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EVALUATION OF VENTILATION CHARACTERISTICS OF RESIDENTIAL BUILDINGS BASED ON MULTI-ROOM TRACER GAS DECAY EXPERIMENTAL TECHNIQUES

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ABSTRACT

Under the conditions that the air in each room is in the state of perfect mixing and ventilation is in steady state, a method to estimate steady state concentration distribution to match an arbitrary contaminant generation distribution is proposed, using concentration data obtained from short-time tracer gas experiment. Also, a method is proposed, which is used to estimate ventilation rate by adding other available equations. The proposed method was tested on full-scale house models installed in the environmental test room, and it was confirmed that the steady state concentration by the proposed method corresponds well to the steady state concentration obtained by tracer gas continuous generating method. The proposed method was applied on one each of a single house and a collective house with high air tightness performance, for which elaborate equipment for ventilation has been adopted, and ventilation characteristics was evaluated from multilateral viewpoints.

KEYWORDS
Air tightness, Contaminant sources, Full-scale experiments, Measuring techniques, Residential buildings

INTRODUCTION

In the housing construction in Japanese urban area in recent years, much improvement has been made on air tightness performance to ensure comfortableness even in the regions of warm climate. Under such circumstances, natural ventilation rate decreased, and there arose problems such as vapor condensation, growth of mildew, etc. Impairment of health of the residents caused by contaminants such as formaldehyde generated from building materials has become a serious issue. For this reason, the facilities exclusively provided for permanent ventilation have been introduced in many houses. At present, however, no reliable method has been established yet to quickly diagnose at site the problems of ventilation or effect of the measures for ventilation, and this hinders complete solution of the problems.

The problem of ventilation in housing is characterized in that the site and quantity of generated contaminants extremely differ according to the types of contaminants. Yoshino et al. evaluated ventilation performance of housing using age of air, while this is an evaluation under the assumption that a constant quantity of contaminants is generated per unit volume in the whole housing, and this evaluation may be inadequate depending upon the types of contaminants.

With the above situations as background, we propose in the present study a method to estimate steady state concentration distribution corresponding to an arbitrary generated contaminant quantity primarily using experimental data of tracer gas decay and also refers to a method to calculate inter-room ventilation rate. The proposed method was verified by laboratory experiments and we applied the method to each of a single house and a collective house.

TRACER GAS DECAY EXPERIMENTS FOR EVALUATION OF VENTILATION CHARACTERISTICS

Fundamental Assumptions and Integral Equations

In the present method to evaluate ventilation characteristics, we assumed the following conditions:

1) The air in each room is in the state of perfect mixing.
2) Ventilation is generally in steady state.
3) Adsorption and desorption effect of gas in each room is neglected.

With regard to 1) above, it is necessary to stir up the air in each room in a building using fans to ensure approximation to the prescribed conditions. This is different from actual living conditions. Because the purpose of the proposed method is to identify the influence of air supply and exhaust quantity in each room and inter-room ventilation rate, the effect of ventilation efficiency in each room is neglected. Based on the above assumption, the concentration in each room can be expressed by the equation (1) using the symbols shown in Fig. 1. When the equation (1), omitting the contaminant generation, is integrated for the arbitrary time section t_1 - t_2 as shown in Fig. 2, the transport equation (2) of the concentration integral value is obtained. If the equation (2) is applied to the total elapsed time of tracer step-down experiment, transport equation of age of air as given in the equations (3) is obtained

, where c_k^o and τ_k^{down} denote initial concentration and step-down age of air of room k respectively.

By dividing the results of one experiment, apart from independency of each equation, many equations can be obtained. If the equation (2) is compared with the transport equation of steady state concentration given in the equation (4)

,where c_k^∞ denotes steady state concentration of room k, the steady state concentration corresponds to the concentration integral value, and the generated contaminant quantity corresponds to the product of concentration change and room volume. From the similarity of the equations (3) and (4), it becomes evident that the product of age of air obtained by the step-down experiment and initial concentration corresponds to the steady state concentration.

