Investigation of indoor air quality and ventilation rate for sick houses in Japan

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ABSTRACT
This paper describes the results of indoor air quality and ventilation rate during winter in 12 Japanese houses that are suspected to be sick houses, judging from the occupants' health condition. Three methods of measuring the ventilation rate, i.e. the PFT method, the constant concentration method and the measurement of airflow at inlet/outlet, are compared. Each of the methods has its own characteristics and differences in the results obtained are shown. For indoor air quality, formaldehyde and VOC concentration in the air and the spaces in the inside wall are measured. Formaldehyde concentrations found in all the houses are below the guideline values. On the other hand, VOC concentration is observed beyond the guideline values in three-quarters of the investigated houses. Sources of pollutants are estimated by comparing concentrations at three places, i.e. indoor air, the spaces in the inside wall and the surface of surrounding walls. The relationship between indoor air quality and ventilation rate is highlighted.

INDEX TERMS
SBS; Formaldehyde; TVOC; Ventilation rate; Field measurement

INTRODUCTION
Recently, newly constructed detached houses in Japan, especially in the northern portion of Japan, have become more and more airtight and highly insulated due to the necessity of conserving energy and the demand for thermal comfort. However, there is the possibility that ventilation rates in such houses have become lower compared with traditional Japanese houses. In Japan, many studies regarding SBS have been carried out (Yoshino *et al.*, 2001, etc.), and recently the guideline for indoor VOC concentrations has been designated. On the other hand, it is still difficult to confirm the actual conditions and the causes for SBS, and also it has not been entirely made clear how these affect the Japanese type of houses. In order to take measures to prevent indoor chemical pollutants, it is important to investigate not only indoor air pollutants but also the air-tightness of buildings, ventilation methods and ventilation rate. However, previous studies of indoor air quality with measurements of ventilation rates are very few.

The purposes of this study is to investigate the actual condition of indoor air quality and the performance of the ventilation equipment in residential houses, and make clear the relationships between indoor air quality, sources of pollutants, air-tightness of buildings, ventilation methods and ventilation rate.

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METHODS

Investigated Houses

Twelve detached houses in Miyagi prefecture of Japan were investigated. These houses are similar to those used in the previous investigation (Yoshino *et al.*, 2001) and meet the selection requirements (Table 1). The occupants in these houses are suspected to be afflicted with the sick building syndrome, judging from their health condition. Outlines of the 12 investigated houses are shown in Table 2.

Table 1 Requirements of investigated houses

1	Built in 5 years
2	Equipped the mechanical ventilation
3	Highly air tightness
4	Comparatively small
5	Get the plan of the house

Table 2 Outline of the 12 investigated houses

ID	*Constriction age (months / years)*	*Floor area (m^2)*	*Air tightness (cm^2/m^2)*	*Ventilation System*
A	9 / 0	135.1	0.43	Forced exhaust
B	1 / 4	126	1.37	Forced exhaust
C	6 / 0	136.22	3.33	Forced supply and exhaust
D	1 / 2	153.44	0.93	Forced exhaust
E	1 / 2	115.94	0.76	Forced exhaust
F	6 / 0	146.99	1	Forced supply and exhaust
G	11 / 1	145.55	1.48	Forced supply and exhaust
H	10 / 2	144	0.69	Forced exhaust
I	9 / 3	127.12	0.99	Forced supply and exhaust
J	10 / 3	134.02	2.68	Forced exhaust
K	3 / 0	131.65	2.79	Forced supply and exhaust
L	6 / 8	182.4	1.52	Forced supply and exhaust

Measurement Period

The period of investigation was from October 2001 to February 2002. The emission rate of indoor chemical pollutants would be higher in summer when the indoor temperature increased. However, in order to make clear the relationship between indoor air quality and ventilation rate, the measurement period was about a month in winter when the windows in buildings were closed.

Measurement of Air Tightness and Ventilation Rate

Air tightness in buildings was measured using the depressurized method. For the measurement of ventilation rate, three methods, namely the PFT method (Stymne *et al.*, 1994), the constant concentration method and the measurement of airflow at inlet/outlet, were used. In the PFT method, passive tracer gas samplers and dozers were set up in each room for a month. In the constant concentration method, tracer gas sampling and dozing tubes were put around each room for a week. The PFT method and the measurement of airflow were carried out in 11 houses, while the constant concentration method was used in six houses.

