Outdoor airflow rates and convection airflow in a model house with the passive ventilation design

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ABSTRACT

Recently most houses in northern Japan have become highly insulated and airtight, which have caused serious problems such as indoor air pollution. Therefore, it is important to evaluate the performance of an airtight house from the viewpoint of ventilation. The aim of this paper is to clarify airflow rates in a house by measuring outdoor airflow rates and convection air with single/multiple tracer gas techniques. The model house has an underground crawl basement space with outer insulation and is designed with a passive ventilation design. Interzonal airflow rates are usually measured with a technique which uses multiple tracer gases. In this paper, a simplified method which uses a single tracer gas is proposed. Results of the experiments show that the single tracer gas technique is useful for measuring outdoor airflow rates and interzonal airflow rates in a house with multiple zones. Further more, the proposed single tracer gas technique can be a simplified method for verifying actual ventilation rates.

1. INTRODUCTION

The first commitment period of the Kyoto Protocol to reduce greenhouse gases will start in 2008. Over a long period of time, most houses in Hokkaido have become highly insulated and airtight in order to save energy. On the other hand, health problems, such as a sick building syndrome, caused by indoor air pollution have become serious, and the need for proper ventilation has increased. Under these circumstances, a passive ventilation design, which utilizes outdoor and indoor temperature differences and wind speed as power for ventilation, was proposed and introduced to houses in Hokkaido[8] and is expected to be more widely used in the future. Generally a house consists of multiple spaces. Since the movement of air is not in one single direction and airflows mix with each other, it is very difficult to estimate correct interzonal airflow rates. The method that is usually used for measuring interzonal airflow rates in a house with multiple rooms is a multiple tracer gas technique.[4] When this technique is applied, a different tracer gas is released in each room and gas concentrations in each room are simultaneously measured, and very costly tracer gases and measuring instrument are needed.

A single tracer gas technique[3] is a simplified method that has been proposed for measuring interzonal airflow rates. The aim of this paper is to clarify airflow rates in a house designed with the passive ventilation system and compare the two methods for calculating interzonal airflow rates during a period when outdoor and indoor temperature differences are large.

Photo. 1: The subject house

Photo. 2: Supply tubes

Table 1: Spec. of the subject house

Heating system	Under floor air supply
Site area	269.56 [m^2]
Gross floor area	97.61 [m^2]
Total air volume in house	307.8 [m^3]
Air volume in underground crawl basement space	45.36 [m^3]
Air volume in the first floor	181.44 [m^3]
Air volume in loft	81 [m^3]
Airtightness performance of per floor area (Japanese regulation)	0.7 [cm^2/m^2]

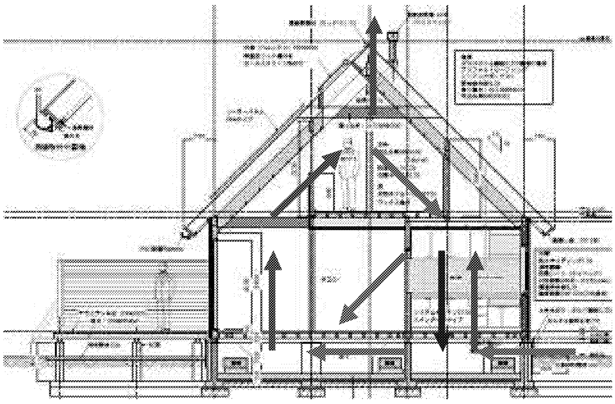
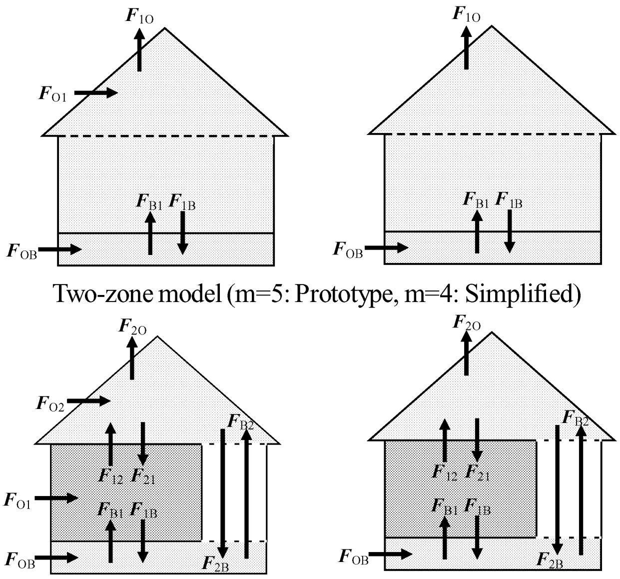


