OF THE TEST HOUSES

### 2.1 House A

#### (1) The plan of the house

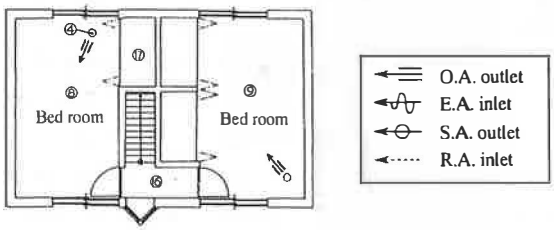
Figure 1 shows the floor plan of House A. House A is a 2-story wood house, which has 5 rooms with a total floor area of 108m$^2$ and a total room air volume of 253m$^3$. The air-tightness of the house was measured by both the fan pressurization and depressurization methods. The equivalent leakage area per floor area with an indoor-outdoor pressure difference of 10 pa is about 10cm$^2$/m$^2$.

#### (2) Ventilation system

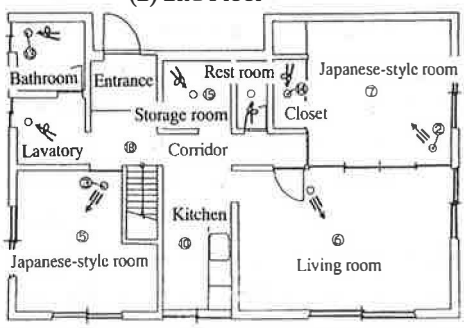
Figure 2 shows the outline of the ventilation

Table 1 Outline of test houses

| | Total Floorage | Volume | Equivalent leakage area | |
|---|---|---|---|---|
| | | | pressurization | depressurization |
| House A | 108 m$^2$ | 253 m$^3$ | 10.2 cm$^2$/m$^2$ | 10.0 cm$^2$/m$^2$ |
| House B | 127 m$^2$ | 497 m$^3$ | 3.08 cm$^2$/m$^2$ | 3.23 cm$^2$/m$^2$ |




(2) 2nd Floor




(1) 1st Floor

Figure 1 Floor plan of House A

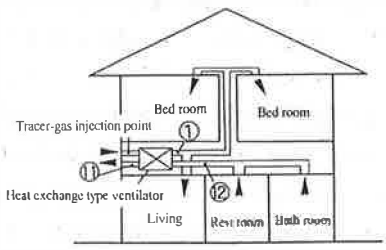
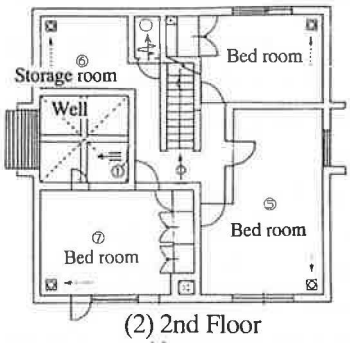
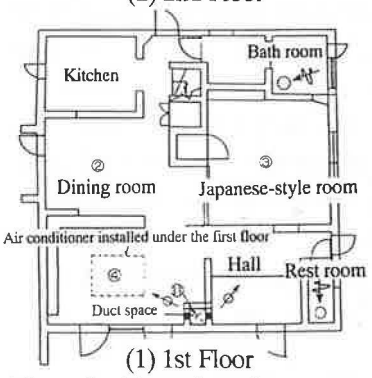



Figure 2 Ventilation system of House A




(2) 2nd Floor




(1) 1st Floor

Figure 3 Floor plan of House B

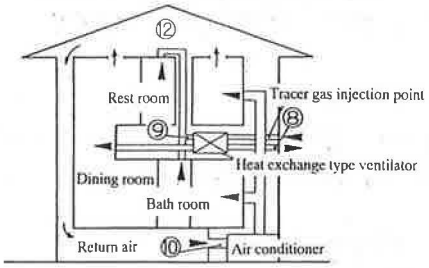



Figure 4 Ventilation system of House B

system. Fresh air is supplied to the each room of the first and second floors with the heat exchange type ventilator installed in the kitchen. Exhaust inlets are installed in the storeroom, bathroom and the rest room.