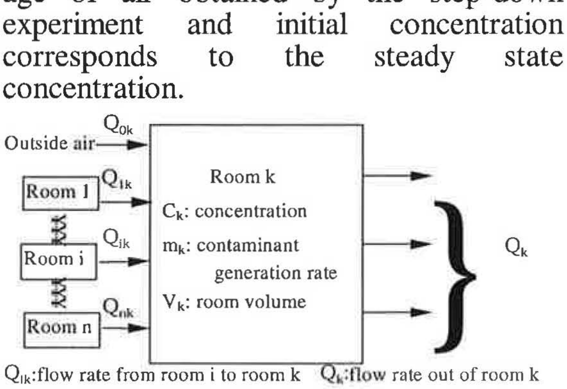


Figure 1 Airflow network around room k and list of symbols

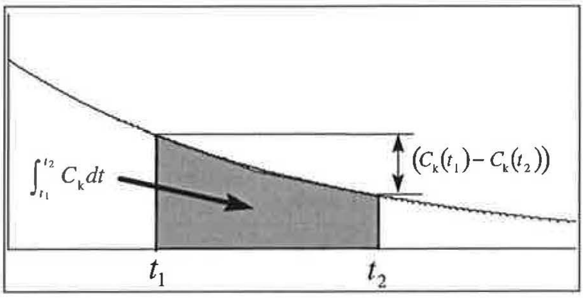


Figure 2 Integration of equation (1)

$$V_k \frac{dc_k}{dt} = \sum_{i=0}^{n} c_i Q_{ik} - c_k Q_k + m_k \quad ...(1)$$

$$\left[\int_{t_1}^{t_2} c_k dt\right] Q_k = \sum_{i=0}^{n}\left[\int_{t_1}^{t_2} c_i dt\right] Q_{ik} + \left[V_k\left(c_k(t_1) - c_k(t_2)\right)\right] \quad ...(2)$$

$$\left[c_k^0 \tau_k^{down}\right] Q_k = \sum_{i=0}^{n}\left[c_i^0 \tau_i^{down}\right] Q_{ik} + \left[c_k^0 V_k\right] \quad ...(3)$$

$$c_k^\infty Q_k = \sum_{i=0}^{n} c_i^\infty Q_{ik} + m_k \quad ...(4)$$

$$Q = \begin{pmatrix} Q_1 & & -Q_{n1} \\ -Q_{1k} & Q_k & -Q_{nk} \\ -Q_{1n} & & Q_n \end{pmatrix} \quad ...(5)$$

$$Q \quad * \quad \vec{C} \quad = \quad \vec{M} \quad .... \quad ...(6)$$

Where $\vec{C} = {}^t\left[\int_{t_1}^{t_2} c_1 dt, \int_{t_2}^{t_3} c_2 dt, \quad , \int_{t_n}^{t_{n+1}} c_n dt\right]$

... $\vec{M} = {}^t(s_1, s_2, \quad , s_n)$

... $s_i = V_i\left(c_i(t_1) - c_i(t_2)\right)$

$$Q \sum_i w_i \vec{C}_i = \sum_i w_i \vec{M}_i \quad ....(7)$$

$$CM^{-1}\vec{m} = \vec{c}^{\,\infty} \quad ....(8)$$

Where

$$M = (\vec{M}_1, \vec{M}_2, \quad , \vec{M}_n), C = (\vec{C}_1, \vec{C}_2, \quad , \vec{C}_n)$$

$$Q = MC^{-1} = \left(CM^{-1}\right)^{-1} \quad ....(9)$$

Estimation of Steady State Concentration

Evaluation is now made on the method to estimate the steady state concentration corresponding to an arbitrary generated contaminant quantity from the experiment of tracer gas decay.

If background concentration is neglected and ventilation rate flowing into a room k is taken as non-diagonal element and ventilation rate flowing out of the room k is taken as diagonal element, ventilation rate matrix n x n is obtained, as showing equation (5), where n represents the number of rooms. When concentration integral value of the equation (2) and the product of concentration difference and room volume are shown in vector form respectively, the product of ventilation rate matrix and concentration vector is turned to generation quantity vector as shown in the equation (6). Because the ventilation rate matrix is invariable, the equation (7) is established for arbitrary weighting factors of w_i. Therefore, in case a certain generation quantity distribution is given as linear combination of the generation quantity vector already known, the concentration distribution is expressed by linear combination of the corresponding concentration vectors.