Figure 1: Cross section and airflow paths



Two-zone model (m=5: Prototype, m=4: Simplified)

Three-zone model (m=10: Prototype, m=8: Simplified)

Figure 2: Model of airflow paths

2. A SUBJECT HOUSE

Photo. 1 shows the subject house, Table 1 its specification and Figure 1 its cross section. The heating system used in this house is a heat storage system which utilizes inexpensive night-time electricity. The ventilation system is as follows: Outdoor air is let into the underground crawl basement space (BF) through tubes as shown in Photo. 2. Exhaust air is let out through outlet ventilators installed on the roof as shown in Figure 1. In the experiments, we paid attention to convection air, especially upstream and downstream air, and used a multi-zone model instead of a multi-room model. In this house the airtightness performance, value C, was 0.7 [cm^2/m^2], which exceeded the standard required by a Japanese regulation.

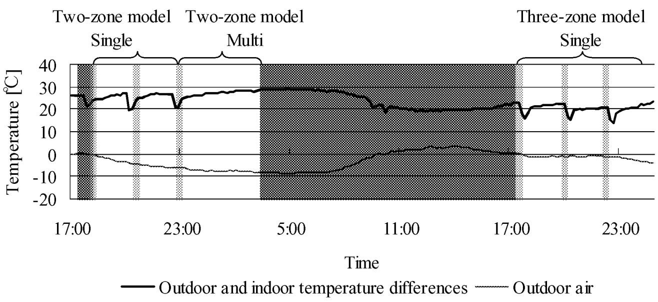


Figure 3: Change in outdoor air temp. & outdoor and indoor temp. differences (10^{th}-11^{th}, Dec.)

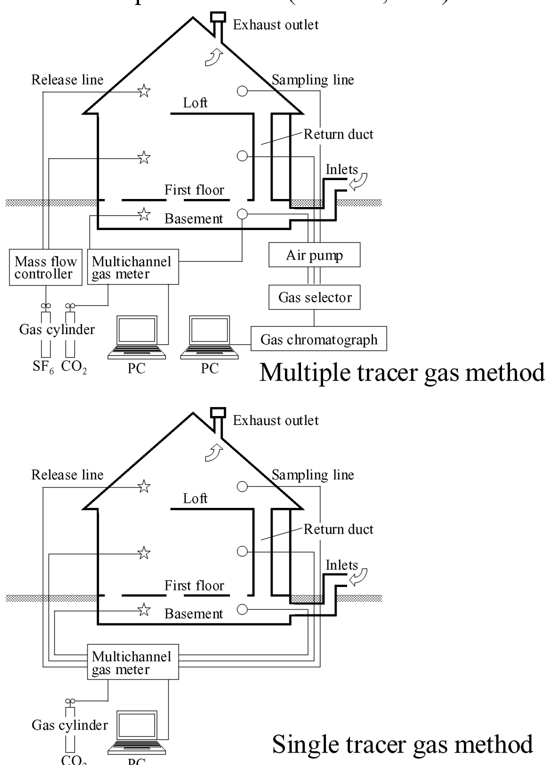


Figure 4: Measurement systems for two-zone model

3. OUTLINE OF MEASUREMENTS

Figure 2 shows ventilation models postulated for this subject house. In this paper, a two-zone model and a three-zone model are discussed. Outdoor and indoor temperature differences were 20 to 25 degrees during the measurements. In Figure 3 airflow rates were calculated during the time shown in white and not in the dark gray zone periods, and light gray zones show the time when windows were open to lower gas concentrations to the normal level.

Other conditions for measurements were as follows: 1) Gas was supplied at a constant rate by using mass-flow-controllers. 2) To obtain average gas concentrations in each space, manifold sampling method was adopted. In addition, small diffusing fans which would not interfere with thermal stratification were installed . 3) During the measurements, all windows and the entrance door were closed, and all indoor doors were open. The length of vinyl tubes used for releasing and sampling tracer gases were the same each time as shown in Figure 4.