Measurement of Chemical Pollutants

Formaldehyde and VOC concentration in the air were measured in the living rooms and bedrooms of all investigated houses. In addition, concentrations in the space in the inside wall and the emission rate from the surface of the floor or wall were also measured in some of the houses. Concentration in the air was measured at a height of 1.1 m above the floor. For the measurement in the spaces in the inside wall, the sampling tube was put into the hole obtained by removing the consent box on the wall. The emission rate from the surface of the floor or wall was measured by the FLEC (Wolkoff *et al.*, 1991). The methods used for measuring the concentrations are shown in Table 3.

Table 3 Methods of measurement of formaldehyde and VOC concentrations

Items	*Location*	*Sampler*	*Sampling method*
Formaldehyde	Indoor air	DNPH cartridge (SUPELCO)	Passive (24 hours)
	Surface of the floor or wall	DNPH cartridge (Waters)	Active (0.1l/min, 1 hour)
	Space of the inside wall		Active (1.0 l/min, 0.5 hour)
VOC	Indoor air	Charcoal absorption tube (SUPELCO)	Active (0.1l/min, 24 hours)
	Surface of the floor or wall		Active (0.1l/min, 1 hour)
	Space of the inside wall		Active (1.0 l/min, 0.5 hour)

Other Parameters Investigated

Other parameters investigated in this study were indoor temperature and humidity . In addition, occupants' life style, health conditions and ventilation strategies etc. were also investigated using the questionnaire sheet, as well as by interviewing the occupants.

RESULTS AND DISCUSSION

Ventilation Rate

The ventilation rate in the whole house is shown in Figure 1. The differences between the three methods: (1) the PFT method, (2) the constant concentration method, (3) the measurement of airflow at inlet/outlet, were not very significant in Houses A, D, E and L. On the other hand, the differences between the three methods were large and varied in various levels in other houses. The average ventilation rate was about 0.45 per hour. In order to discuss the results obtained by the three methods, the following characteristics should be considered. With the PFT method there is a possibility that the measured value will be larger than that obtained by other methods. Because the measurement period was longer (one month), the influence of opening the window would be more. In addition, according to measurement principles tracer gas has to be generated equally; however, these principles were not be satisfied in actual measurements because only two or three dozing points were provided in the room. The measurement of airflow means just airflow through the inlet or outlet, so the result of the measurement would be smaller than the actual airflow in the whole building because of air leakage through the crack especially during the heating period. The constant concentration method would be most accurate in the measurement of infiltration, if the concentration of tracer gas could be measured precisely and kept constant at the set point concentration.

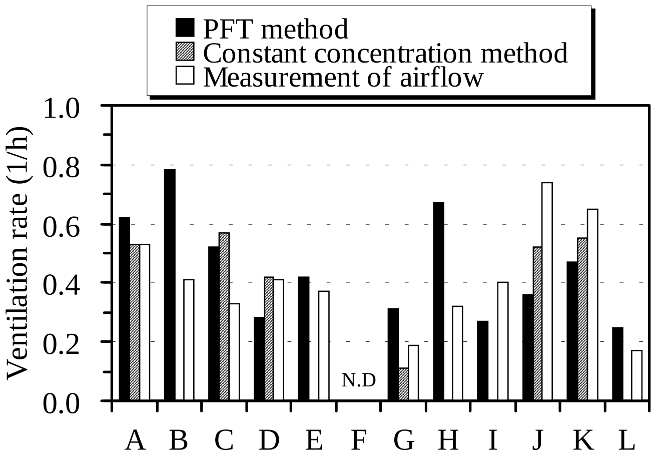

Figure 1 Ventilation rate in the whole building

The ventilation rate in each floor is shown in Figure 2. For the results of the PFT method and the measurement of airflow, the difference between the first and second floors varied in various levels, and it was large in the case of the PFT method. In the constant concentration method, the measured value for the second floor was smaller than that of the first floor in all houses. Except for House G, ventilation rate was 0.5 per hour on the first floor, but it was found to be different on the second floor.