### 2.2 House B

#### (1) The plan of the house

Figure 3 shows the floor plan of House B. House B is 2-story wood house, which has 6 rooms with a total floor area of 127m$^2$, and a total room air volume of 497m$^3$. The equivalent leakage area is about 3cm$^2$/m$^2$, and air-tightness is comparatively high.

#### (2) Ventilation system

Figure 4 shows the outline of the ventilation system. Fresh air is supplied to the well of the living room with the total heat exchange type ventilator, and it is exhausted from the rest room and the bathroom. This house has a central air conditioning system, which can circulate the air of all the rooms. The supply outlets of the air conditioning system are installed in the living room and in the corridor of the second floor. The return inlets for the air conditioner are installed in the ceiling of each room. Indoor air is returned to the air conditioner -installed under the first floor- through the attic area and between the first floor ceiling and the second floor.

## 3. MEASUREMENT METHOD OF VENTILATION EFFICIENCY

### 3.1 Ventilation Efficiency

Tracer gas ($C_2H_4$) is injected at a constant rate into the entrance of the fresh air supply inlet of the heat exchange type ventilator. Tracer gas is injected until the gas concentration at each measuring point reaches a steady state. Local mean age of air and local air exchange efficiency are calculated from a concentration profile of the tracer gas measured in the room, the supply outlets and the exhaust inlets. We use a multi-gas monitor (B&K) for the measurement of the concentration, figure 1 - 4 show measurement points in the rooms. All the space partition doors are closed at the time of the measurement. The height of the measurement points in the rooms is 1m from the floor in the center of the room except for supply outlets and the exhaust inlets, which are at different heights. The outdoor wind speed during the measurement uses 10-minute average wind speed at a point 2m above the roof top.

### 3.2 Experimental Conditions and Measurement Periods

Table 2 shows experimental conditions and measurement periods. In case of House A, the air conditioner is stopped during measurement. In case of House B with the central air conditioner, we carried out 2 sets of measurements. One set is while the air conditioner circulated all the air of the room, and the other set is while the air conditioner was stopped. Table 2 shows the outdoor temperature, room temperature and outdoor wind speed during the measurements.

### 3.3 The Calculation Method of the Local Mean Age of Air and Local Air Exchange Efficiency

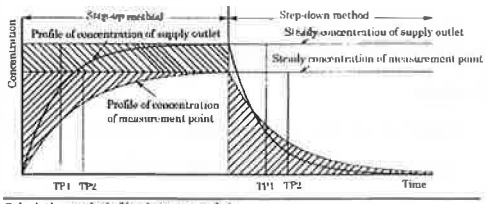
In a house the infiltration rate is the same as the mechanical ventilation rate, so infiltration can't be ignored when calculating the age of air and the air exchange efficiency. After a long time passes, the gas concentration becomes the same value at all measurement points if there is no infiltration. But, if there is infiltration, tracer gas concentration at each measurement point decreases due to the infiltration, and the steady state gas concentration doesn't become a

constant. So it is necessary to examine a new method to calculate age of air and ventilation efficiency. Figure 5 shows the calculation method of local mean age of air, nominal time constant and local air exchange efficiency.

In the case of the step up method, infiltration makes the concentration of tracer gas at each measurement point decrease because tracer gas isn't contained in the infiltration but only in the fresh air due to mechanical ventilation. Therefore, the age of air calculated from the step up method is determined the age of air only due to mechanical ventilation. Otherwise the age of air calculated from the step down method is determined to be shorter than the age of air only due to mechanical ventilation because infiltration can't be distinguished by the step down method. TP1 is a local mean age of air by AIVC [1]. The calculated result from the step up method and the step down method varies greatly in TP1 because the difference in steady concentration of the supply outlet and at each measurement point becomes greater with the room where infiltration is much more than mechanical ventilation. TP2 is the local average age of air that is defined by Sandberg and Fisk [2]. If it is supposed that levels of infiltration air at each measurement point are always constant, infiltration air doesn't influence the calculated result of the local mean age of air by the step up method. This is because the tracer gas, which reached each measurement point by infiltration, is rarefied constantly. It is possible, therefore, to calculate the local mean age of only the air introduced by the mechanical ventilation. In the step down method, infiltration can't be distinguished from the mechanical ventilation, so a local mean age of air including the infiltration is calculated. TN1 is the nominal time constant derived from the amount of mechanical ventilation calculated from the steady concentration of the supply outlet, and the room air volume. TN2 is the nominal time constant derived from the amount of ventilation including the infiltration that was calculated from the steady concentration of each measurement point. EP1 is the air exchange efficiency calculated from TP1 and TN1. Age of air uses TP2 for EP2 and EP3, and a nominal time constant is the air exchange efficiency