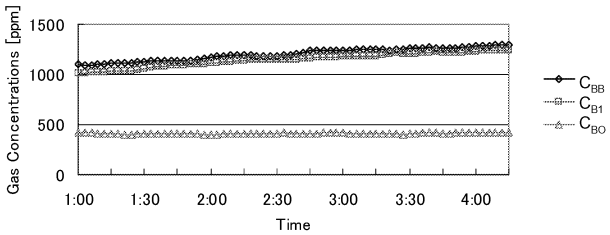


Figure 5: CO_2 gas concentrations of two-zone model

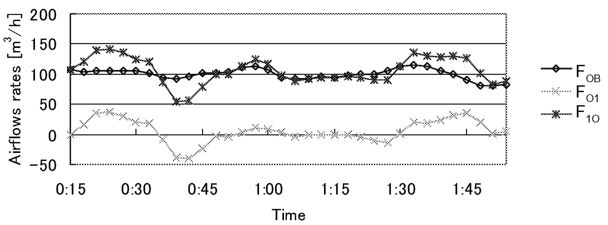


Figure 7: Outdoor airflow rates, air-leakage rates and exhausted airflow rates (Multi, Proto)

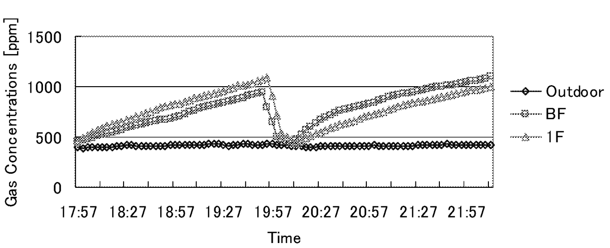


Figure 9: CO_2 gas concentrations of single tracer gas

4. CALCULATION OF AIRFLOW RATES IN THE TWO-ZONE MODEL BY THE MULTIPLE TRACER GAS METHOD

In the case of the multiple tracer gas method, CO_2 gas was released in the underground crawl basement space at a constant rate of 0.1 [m³/h], and on the first floor and in the loft SF_6 gas was released at 0.006 [m³/h]. Gas concentrations in each space were measured by using the gas chromatograph (P200 GC: HP) and the gas selector. Measurement time was three minutes for three channels (measurement interval: nine minutes). Figure 5 and Figure 6 show the results of the average gas concentrations two hours after the start of the measurement.

Differential method was used to calculate interzonal airflow rates. A prerequisite for this method is instant uniform diffusion of the gas in each space. Under such a hypothesis, simultaneous equations were formulated with the balance of airflow rates and the balance of matter, such as gas, to obtain the value of airflow rates. With the multiple tracer gas method, it was possible to see influences of changes in outdoor conditions. Differential equations for a prototype model is demonstrated as follows:

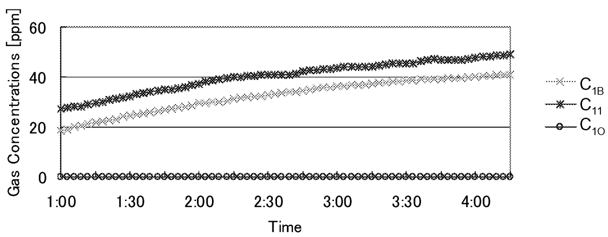


Figure 6: SF_6 gas concentrations of two-zone model

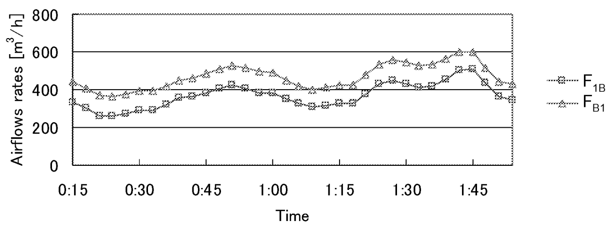


Figure 8: Convection airflow rates (Multi, Proto)

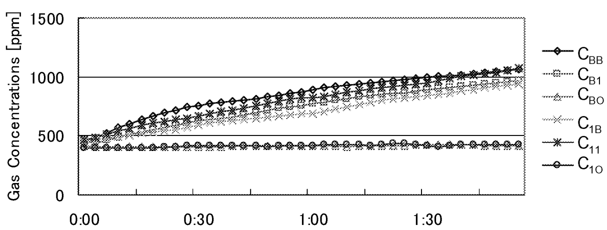


Figure 10: Superposition of CO_2 gas concentrations (Single)