That is, concentration matrix and generation quantity matrix is formed from the concentration vector and the generation quantity vector. Once the product of concentration matrix and inverse matrix of the generation quantity matrix is obtained, steady state concentration distribution denoting $\vec{c}^{\infty}$, is readily calculated for arbitrary contaminant generation distribution, denoting $\vec{m}$, as shown in equation (8). In case the number of data sets is less than n, the solution of least squares method should be used. In case it is more than n, minimum norm solution of least squares should be used.

As additional application of this method, there are improvement of accuracy or reduction of experiment duration of the age of air experiment based on the tracer step-down method. In the step-down experiment, initial concentration and final concentration are known. Thus, generation quantity vector of the equation (2) is known. By time division of the experimental data, concentration vector and generation quantity vector are prepared, and integral concentration corresponding to the area under curve can be estimated by the same procedure as described above.

The accuracy of the estimated concentration depends upon accuracy of inverse matrix of the generation quantity matrix. In order to improve accuracy, it is desirable that generation quantity vectors are set to be orthogonal to each other. For this purpose, sequential pulse injection method to inject tracer gas sequentially to each room was adopted.

Evaluation of Inter-Room Ventilation Rate

Inter-room ventilation rate can be calculated in principle as the product of the generation quantity matrix and inverse matrix of concentration matrix as shown in the equation (9). However, it is more difficult to control the concentration matrix compared with the generation quantity matrix, and it is not very practical to calculate the ventilation rate by this method. In this connection, we decided to evaluate the ventilation rate according to least squares method by specifying the ventilation rate already known and, if available, using experimental results based on constant concentration method. A method to evaluate ventilation rate using the data from the sequential pulse injection method has been proposed by Okuyama. In the present study, the step-down experiment or the sequential pulse injection method were employed as tracer gas experiment, and basic data are obtained by time integration of the experimental results.

VALIDATION OF PROPOSED EVALUATION METHOD OF VENTILATION CHARACTERISTICS

Full-Scale Model Experiments

The experiments were performed using the full-scale house model developed by Building Research Institute of the Japanese Ministry of Construction. Fig. 3 shows a plan view of the house models. Because the house models are installed in an environmental test room, outdoor conditions are considered to be constant, and air tightness performance can be controlled by operating cylinders mounted between rooms or on outer walls. From the relationship between cylinder air volume and internal/external pressure difference, air volume can be directly evaluated from the measurement of pressure difference. Experiments were carried out under the conditions shown in Table 1.

Comparison of Measured and Estimated Steady State Concentration

In experiment cases 1 - 3, the measured steady state concentration based on continuous generation of tracer gas was compared with the steady state concentration estimated by the sequential pulse injection method. The time interval of tracer injection was set to 30 minutes. Observed concentration between interval of tracer injection was defined as the one-time data, and generation quantity vector was prepared from the variation of concentration, and concentration vector was prepared from the area under curve of concentration in each room. By collecting as many data sets as the number of rooms, the steady state concentration was calculated. Fig. 4 shows comparison of the calculated results with the steady state concentration and temporal variations of concentration. Experimental values of steady state concentration agreed well with the calculated values. Under the present conditions, the time required until the concentration in each room reaches steady state was about 6 hours as shown in Fig. 5, while it was about 3 hours in the experiments based on the sequential pulse injection method. If two or more tracer gases are used, it may be possible to reduce the duration of experiment further. It should be noted that, in case the data during tracer gas injection are not used as in the present experiments, there is no need to accurately control tracer gas injection quantity.

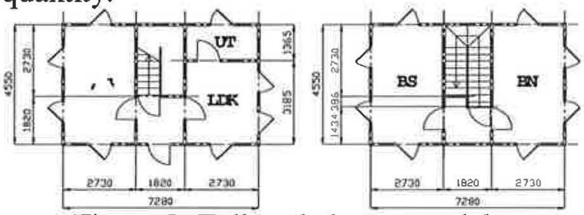


Figure 3 Full-scale house model

Table 1 Experimental cases

Case	Ventilation System	ƒ δ'	Inter-room Effective Leakage Area	Temperature Difference Between Inside and Outside Air
Case1	Central Exhaust System	3 (cm²/m²)	136 (cm²)	20 (•)
Case2	Central Exhaust System	1	136	20
Case3	Ducted Air Supply With Central Exhaust System	3	136	20
Case4	Central Exhaust System	1	136	0
Case5	Central Exhaust System	2	17	0
Case6	Central Exhaust System	3	136	30

