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# MEASUREMENT OF VENTILATION EFFECTIVENESS IN AN AIRTIGHT HOUSE WITH MECHANICAL VENTILATION SYSTEM

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## ABSTRACT

In airtight houses, the outdoor air should be effectively delivered to each room through ventilation air paths in order to keep indoor air clean.

This paper reports measurement results of ventilation effectiveness in a detached wooden house with a central ventilation system. Firstly, the airtightness of this house and the airflow volumes of all ducts were measured. Secondly, after $CO_2$ gas was injected into the inlet of the air supply duct, the $CO_2$ concentrations at various points in the house were continuously measured through a whole day, and the age of air was calculated. Thirdly, the pattern of the way how the outdoor air was delivered to each room was analyzed. As a result, it was clarified the circulation of outdoor air is estimated from measurement results of ventilation effectiveness.

**KEYWORDS** Ventilation Effectiveness, Mechanical Ventilation, Field Measurement

## INTRODUCTION

In airtight houses, the outdoor air should be effectively delivered to each room through ventilation air paths in order to keep indoor air clean.

This paper reports measurement results of ventilation effectiveness in a detached wooden house with a central ventilation system. Firstly, the airtightness of this house and the airflow volumes of all ducts were measured. Secondly, after $CO_2$ gas was injected into the inlet of the air supply duct, the $CO_2$ concentrations at various points in the house were continuously measured through a whole day, and the age of air was calculated. Thirdly, the pattern of the way how the outdoor air was delivered to each room was analyzed.

## EXPERIMENT HOUSE AND VENTILATION SYSTEM

**Description of Experiment House**

The two-storied wooden house with a floor area of 153m$^2$ used for the experiment on the ventilation effectiveness is located in the city of Morioka. Figures 1 and 2 show the house plans and the ventilation system. The walls are insulated with both 100 mm thick glass wool and 50 mm thick foam-polystylene. The floors and the ceilings are insulated with 100 mm and 200 mm thick glass wool, respectively. The windows have double glazing. The heat loss coefficient per floor area was measured on January 8 to 11,1991 by the method described in the draft of the Japanese Industrial Standard entitled "Field Measuring Method for Total Heat Loss Coefficient of Room", and was evaluated to be 1.1 kcal/m$^2$h.

**Ventilation System**

Other than the ventilation system illustrated in Figure 1, there is an exhaust fan and a supply duct for the kitchen. But the exhaust fan was not operated during the measurement. As shown in Figure 2, the outdoor air taken from the attic goes through the air-to-air heat exchanger and enters the upper part of the heating unit. After that, it is mixed with the return air. The mixed air goes through heating coils and is delivered to the rooms upstairs. The room air upstairs passes through the staircase and comes down to the corridor on the first floor. The air of the corridor is taken from the air inlet installed beside the lavatory and returned to the upper and lower parts of the heating unit. The return air to the lower part of the heating unit passes through heating coils and is delivered to the rooms on the first floor.

On the other hand, there are outlets for exhausting room air in lavatories situated on the first and second floors. The air exhaust from the two lavatories is mixed in the duct, passes through the heat exchanger and then is exhausted to the outside. The air in the lavatory on the first floor passes through the narrow space between the bath unit and the walls and goes to the heat exchanger from the upper part of the bath unit. The heat exchanger made of plastic transfers latent heat and includes centrifugal fans for supplying and exhausting air. The capacity of the fan is 113m$^3$/h for a pressure difference of 100 Pa.

## AIRTIGHTNESS PERFORMANCE

The airtightness performance of the house was measured by the pressurization test method under the condition that only the inlet and outlet of the central duct system were sealed. The measurement was conducted on December 18, 1990.

The equivalent leakage area per floor area for an indoor-outdoor pressure difference of 10 Pa is 1.7 cm$^2$/m$^2$. This house is so airtight as to be equal to the Swedish Building Standard.

## MEASUREMENT OF AIRFLOW VOLUME AT VARIOUS POINTS OF CENTRAL DUCT SYSTEM

The airflow volume at various points of the central duct system was measured under the condition that internal doors were closed, the fans in the heat exchanger and heating unit were operated at high mode, and space heating was not used.