Underground crawl basement space

$$F_{OB} + F_{1B} - F_{B1} = 0$$
$$F_{OB}C_{BO} + F_{1B}C_{B1} - F_{B1}C_{BB} = V_B dC_{BB}/dt - M_B$$
$$F_{OB}C_{1O} + F_{1B}C_{11} - F_{B1}C_{1B} = V_B dC_{1B}/dt$$

First floor and Loft

$$F_{O1} + F_{B1} - (F_{1O} + F_{1B}) = 0$$
$$F_{O1}C_{BO} + F_{B1}C_{BB} - (F_{1O}C_{B1} + F_{1B}C_{B1}) = V_1 dC_{B1}/dt$$
$$F_{O1}C_{1O} + F_{B1}C_{1B} - (F_{1O}C_{11} + F_{1B}C_{11}) = V_1 dC_{11}/dt - M_1$$

Legend

F_{ik}: airflow rates from the i^{th} floor to the k^{th} floor [m^3/h]
C_{ih}: gas concentration on the h^{th} floor when CO_2 was released on the i^{th} floor [m^3/m^3]
V_i: air volume on the i^{th} floor [m^3]
M_h: release rates of the tracer gas on the h^{th} floor [m^3/h]
dt: time interval for differentiation (t_2-t_1) [h]

When a simplified model was used, if the number of simultaneous equations became more than that of unknown quantity, the least square method was applied according to unknown quantities. Previous studies report that when the multiple tracer gas method was used, the margin of error was plus or minus 20%. Interzonal airflow rates calculated by this method for the two-zone model are shown in Figure 7 and Figure 8. Outdoor airflow rates (F_{OB}) was calculated to be about 80 to 130 [m^3/h], and exhaust air was calculated at about 80 to 150 [m^3/h]. These values did not fluctuate much. Upstream of convection airflow rates (F_{B1}) was calculated at about 500 to 600 [m^3/h], and the downstream (F_{1B}) was about 400 to 500 [m^3/h]. In addition, there were periods when air-leakage rates (F_{O1}) were negative values, but this can be considered as within allowable error margin of the measurements.

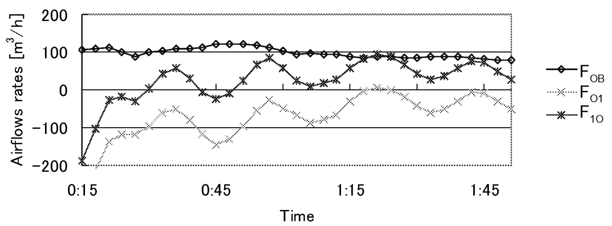


Figure 11: Outdoor airflow rates, air-leakage rates and exhausted airflow rates (Single, Proto)

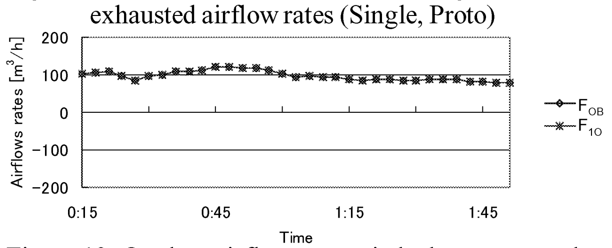


Figure 13: Outdoor airflow rates, air-leakage rates and exhausted airflow rates (Single, Simplified)

5. SUPERPOSITION USED IN THE SINGLE TRACER GAS METHOD

Even with the single tracer gas method, when indoor and outdoor environmental conditions do not change much, interzonal airflow rates can be calculated by superposing changes in gas concentration, and an analysis similar to the case of the multiple tracer gas method is possible. Procedures for the superposition in the case of a three-zone model are as follows:

STEP 1

CO_2 gas is released in the top zone for a predefined period of time. After sampling gas, the condition in each space should be restored to the beginning state. By opening windows, CO_2 gas concentration is reduced to the outdoor level. After that, windows are closed tightly and each room temperature goes back to the normal level. These conditions need to be achieved before proceeding to STEP 2.

STEP 2

CO_2 gas is released in the middle zone for a predefined period of time. After sampling gas, the condition in each space should be restored to the beginning state. By opening windows, CO_2 gas concentration is reduced to the outdoor level. After that, windows are closed tightly and room temperature goes back to the normal level again. These conditions need to be achieved before proceeding to STEP 3.