Table 2 Experimental conditions

| | Condition | | Outdoor Temperature | Indoor Temperature | Outdoor Wind speed |
|---|---|---|---|---|---|
| House A | Without air circulation | | 5~20℃ | 16~23℃ | 1~6m/s |
| House B | B-1 | With Air circulation | 1~15℃ | 21~32℃ | 0~4m/s |
| | B-2 | Without Air circulation | 0~9℃ | 8~26℃ | 0~10m/s |




Calculation method of local mean age of air

TP1 { Step Up Method + Step Down Method }

TP1 is the value that this area was divided by in the steady concentration of supply air outlet

$$TP1 = \int_0^\infty \left\{1 - \frac{C_p(t)}{C_s(\infty)}\right\} dt \quad \text{(Step up Method)} \quad \cdots(1)$$

$$TP1 = \int_0^\infty \left\{\frac{C_p(t)}{C_s(0)}\right\} dt \quad \text{(Step down Method)} \quad \cdots(2)$$

TP2 { Step Up Method / Step Down Method }

TP2 is the value that this area was divided by in the steady concentration of the measurement point

$$TP2 = \int_0^\infty \left\{1 - \frac{C_p(t)}{C_p(\infty)}\right\} dt \quad \text{(Step up Method)} \quad \cdots(3)$$

$$TP2 = \int_0^\infty \left\{\frac{C_p(t)}{C_p(0)}\right\} dt \quad \text{(Step down Method)} \quad \cdots(4)$$

Calculation method of nominal time constant

$$TN1 = \frac{V}{\left(\frac{K}{C_s}\right)} \quad \cdots(5) \qquad TN2 = \frac{V}{\left(\frac{K}{C_p}\right)} \quad \cdots(6)$$

Calculation method of local air exchange efficiency

$$EP1 = \frac{TN1}{TP1} \quad \cdots(7) \qquad EP2 = \frac{TN1}{TP2} \quad \cdots(8) \qquad EP3 = \frac{TN2}{TP2} \quad \cdots(9)$$

| | |
|---|---|
| EP1 | Local air exchange efficiency with the infiltration rate |
| EP2 | Local air exchange efficiency only with the mechanical ventilation rate |
| EP3 | Local air exchange efficiency using nominal time constant of each measuring point |

Nomenclature

$V$: Room volume($m^3$) $K$: The amount of supply of the Tracer gas($m^3/h$)
Cs: Concentration of supply outlet (ppm)
Cp: Concentration of the measurement points (ppm)
$\tau_{n1}$: Nominal time constant 1 (hour) $\tau_{n2}$: Nominal time constant 2 (hour)
$\tau_{p1}$: Local mean age of air 1 (hour) $\tau_{p2}$: Local mean age of air 2 (hour)
$\varepsilon_{p1}$: Local air exchange efficiency 1 $\varepsilon_{p2}$: Local air exchange efficiency 2
$\varepsilon_{p3}$: Local air exchange efficiency 3

Figure 5 Calculation method of local mean age of air and local air exchange efficiency

which TN1, TN2 were used for respectively. TP2 is the local mean age of air which includes not only mechanical ventilation but also infiltration, so that EP3 becomes the value of the actual air exchange efficiency by using TN2 that was calculated from the ventilation including the infiltration. It is possible to examine the influence of infiltration by comparing EP2 and EP3.

## 4. MEASUREMENT RESULTS OF HOUSE A

### 4.1 Concentration Profile

Figure 6 shows the measurement results of the concentration profile. At the supply outlet in the case of the step up method, right after tracer gas was injected, concentration rises to 850ppm, and becomes stables. The measurement points in the rooms become stable after the tracer gas injection in about 8 hours and the concentration is about 600ppm. Even the concentration at the return outlets stabilizes in the same way as the room after about 8 hours, and the concentration of the steady states value is about 400ppm, but the concentration fluctuates due to the influence of outdoor wind. The difference in concentration at the return inlets and supply outlets is due o the influence of infiltration.