Concentration of Formaldehyde and VOC

(a) Indoor air

The concentrations of formaldehyde in the living room and bedroom are shown in Figure 3. Although the concentration in House A was higher in comparison with other houses, it was below the guideline value of 100 μg/m^3.

The concentrations of VOC in the living room and bedroom are shown in Figure 4. The number of houses for which the concentrations of TVOC were below the guideline value of 400 μg/m^3 was eight. TVOC concentrations in the other four houses were from 600 to 1000 μg/m^3. Aliphatic hydrocarbons in House F, aromatic hydrocarbons in House K, terpenes in House I, and alcohols in Houses K and I were detected in comparably high concentrations.

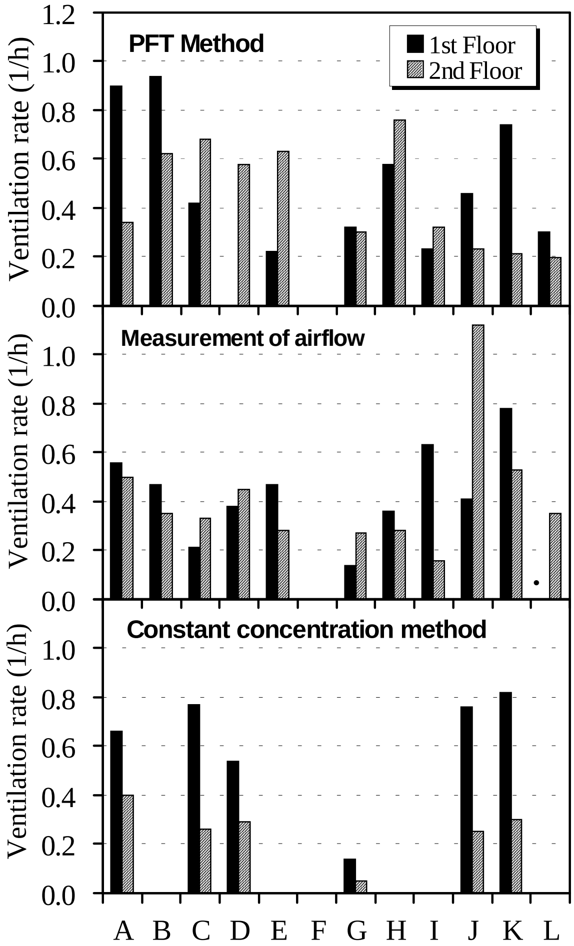

Figure 2 Ventilation rate in each floor.

(b) Spaces in the inside wall

Concentrations of indoor air and in the spaces in the inside wall are shown in Figure 5. Concentrations of some of the chemical pollutants in the spaces in the inside wall were extremely high. The reason was that the inside wall was a closed space and the volume was small in comparison to the surface area of the wall. Especially, hexane, toluene, styrene, α-pinene, ethanol and acetone were detected in high concentrations. If the concentration in the spaces in the inside wall was high, the concentration of indoor air would become relatively high. In this case, it was believed that one of the sources of pollutants was from the inside wall. On the other hand, if the concentration of indoor air was higher than that in the spaces in the inside wall, it could be suggested that there were other sources of pollutants, i.e. surface of the wall, furniture, etc.

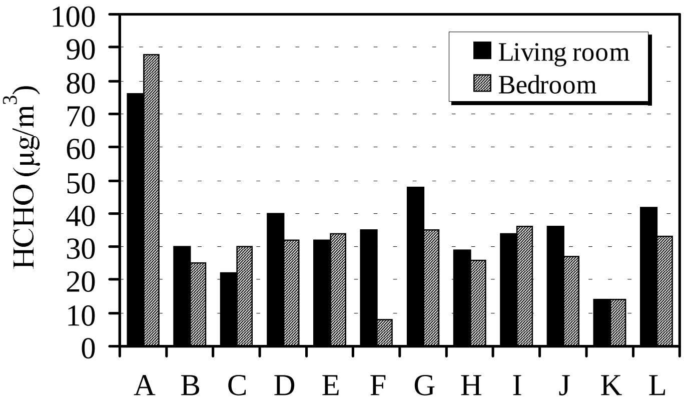

Figure 3 HCHO in the living room and bedroom.