STEP 3

CO_2 gas is released in the bottom zone for a

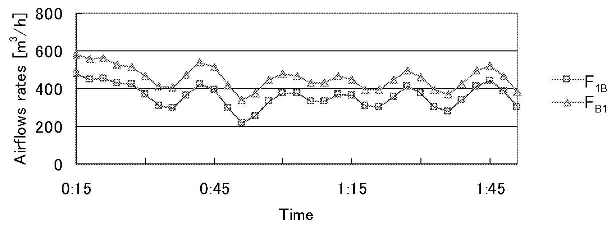


Figure 12: Convection airflow rates (Single, Proto)

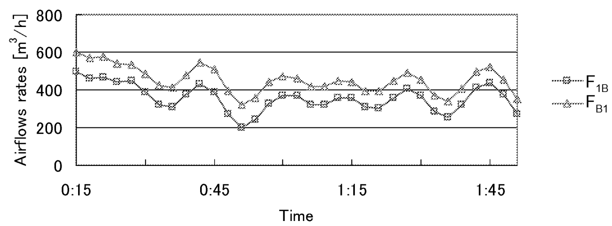


Figure 14: Convection airflow rates (Single, Simplified)

predefined period of time.

STEP 4

Data of gas concentrations from STEP 1 to STEP 3 are superposed.

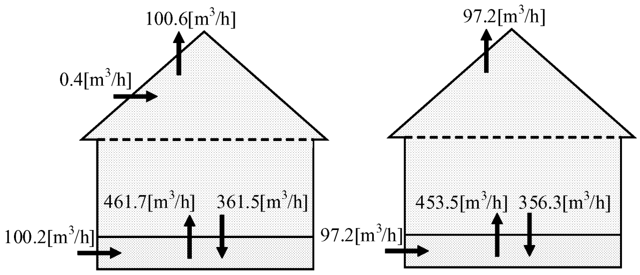
6. CALCULATION OF AIRFLOW RATES IN THE TWO-ZONE MODEL BY THE SINGLE TRACER GAS METHOD

In the case of the single tracer gas method, CO_2 gas was released at a constant rate of 0.1 [m³/h]. Gas concentrations in each zone were measured by using the multichannel gas meter (KONA-SK001). Measurement time was three minutes for three channels (measurement interval: nine minutes). Figure 9 and Figure 10 show the results of the average gas concentrations and superposition.

Airflow rates for the two-zone prototype model were calculated from the above mentioned superposition results (as shown in Figure 11, Figure 12). When the single tracer gas method is applied, it is necessary to chose appropriate values from calculated results. In this experiment, two conditions were used for this purpose: outdoor airflow rates (F_{OB})< exhaust air (F_{1O}). No airflow values are negative values. In the case of the two-zone prototype model, values of outdoor airflow rates were larger than those of exhaust air, and values of air-leakage were negative. Therefore, this model did not meet the above mentioned conditions.

Since this subject house is supposedly highly airtight, air-leakage rate can be considered zero. Therefore airflow rates for the two-zone simplified model could be calculated without considering air leakage, and the results were as follows (See Figure 13 and Figure 14.): outdoor airflow rates (F_{OB}) was about 80 to 130 [m³/h], and exhaust air was about 80 to 130 [m³/h]. These values were constant. Upstream of convection airflow rates (F_{B1}) was about 400 to 500 [m³/h], and the downstream (F_{1B}) was about 300 to 400 [m³/h].

By using the simplified model, it was possible to



Average values during time zone suitable for data analysis

Figure 15: Comparison of multi TG method (Left) and single TG method (Right)