### Airflow Volume

Table 1 shows airflow volumes distributed from the diffusers and exhausted from the lavatories, which were measured by the pressure-compensation method. The totals of distributed airflow volumes on the first floor and the second floor are 199m$^3$/h and 204m$^3$/h, respectively. The total of these two volumes is 403m$^3$/h. On the other hand, the return air flow volume is 457m$^3$/h. As the return air is recirculated to the rooms after mixing with outdoor air, the return airflow volume should be less than the total of the distributed airflow. The total of the exhausted airflow volume from the lavatories is 61m$^3$/h. The total volume of the air exhausted from the room is 518m$^3$/h, which is 115m$^3$/h more than the total of the supply air.

### Measurement of Airflow Volume in Ducts Connected to Heat Exchanger and in Space around Bath Unit

**Measurement method** $CO_2$ gas was injected into a duct at a constant flow rate and the air flow volume was calculated by the $CO_2$ concentration measured at a point more than 1 meter from the injection point.

**Measurement result** Figure 4 shows the measurement results. The outdoor airflow volume which entered the heat exchanger is 71m$^3$/h. The distance from the $CO_2$ injection point to the measurement point is not long enough for the $CO_2$ concentration to be stable. However, the airflow volume in the supply duct after the heat exchanger is 155m$^3$/h. In the exhaust duct, the airflow volume which entered into the heat exchanger is 156m$^3$/h and that which left from the heat exchanger is 127m$^3$/h. The airflow volumes are not equal to each other. This fact indicates that probably supply air and exhaust air mixed in the heat exchanger, because when $CO_2$ gas was injected at 5 l/min in the exhaust duct of the upper part of the bath unit, the $CO_2$ concentration was 852 ppm in the supply duct just after the heat exchanger. This fact leads to the supposition of infiltration from the exhaust duct to the supply duct in the heat exchanger. and the air infiltration from the exchanger to the room. The airflow volume just before and after the bath unit is 27m$^3$/h and 118m$^3$/h, respectively. It is expected that the air infiltrated into the exhaust duct system around the bath unit.

## MEASUREMENT OF VENTILATION EFFECTIVENESS

### Measurement Method

$CO_2$ gas was used for the measurement of the age of the air. After the $CO_2$ concentration in the room became almost equal to that of outdoor air, $CO_2$ gas was injected into the supply duct just after the heat exchanger at a constant rate of 5 l/min. $CO_2$ concentration was measured at each measurement point until the $CO_2$ concentration reached a steady state at every measurement point (step-up method). After that, the injection of $CO_2$ gas was stopped and the $CO_2$ concentration decay was measured (step-down method).

The ten measurement points are shown in Figure 1. The room air was sucked through sampling tubes to the outside and the $CO_2$ concentration of the air was measured by two infrared analyzers. During the measurement, all internal doors were closed and the fans of the heat exchanger and heating unit were operated at high speed mode. The boiler for space heating was not operated. The period for the measurement was from the 15th to the 16th in April, 1991. The mean outdoor temperature was 17.2. The mean wind speed at a point 15.7 m high at the Morioka meteorological observatory (about 7 km far from the site) was 3.7 m/s (3.0 m/s on 15th and 4.4 m/s on 16th)

### Measurement Results of the Time History of $CO_2$ Concentration

Figure 5 shows the time history of $CO_2$ concentration at 10 measurement points. First of all, the concentration at the diffuser of bedroom 2 increases after the injection of $CO_2$ gas. Following that, the concentration in rooms of the second floor increases. After that, the concentration in rooms of the first floor increases. Lastly, an increase in the concentration in the exhaust duct just after the heat exchanger follows. In nine hours after the start of the injection, the concentration at all points reaches a steady state.

At the steady state, the average $CO_2$ concentration on the second floor is 2461 ppm. That on the first floor is 2291 ppm, and that in the exhaust duct just after the heat exchanger is 1860 ppm. The reason why the concentration of the first floor is less than that of the second floor is expected to be due to air infiltration from the outside. The reason that the concentration in the exhaust duct after the heat exchanger is less than that of the first floor is expected to be also due to air infiltration from the outside. It corresponds to the result of the airflow volume measurement. The infiltration ratio, F, is calculated by an equation from the $CO_2$ concentration at the steady state(AIVC 1988).

$$F = 1 - C_0/C_P$$

where

$C_0$ = the concentration before infiltration

$C_P$ = the concentration after infiltration

Based on the average concentration of the first and second floors, the infiltration ratio between the second floor and the first floor is estimated to be 9%. Based on the average concentration of all rooms and the concentration in the duct just after the heat exchanger, the infiltration ratio is 34%.