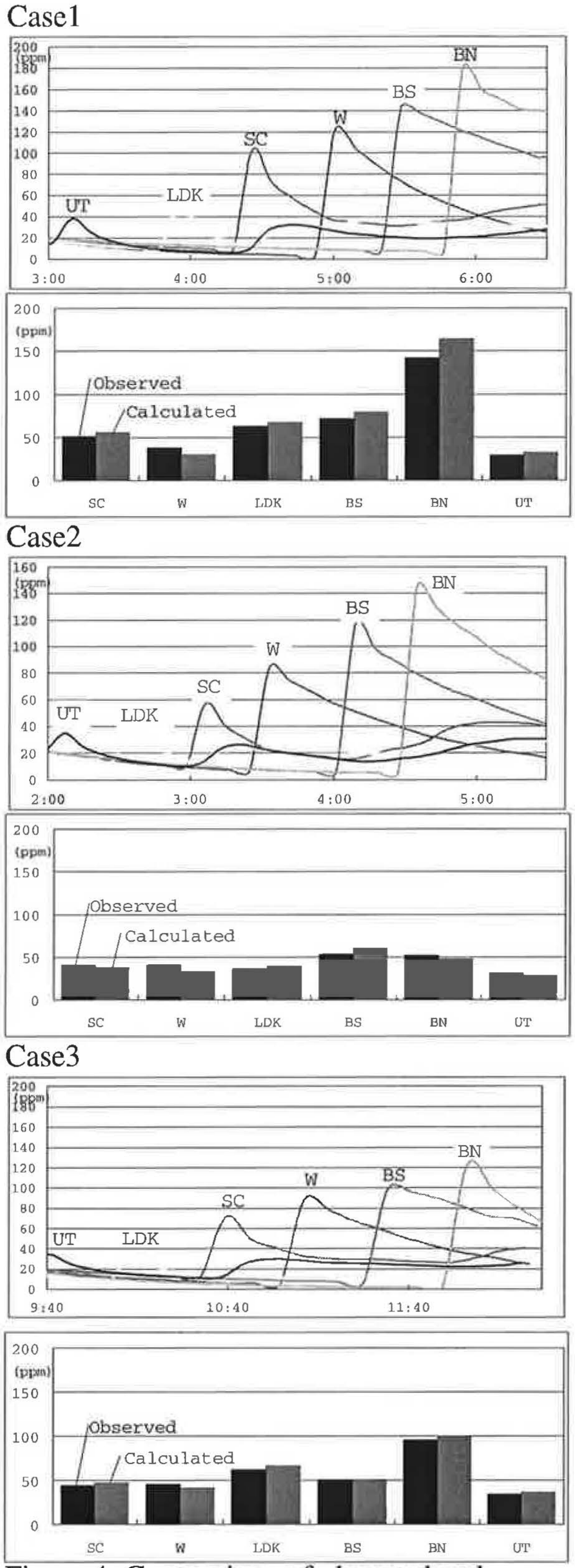


Figure 4 Comparison of observed and calculated concentration and temporal variations of concentration

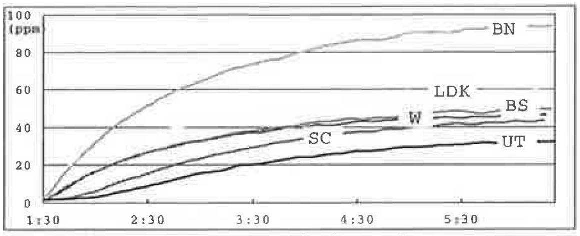


Figure 5 Temporal variation of concentration for continuous generation of tracer gases

Refinement of Measured Room Ages of Air

Unacceptably long time may be required for accurate measurement of the age of air applied on a building, which has smaller air change rate. In some cases, we have to give up experiment before completion, or outdoor conditions may change during the experiment. To cope with such situations, we tried to apply the method described above. Fig. 6 represents the course of the tracer step-down experiment performed on the house model. By time-division of the data of the time range shown in the figure, it was attempted to estimate the age of air. The estimated result and the measured result of the age of air are compared in Fig. 7. From this figure, it is evident that the age of air can be estimated with high accuracy if the time range of the data is as long as the longest age of air among rooms.