After stopping the injection of tracer gas (step down method), concentration almost becomes 0 ppm in about 8 hours at any measurement point.

### 4.2 Local Mean Age of Air

Figure 7 shows the calculated results of the local mean age of air. Both TP1 and TP2 are about 20 minutes at the supply outlet. For the measurement point is in the room with a supply outlet and an exhaust inlet, and TP1 is within 160-260 minutes and TP2 is within 70-120 minutes by the step up method. For the measurement point in the room without a supply outlet and an exhaust inlet, TP1 is within 220-300 minutes and TP2 is within 120-160 minutes by the step up method. TP1 becomes 280-360 minutes and TP2 becomes 120-160 minutes at the return outlet by the step up method.

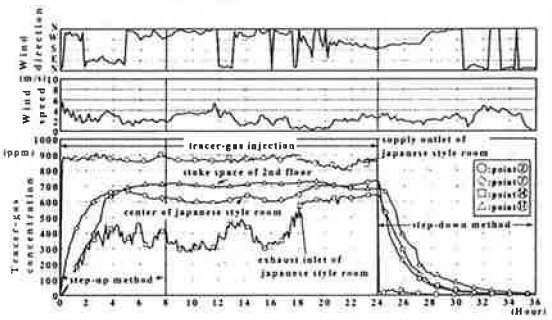



Figure 6 Concentration profile of House A

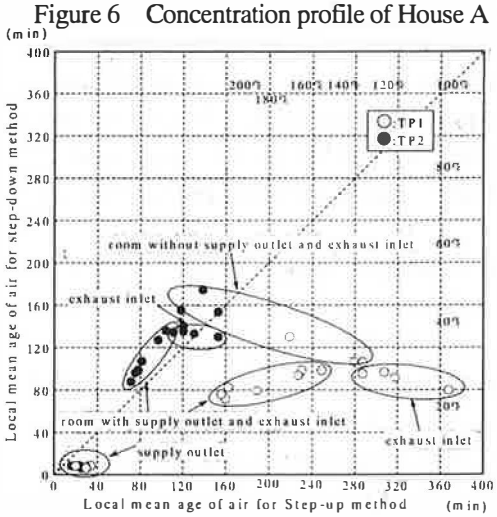



Figure 7 Local mean age of air of House A

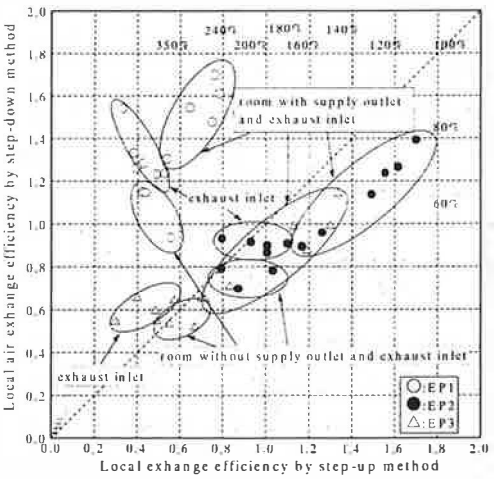



Figure 8 Air exchange efficiency of House

### 4.3 Local Air Exchange Efficiency

Figure 8 shows the calculated result of the local air exchange efficiency.

**(1) Local air exchange efficacy (EP1)**

In the room with supply outlets, the value of EP1 is in the range of 0.5-0.8. At the exhaust inlets, the value of EP1 is in the range of 0.3-0.5. In the room without supply outlets and exhaust inlets, the value of EP1 is in the range of 0.4-0.5 by the step up method.

**(2) Local air exchange efficiency (EP2)**

In the room with supply outlets, the value of EP2 is in the range of 1.1-1.8. At the exhaust inlets, the value of EP2 is in the range of 0.8-1.1. In the room without supply outlets and exhaust inlets, the value of EP2 is in the range of 0.8-1.1 by the step up method. The value of EP2 is about the same as the value of perfect mixing.