### Calculation of Age of Air

**Calculation method** Based on the time history of the $CO_2$ concentration as shown in Figure 5, the age of air is calculated by equation 2 and 3(AIVC 1990).

In the case of the step-up method,

$$\bar{\tau}_P=\int_0^{t_e}\{1-C_P(t)/C_P(t_e)\}dt$$

In the case of the step-down method,

$$\bar{\tau}_P=\int_{t_e}^{t_f}\{C_P(t)/C_P(t_e)\}dt$$

where

$C_P(t)$ = the $CO_2$ concentration at t point P

$t_e$ = the time when the concentration reaches the steady state

$t_f$ = the time when the concentration completely decays

**Result of measurement** The results based on the step-up method are described. The age of air at the diffuser of bedroom 2 on the second floor is the shortest, 63.3 minutes. The time elapsed from the $CO_2$ injection point to the diffuser is 3 to 4 seconds which is calculated from the length of the duct and the volumetric air flow rate. The reason why the age of air is old is that the outdoor air is supplied after mixing with the return air.

The average age of air in rooms of the second floor and the first floor are 80 and 127 minutes, respectively. The difference is about 50 minutes. It can be said that the rooms on the second floor are kept more clean than the first floor. The difference of the age of air between the air inlet and the center of bedroom 2 is 8.2 minutes. That in the living room is 19.3 minutes.

The difference in the age of air between the hall on the second floor and the exhaust air at the return grill is 25.9 minutes. The reason why the age of air in the duct just after the heat exchanger is rather shorter than that of the rooms on the first floor is that, before the outdoor air is distributed to each room on the first floor, a part of the outdoor air is exhausted to the outside.

The result from the step-down method indicates the same features of the air distributions. But the age of air calculated by the two methods are extremely different from each other as shown in Figure 5. The age of air calculated by the step-down method is 1.3 to 1.7 times that by the step-up method. The average is 1.5 times. This is because it takes a long time for the $CO_2$ gas to come out from the enclosed spaces, for example, closets.

## CONCLUSION

In order to calculate the age of air, $CO_2$ gas was injected into the supply duct just after the heat exchanger at a constant rate and the $CO_2$ concentration was measured at each measurement point. In nine hours after the start of the measurement, the concentration at all points reaches the steady state. In the case of step-up method, the age of air at each point is 63 to 144 minutes and its average is 109 minutes. In the case of step-down method, it is 102 to 209 minutes and its average is 164 minutes. The latter is about 1.5 times longer than the former.

Based on the step-up method, the average age of air in rooms of the second floor and the first floor are 80 and 127 minutes, respectively. The difference is about 50 minutes.

The age of air in the duct just after the heat exchanger is rather shorter than that of the rooms on the first floor. It is estimated that, before the outdoor air is distributed to every room on the first floor, a part of it is exhausted to the outside.

In a detached wooden house with a central ventilation system, the circulation of outdoor air is estimated from measurement results of ventilation effectiveness.

## ACKNOWLEDGMENT

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William J. Fisk et al. Commercial building ventilation measurements using multiple tracer gases. The proceedings of 9th AIVC Conference, September, 1988

**Table 1** Airflow volume at diffusers and exhausts

| | Place | Q($m^3/h$) | Place | Q($m^3/h$) |
|---|---|---|---|---|
| Diffuser | Bedroom 2<br>Bedroom 3<br>Bedroom 4<br>Closet | 99<br>52<br>35<br>18 | Bedroom 1<br>Dining Room<br>Living Room<br>----------- | 82<br>64<br>53<br>---- |
| | Total of 2nd Floor | 204 | Total of 1st Floor | 199 |
| | Total of Diffuser | | 403 | |
| Exhaust | Return grill | 457 | Exhaust at WC 1 | 26 |
| | ------------ | ---- | Exhaust at WC 2 | 35 |