Comparison of Measured and Evaluated Inter-Room Ventilation Rates

Continuity condition and observed mechanical ventilation rate were added to the data obtained by the sequential pulse injection method, and the ventilation rate was estimated by least squares method. Fig. 8 shows comparison of the measured results of ventilation rate based on the estimated ventilation rate and pressure difference. The ventilation rate as underlined is given as a condition. From this figure, it is obvious that the ventilation rate estimated from the results of tracer gas experiment generally agrees well with the measured ventilation rate.

FIELD SURVEY OF VENTILATION CHARACTERISTICS OF AIR TIGHT HOUSES

Outline of the Ventilation Equipment and Air tightness

On site evaluation of ventilation

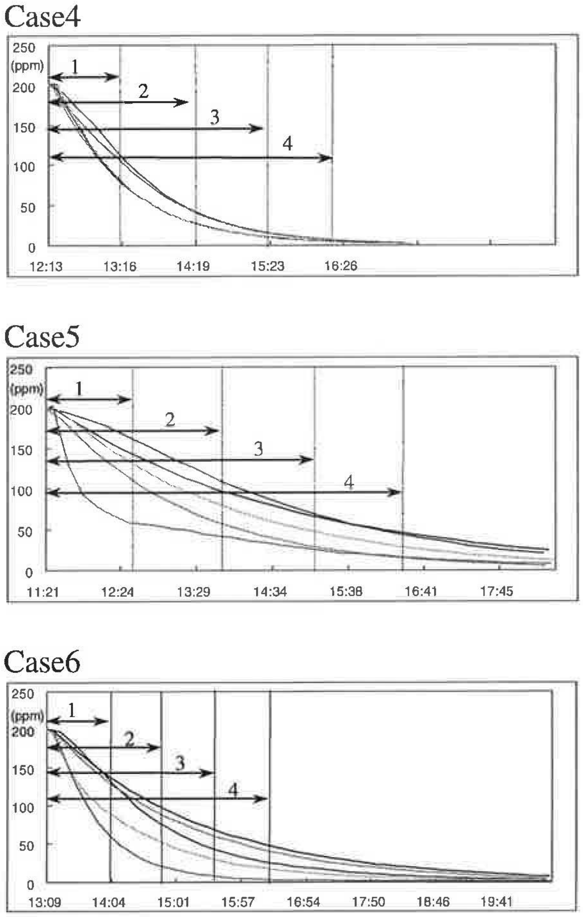
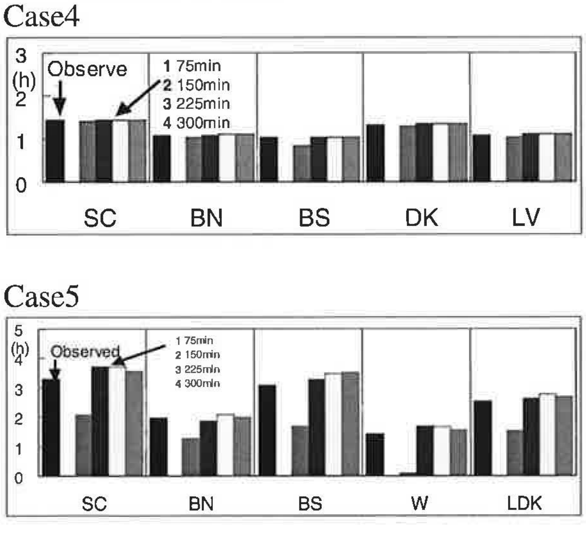


Figure 6 Observed concentration of step-down experiment and time-division of data