(c) Emission rate from the floor or wall

The emission rate of chemical pollutants from the surface of the wall or floor is shown in Table 3. Hexane and styrene in House A and formaldehyde in House D were in particularly high concentrations. If chemical pollutants from the surface were generated in large quantity, these indoor air concentrations would become higher compared with other pollutants. Indoor air concentrations of *p*-dichlorobenzene and ethanol in Houses D and E were higher in comparison with the emission rate. It was believed that these were the sources of pollutants, except for the inside wall and surface of the wall.

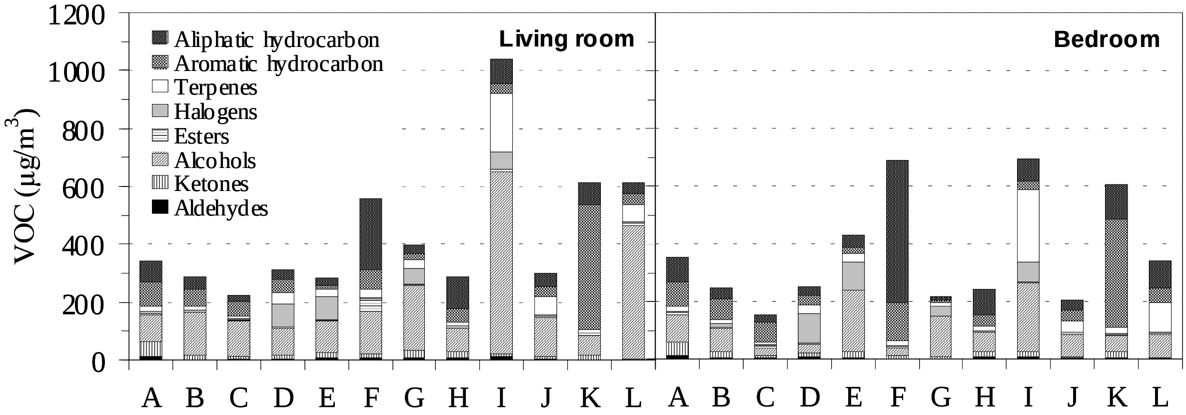

Figure 4 VOC in the living room and bedroom

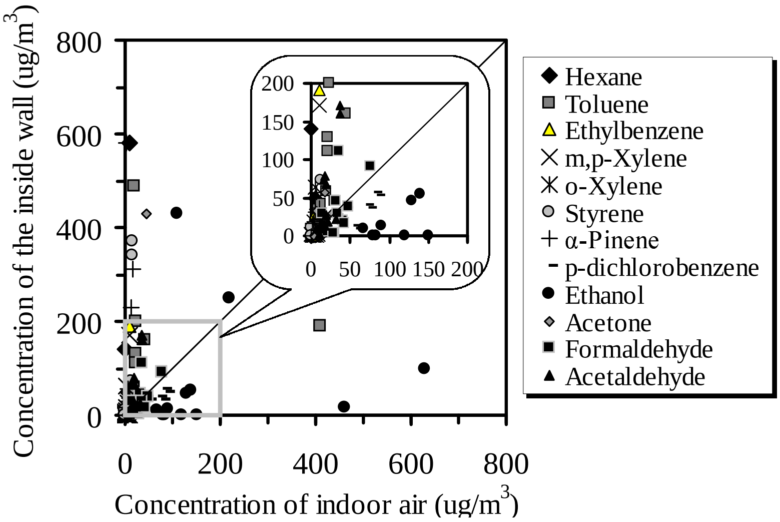

Figure 5 Concentration of indoor air and the space of inside wall

Table 3 The emission rate from the surface of the wall or floor

House	*House A*			*House D*		*House E*			*House F*		
Location	*Indoors*	*Wall*	*Floor*	*Indoors*	*Floor*	*Indoors*	*Wall*	*Floor*	*Indoors*	*Wall*	*Floor*
Unit	μg/m^3	μg/m^{2}h		μg/m^3	μg/m^{2}h	μg/m^3	μg/m^{2}h		μg/m^3	μg/m^{2}h	
Hexane	10.0	244.1	203.4	7.8	<16	5.4	27.7	<4	1.7	<4	25.2
Toluene	43.5	46.1	39.2	29.3	27.1	8.4	22.0	40.7	22.0	13.8	13.8
Ethylbenzene	7.0	9.6	9.8	2.6	<16	1.9	11.4	14.6	11.0	12.2	8.1
m,p-Xylene	7.6	8.3	<8	3.5	<16	1.6	4.9	6.5	11.0	8.9	5.7
o-Xylene	3.3	<8	<8	1.7	<16	0.7	<4	<4	4.8	4.1	<4
Styrene	11.7	130.2	170.8	2.1	<16	<0.5	<4	<4	<0.5	<4	<4
α-Pinene	4.2	22.2	<8	13.1	<16	17.0	4.1	<4	6.2	31.7	<4
p-dichlobenzene	3.8	<8	<8	82.0	28.5	70.0	45.6	30.1	5.1	22.8	16.3
Ethanol	83.9	<8	<8	91.0	22.0	110.0	12.2	<4	140.0	16.3	5.7
Acetone	45.5	21.3	10.5	9.8	<16	17.0	<4	<4	6.3	<4	<4
TVOC	341.4	614.4	538.8	313.9	209.9	284.9	206.8	302.2	556.3	334.4	222.1
Formaldehyde	76	9	16	40	98	32	23	16	35	28	28