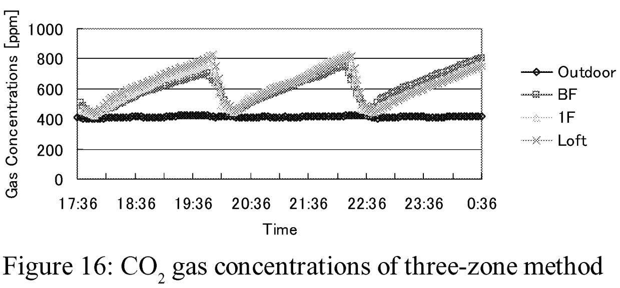


Figure 16: CO_2 gas concentrations of three-zone method

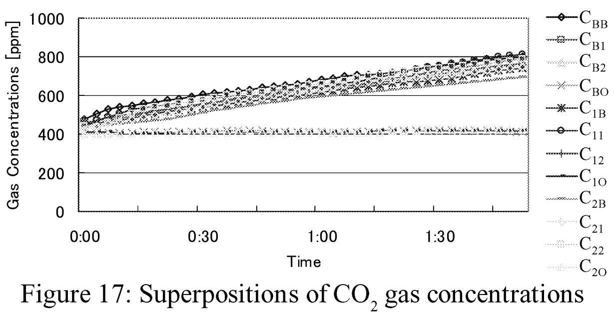


Figure 17: Superpositions of CO_2 gas concentrations

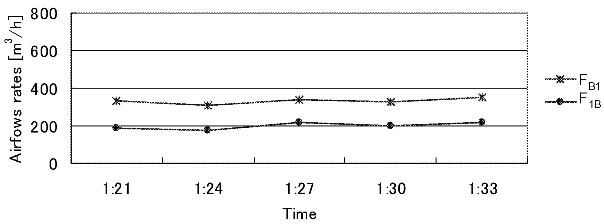


Figure 18: Interzonal airflow rates between 1F and BF (Three-zone, Single, Simplified)

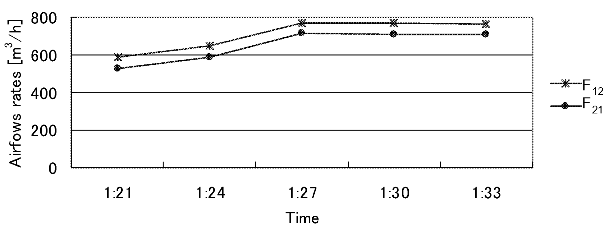


Figure 19: Interzonal airflow rates between 1F and Loft (Three-zone, Single, Simplified)

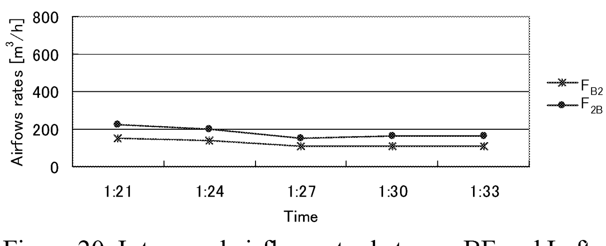


Figure 20: Interzonal airflow rates between BF and Loft (Three-zone, Single, Simplified)

calculate appropriate airflow rates, and the air-change rate of this subject house was 0.3 to 0.4 [n/h]. Comparison of the calculation results by the two methods, the single/multiple tracer gas method, showed average airflow rates during the time suitable for data analysis were almost same between the two methods judging from the value of outdoor airflow rates and exhaust air (See Figure 15.)

7. CALCULATION OF AIRFLOW RATES IN THE THREE-ZONE MODEL BY THE SINGLE TRACER GAS METHOD

Calculation results of the airflow rates for the two-zone simplified model made clear the importance of the convection airflow for ventilation planning in a house with the passive ventilation system. In order to fully explore the details of convection airflow, a three-zone model that has a return duct between the loft and the underground crawl basement space was postulated to evaluate convection. The differences from the two-zone simplified model were: Gas supply rate was 0.05 [m^3/h]. Measurement interval was 12 minutes (three minutes each for four channels). Figure 16 and Figure 17 show measurement results of average gas concentration and superposition of gas concentrations. Airflow rates for the three-zone model were calculated by using the differential method. Figure 18 to 20 show the calculation results during the appropriate time zone, 1:21 to 1:33, when airflows were stable. The interzonal airflow between the first floor and the underground crawl basement space was calculated at 200 to 350 [m^3/h], between the first floor and the loft was 550 to 750 [m^3/h], and between the loft and the underground crawl basement space was 100 to 200 [m^3/h]. Upstream of convection airflow rates like (F_{B2}) did not go through the return duct; it seems that such upstream air moved directly from the underground crawl basement space to the loft through interstices of the partition walls.

8. CONCLUSIONS

In this research, interzonal airflow rates were studied in a detached house with the passive ventilation design when there was a large outdoor and indoor temperature differences, and both single and multiple tracer gas techniques were tried. The results were as follows:

(1) During the nighttime when there were little changes in outdoor conditions, consistency was recognized between interzonal airflow rates measured by the multiple tracer gas method and the single tracer gas method.

(2) When the single tracer gas method was used to calculate interzonal airflow rates for a highly airtight house, appropriate values were obtained when the simplified model that did not consider outdoor airflow rates was used.

(3) Details of convection airflow rates and airflow through the duct between the first floor and the loft were made clear.

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