Case6

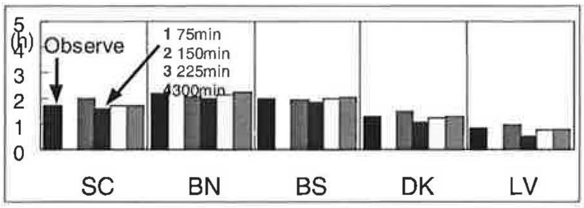
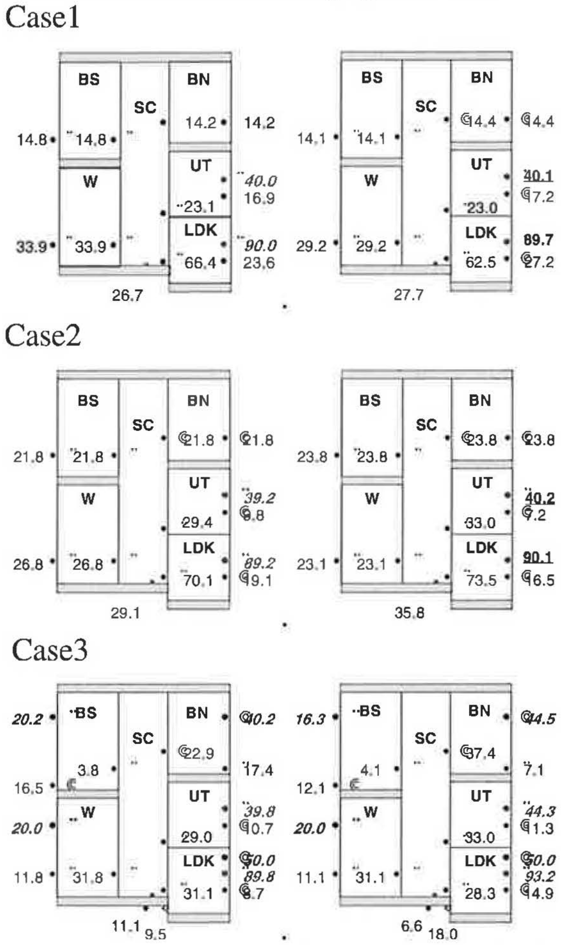


Figure 7 Comparison of observed and estimated room ages of air

characteristics was carried out on a house D and a collective house O as shown in Fig. 9. The house D is an experimental two-storied house model in outdoor environment. As shown in Fig. 13, total heat exchange ventilation fan is installed in the attic, and ventilation is performed at a rate of 0.5 time per hour for the occupied space. The introduced external air is delivered to under-floor space through duct, and air circulation for the whole building is performed using a space between outer and inner walls. Ventilation of each living room is carried out through ventilation hole on inner wall. The house O is a model room positioned on 31st floor of a 33-storied super-high-rise apartment. Room air is ventilated at a rate of 0.4 time per hour from bathroom, toilet and washroom, and external air is introduced through air supply inlet provided each on living room and bedrooms. The value obtained by dividing the equivalent opening area of the houses D and O by floor area was 1.0 and 0.5 cm^2/m^2 respectively, and the rate of natural ventilation of the house O when ventilation equipment was stopped was less than 0.05 time per hour.

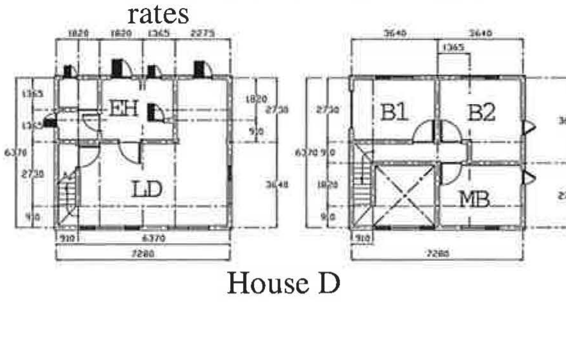
Ventilation Characteristics of House D

Constant concentration was maintained for the whole building including the attic and under-floor space. Then, the supply of tracer gas was stopped, and the step-down experiment was performed. Fig. 10 shows the changes over time of concentration in each room. The age of air was estimated using the data of time range shown by arrow, and the estimated results were compared with the age of air measured for duration of more than half a day as shown in Fig. 11. As it is evident from the figure, the age of air can be estimated with high accuracy if the data of about 2 hours and half after the starting of experiment are used. In the house D, the non-living quarters in the attic and the under-floor space occupy a non-negligible volume in the ventilation route. The age of air is calculated by neglecting generation of contaminants in these regions and this corresponds to the step-down experiment when initial concentration was set to zero only in these regions. The result was compared with the result of the present experiment for the age of air as shown in Fig. 12. Even when the generation of contaminants in non-living spaces was