**(3) Local air exchange efficiency (EP3)**

In the room with supply outlets, EP3 is the range of 0.7-1.4. At the exhaust inlets, EP3 is in the range of 0.3-0.6. In the room without supply outlets and exhaust inlets, EP3 is in the range of 0.5-0.8 by the step up method.

## 5. MEASUREMENT RESULTS OF HOUSE B

### 5.1 Concentration Profile

Figure 9 (Exp.B-1) and 10 (Exp.B-2) shows the measurement results of the concentration profile. At the supply outlet in the case of the step up method, right after tracer gas was injected, concentration rises to 650 ppm, and it rises further by short circuit of the total heat exchange type ventilator, and becomes a steady concentration at about 900 ppm after 12 hours. The concentration profile is different in Exp.B-1 and B-2 in the measurement points of the rooms. In Exp.B-1, there is air circulation by air conditioner, so the difference in steady concentration for each measurement point is small, and it changes in the range of 450-600ppm by the influence of outdoor wind speed. In Exp.B-2, an air conditioner is not operated, and the difference in steady concentration for each measurement point is big. After the injection of the tracer gas stops, gas concentration almost declines to 0 ppm in about 15 hours.

### 5.2 Local Mean Age of Air

Figure 11 shows the calculated results of the local mean age of air. In Exp.B-2, there is no circulation of all the air of the house by the air conditioner, and there is dispersion in the value of TP2 for each measurement point. In Exp.B-1, the dispersion of the value of TP1 is small, and it is within about 400 minutes by the step up method and about 120 minutes by the step down method. When Exp. B-1 and B-2 are compared, TP2 of the under floor (where the air conditioner is located) is different from other measurement points. In this area TP2 is calculated longer than other measurement points by the step up method. It is thought that the characteristic of ventilation under the floor is different due to the existence of the circulation of air by the air conditioner.

### 5.3 Local Air Exchange Efficiency

Figure 12 shows the calculated results of the local air exchange efficiency.

**(1) Local air exchange efficiency (EP1)**

In Exp.B-1, the value of EP1 at the measurement points in the rooms is within the range of 0.8-1.2 by the step up method and 2.5-5.5 by the step down method except at the supply outlets. As for the value of EP1 of the step down method becoming relatively greater, it is because the TP1 of the step down method is smaller than the TP1 of the step up method.

**(2) Local air exchange efficiency (EP2)**

It becomes a similar value with both the step up method and the step down method. Dispersion of EP2 value at the measurement point becomes greater in the Exp.B-1 because of a lack of air circulation. EP2 is within the range of 1.5-2.3 in Exp.B-1, and 1.0-2.3 in Exp.B-2.

**(3) Local air exchange efficiency (EP3)**

It becomes a similar value with both the step up method and the step down method, and about 60% of the value of EP2

## 6. COMPARISON OF THE RESULTS OF HOUSE A

### 6.2 Local Mean Age of Air (TP)

TP1 by the step down method is within about 20-50% of ranges compared with TP1 by the step up method, so the influence of infiltration is remarkable. TP2 becomes the same value with both the step up method and the step down method. TP value of the outdoor air supply outlet is considered to be very short. But there is a short circuit inside the heat exchange type ventilator, so the exhaust air is recirculated to the room and TP value becomes relatively long. The TP value of House A is shorter than House B because the air exchange rate of House A is greater and all the rooms of House A have an air supply outlet.

### 6.3 Local Air Exchange Efficiency (EP)

Comparing the results of Exp.B-1 and B-2, when the air in the rooms is circulated, the dispersion of EP as shown by the differences at the measurement points becomes small. The step down method is calculated 2-3 times higher with EP1 in comparison to the step up method. EP1 is considered to be an inappropriate measure when compared to EP2 when there is much infiltration. With the step