Acetaldehyde	37	16	23	15	12	16	8	<7	37	7	11

Relationship between Indoor Air Quality and Ventilation Rate

A comparison between ventilation rate (PFT method) and concentration of chemical pollutants is shown in Figure 6. Ventilation rates in the living room and bedroom are shown as the average values for each floor. It is seen that the concentration of formaldehyde is lower and is proportional to a larger ventilation rate. In the case of TVOC, it can be seen more clearly.

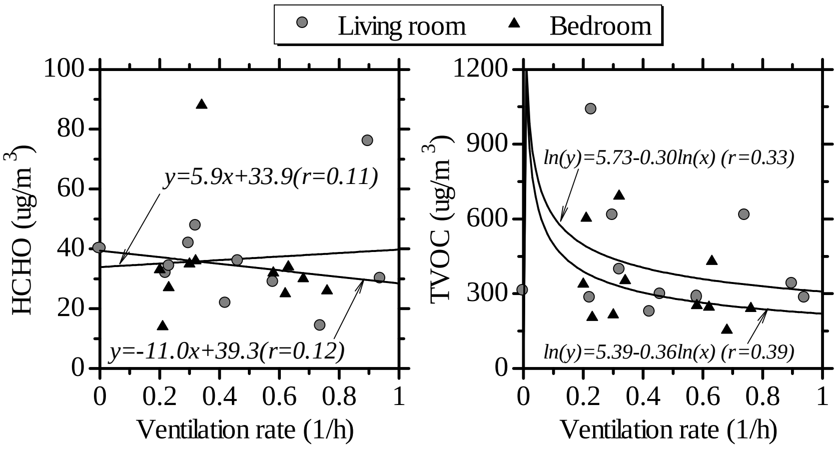

Figure 6 Comparison between ventilation rate (PFT method) and concentration of chemical pollutants.

CONCLUSION AND IMPLICATIONS

For the measurements of ventilation rates, the results obtained by the three measuring methods varied in various levels. The average value for the whole house was about 0.45 per hour, and the ventilation rate on the second floor was lower than that of the first floor in all houses. Formaldehyde concentrations found in all the houses are below the guideline values. On the other hand, VOC concentration is observed to be beyond the guideline values even for a quarter of the investigated houses. The source of each pollutant was estimated by comparison between the indoor air concentration and in the spaces in the inside wall or the emission rate from the surrounding walls. Relationship between indoor air quality and ventilation rate was observed, the concentrations of formaldehyde and TVOC were lower in correspondence with the larger ventilation rate.

ACKNOWLEDGEMENTS

This study was carried out as part of the research work in the committee established in the Building Center of Japan (led by Prof. H. Yoshino of Tohoku University), and supported by the ministry of education, culture, sports, science and technology of Japan.

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