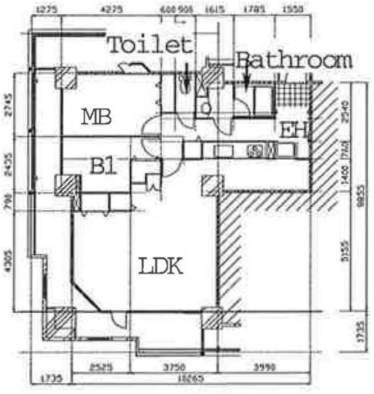


(L:Observed,R:Calculated,Dimensions in CMH)

Figure 8 Comparison of measured and evaluated inter-room airflow rates



House D



House O

Figure 9 Air tight houses to be tested

neglected, the age of air in each occupied room was calculated as 3 hours or more. After airflow inside the heat exchanger was estimated separately by tracer gas experiment, inter-room ventilation rate was estimated using the data of the step-down experiment, the data of constant concentration method, and continuity condition of each room. The results are shown in Fig. 13. Airflow route in the house was almost as expected. External air is short-circuited to the return air inside the heat exchanger ventilation fan, and this was estimated as the reason why the age of air was longer than expected.

Ventilation Characteristics of House O

Fig. 14 summarizes the result of the experiment, in which the sequential pulse injection method was applied to the house O. Using these concentration data, ventilation characteristics were evaluated from multilateral viewpoints. Fig. 15 shows the results of the estimation of the age of air in each room. The age of air is relatively long in LDK, while it was less than 2 hours in each of the other bedrooms, and it was nearly 2 hours in bathroom, toilet and entrance hall. Fig. 16 shows steady state CO_2 concentration distribution when it is assumed that the background concentration is 400 ppm and that gas is generated by occupants in rooms during sleep. It slightly exceeded 1000 ppm in the main bedroom, but the concentration was at relatively low level in the other bedrooms. In order to evaluate diffusion of water vapor generated from bathroom, the concentration of each room was standardized for the bathroom concentration when contaminants were generated only from the bathroom. The results are given in Fig. 17. The concentration in the rooms other than bathroom was sufficiently low, and it was evident that the air of the bathroom did not leak almost at all to the other rooms due to the effect of the ventilation equipment. Fig. 18 shows concentration in each room when it is assumed that contaminants are generated from wall cloth and floor material in each room and that contaminants are generated in proportion to indoor surface area except the bathroom. From this figure, it is apparent that concentration is kept at uniform level for the whole building under such contaminant generating conditions.

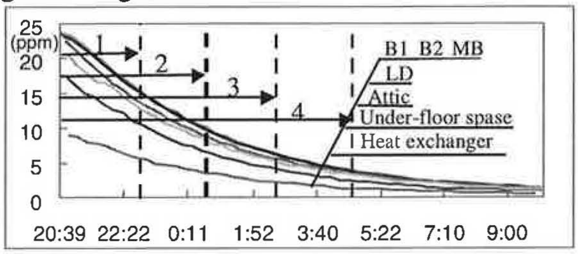


Figure 10 Temporal variation of concentration of step-down experiment for house D

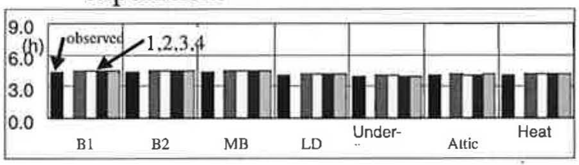


Figure 11 Comparison of observed and estimated room ages of air

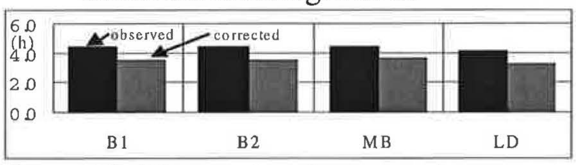
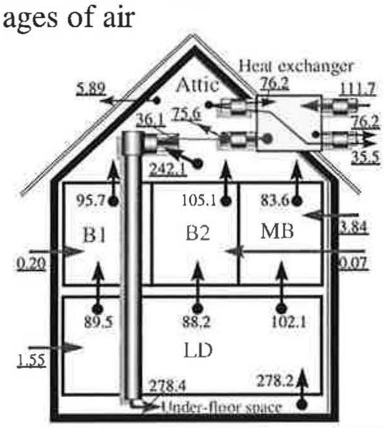