**Table 2** Local mean age of air

| | Local mean age (min) | |
|---|---|---|
| | Step-up Method | Step-down Method |
| ①Diffuser at BR 2 | 63.3 | 102.1 |
| ②Center of BR 2 | 71.5 | 120.4 |
| ③Center of BR 4 | 92.4 | 144.3 |
| ④Hall beside WC 2 | 92.5 | 151.2 |
| ⑤Exhaust duct after Heat Exchanger | 135.9 | 183.9 |
| ⑥Diffuser at LR | 124.6 | 184.2 |
| ⑦Center of LR | 143.9 | 209.1 |
| ⑧Center of BR 1 | 137.4 | 200.8 |
| ⑨Bathroom | 110.8 | 180.6 |
| ⑩Return grill | 118.4 | 159.8 |

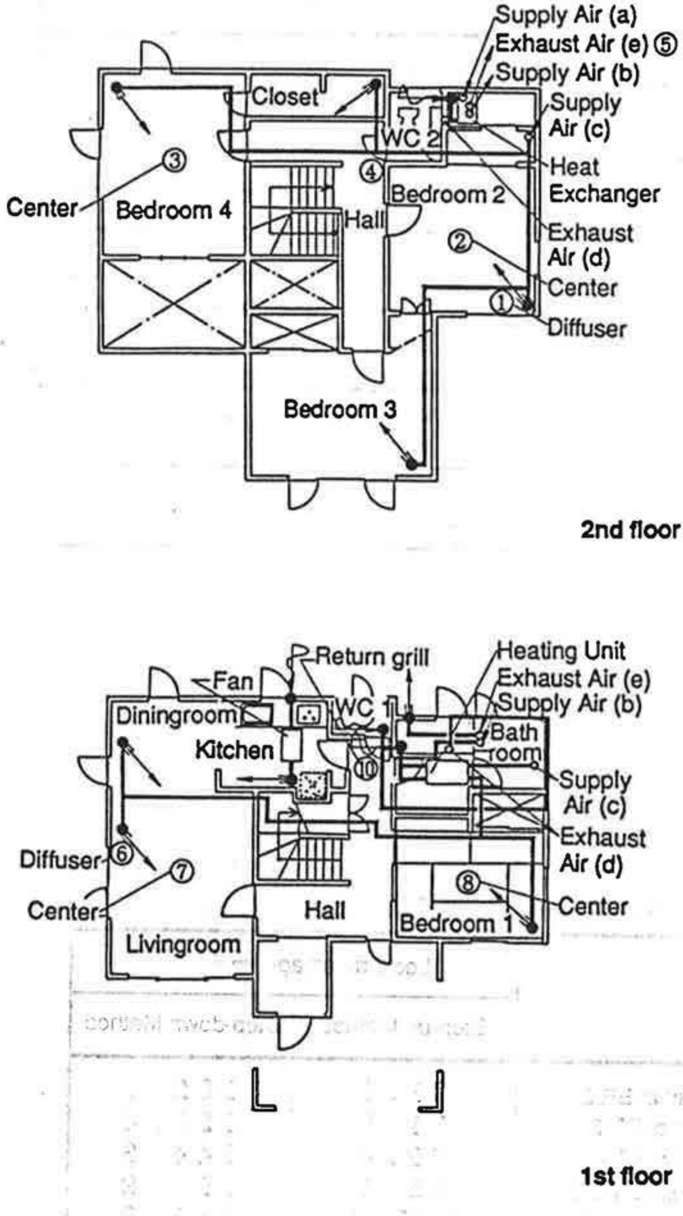


**Figure 1** House plans and ventilation system

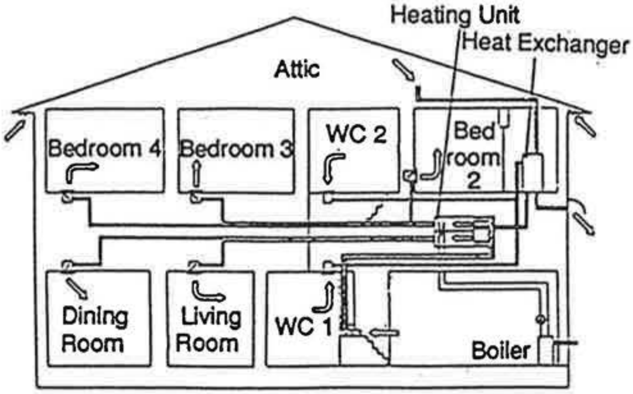


**Figure 2** Ventilation system

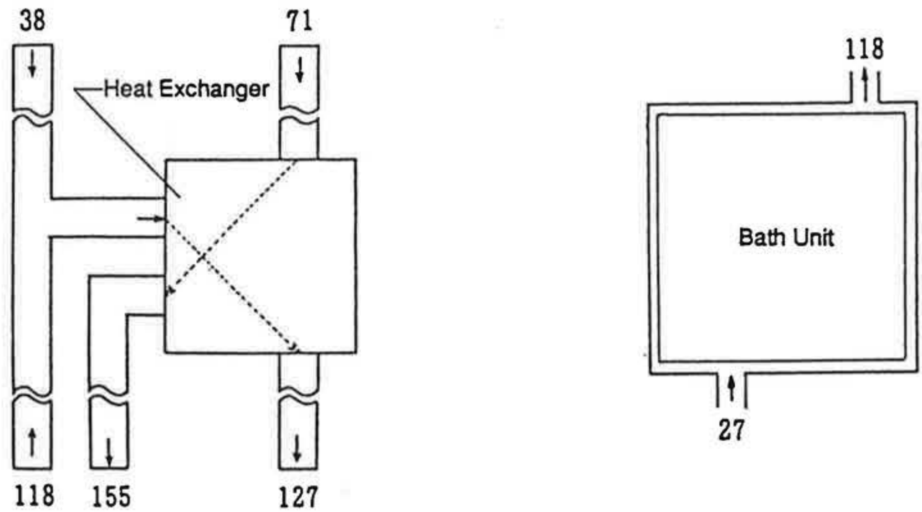


**Figure 3** Airflow volume in ducts

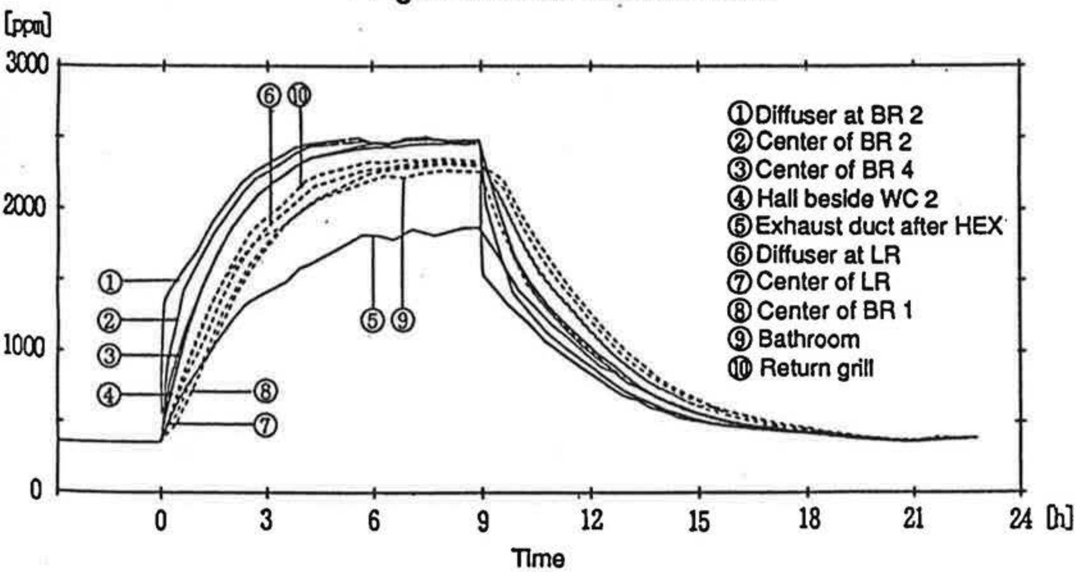


**Figure 4** Time history of $CO_2$ concentration