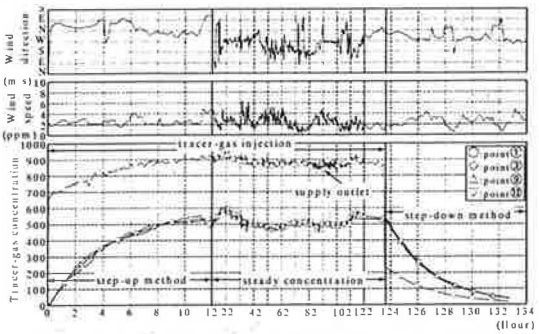



Figure 9 Concentration profile of Exp.B-1

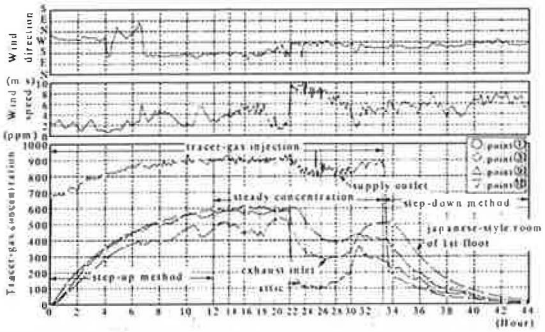



Figure 10 Concentration profile of Exp.B-2

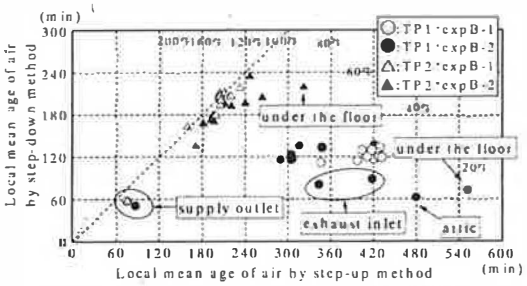



Figure 11 Local mean age of air of House B

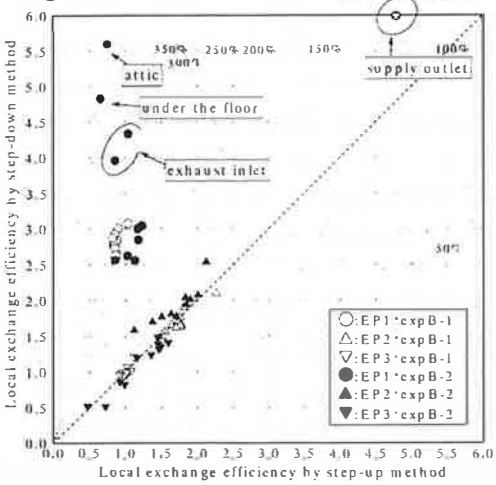



Figure 12 Air exchange efficiency of House B

up method, that shows the air exchange efficiency of only the mechanical ventilation, EP2 becomes 0.8-1.7 in House A except at the supply outlet, and becomes 1.0-2.2 in the case of Exp.B-1 (with air circulation) and 0.5-2.2 in the case of B-2 (without air circulation) in House B. The value of EP2 with the step up method (the air exchange efficiency only by mechanical ventilation) becomes 0.8-1.7 in House A except at the supply outlet. The value of EP2 becomes 1.2-2.0 in Exp.B-1 and 0.5-2.5 in Exp.B-2.

## 7. CONCLUSION

(1) When there is infiltration, the value of TP1 with the step down method becomes about 20-50% of the value of the step up method.

(2) The value of TP2 becomes about the same value in both the step up method and the step down method, while the value of TP2 with the step up method is only influenced by the mechanical ventilation rate, while the value of TP2 with the step down method is influenced by mechanical and natural ventilation. Therefore the age of infiltration air is about the same value as that of mechanically ventilated air.

(3) The value of EP1 with the step down method is calculated 2-3 times higher than with the step up method. The value of EP2 with the step up method is calculated to be equal in all the rooms because of the equal distribution of air due to mechanical ventilation.

(4) To shorten the TP of the room and to enlarge EP, the following methods are effective.

(a) Reduce the short circuits, which occur inside the heat exchange ventilator.
(b) Increase air exchange rate.
(c) Introduce outdoor air directly into the room.

(5) When the circulation fan of the air conditioner is operated, dispersion by the difference in the measurement point of TP and EP decreases. When operation is stopped, the dispersion of EP increases. Therefore, it is important to install the ventilation system that supplies the air only to the residence area.

(6) The outside wind and the difference of indoor and outside temperature must influence the concentration profile. It is necessary to examine the method of calculating the ventilation effectiveness in consideration of those changes.

**Note**: The steady concentration used when a local mean age of air was calculated is at the highest concentration during the measurement time of the step up method. With the step down method, the steady concentration occurs just before the starting of measurement.

## ACKNOWLEDGMENT

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