Figure 12 Observed and corrected room ages of air



(Dimensions in CMH)

Figure 13 Evaluated airflow network of house D

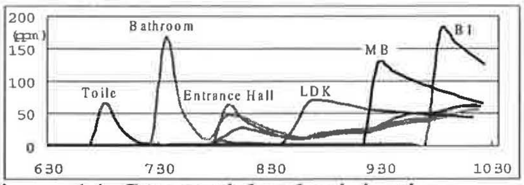


Figure 14 Sequential pulse injection experiment for house O

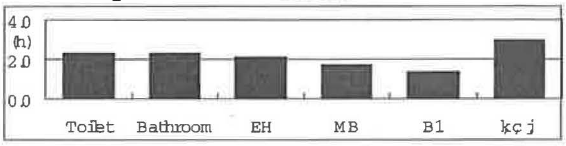


Figure 15 Estimated room ages of air

Finally, the evaluation result of ventilation rate is shown in Fig. 19. Air supply quantity to LDK is considerably low for room volume, but it is evident that ventilation route is as expected followed by supplying the air from the living rooms and bedrooms and discharging through bathroom and toilet.

	Toilet	Bathroom	EH	MB	B1	LDk
Emission rate (m^3/,)	0.0	0.0	0.0	347.7	91.5	0.0

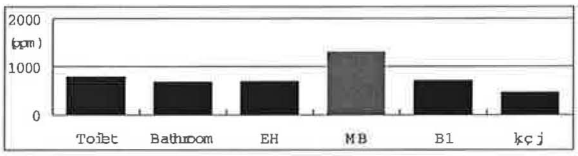


Figure 16 Estimated CO_2 concentration

	Toilet	Bathroom	EH	MB	B1	LDk
Emission rate	0.0	1.0	0.0	0.0	0.0	0.0

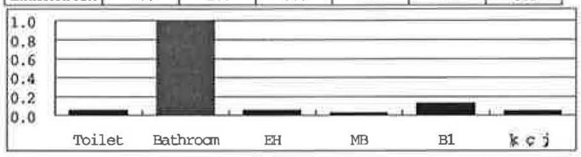
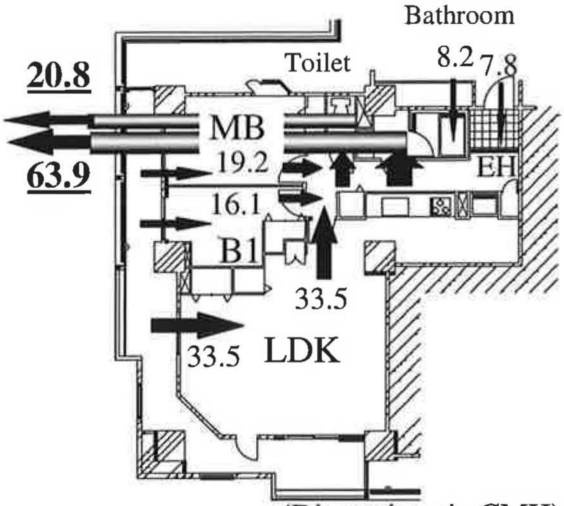


Figure 17 Estimated relative concentration of water vapor

	Toilet	Bathroom	EH	MB	B1	LDk
Emission rate	15.8	0.0	55.8	60.9	49.7	161.6

Figure 18 Estimated concentration of Contaminat proportionally generated with surface area



(Dimensions in CMH)

Figure 19 Evaluated airflow network of house O

CONCLUSION

The results of the present study may be summarized as follows:

1)By processing the concentration data obtained using sequential pulse injection method, concentration distribution in each room corresponding to an arbitrary contaminant generation distribution can be estimated with high accuracy.

2)By applying the same procedure on the results of tracer step-down experiment, it is possible to estimate the age of air from short-time data.

3)By adding continuity condition of ventilation rate in each room or supplementary equations to the concentration decay data, inter-room ventilation rate can be estimated.

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