DEVELOPMENT OF VENTILATION MEASUREMENT METHOD USING HUMAN EXPIRATION
- EXPERIMENTAL STUDY FOR ESTIMATION ACCURACY -

Mitsutoshi Fujikawa1†, Hiroshi Yoshino1, Rie Takaki1, Hiroyasu Okuyama2, Motoya Hayashi3, and Masanori Sugawara4

1Department of Architecture & Building Science, Tohoku University, Sendai, Japan
2Institute of Technology, Shimizu Corporation, Tokyo, Japan
3Department of Living and Cultural Science, Miyagi Gakuin Women’s University, Sendai, Japan
4Miyagi University of Education, Sendai, Japan

ABSTRACT
Investigation of ventilation measurement method was carried out in a full-scale test house. The aim of this study was to examine the ventilation rate via human expiration. The adopted method is able to measure multi-zone airflow rates. Airflow rate between rooms was monitored and the outdoor airflow rate was measured by using the constant concentration tracer gases. The rate of outdoor airflow entering the house and the airflow rate between the rooms were estimated by the ventilation measurement method via human expiration based on system identification theory. The estimated results were compared with the measurement results in order to validate its accuracy.

KEYWORDS
Human expiration, system identification theory, measurement method of airflow rate

INTRODUCTION
The method for estimating ventilation rate via human expiration based on system identification theory was investigated in this work. The adopted method is able to measure multi-zone airflow rates. Also, it is a simple and cost effective method that suitable to apply in domestic places. In addition, the method will only have minimal interference in the daily life of the residents concerned. Experiment using this measurement method was carried out in a full-scale test house in order to investigate the accuracy.

OUTLINE OF EXPERIMENT
Forced supply and exhaust ventilation system was used and airflow rate between rooms was controlled by the compact fans. Airflow rate between the rooms was measured. Outdoor airflow rate was measured by using the constant concentration tracer gas (SF6) method. In line with the actual state of residence, various behaviour patterns of a human being were included in the experiment, and CO2 concentration from human expiration was measured. The rate of outdoor airflow entering the house and the airflow rate between the rooms were estimated by the system identification theory. The estimated results were compared with the measurement results in order to validate its accuracy.

†Corresponding Author: Tel: + 81 22-795-7885, Fax: + 81 22-795-7886
E-mail address: fujikawa@sabine.pln.archi.tohoku.ac.jp
Full-scale test house and ventilation system

(1) Description of the test house
The experiment was carried out in a full-scale test house located at the Tohoku University, Japan. The feature of test house and its floor plan are shown in Fig.1 and Fig.2 respectively. The total floor area is 78.9 m² and the volume of the house is 163.9 m³. The equivalent leakage area of the house envelope per floor area was about 1.0cm²/m² measured by the fan pressurization method. An air-conditioning unit is installed in each room except for the hall areas. There are two internal doors between each rooms and the hall. An opening is located between 1st and 2nd floors, at the southern part of the house.

(2) ZONES FOR EXPERIMENT
The test house was divided into four zones within which four CO₂ sensors were placed (Fig.2). West room doors were closed with extruded polystyrene insulation and regarded as one zone. The equivalent leakage areas per zone of the house envelope are shown in Table 1. East side of 1st floor has the largest leakage area (Table 1).

(3) Ventilation airflow control between rooms
Compact fans were fixed on the extruded polystyrene insulations in order to control airflow rate between rooms (Fig.2). The opening between 1st and 2nd floors was also closed with insulation and same fan was fixed for controlling airflow rate. Flexible duct and compact fans were set for mixing indoor air between hall and east side room (Fig.2).

(4) Ventilation system
Forced supply and exhaust ventilation system was used. All zones, except 1E, were conducted forced supply and exhaust ventilations. Because zone 1E has large leakage, therefore a huge amount of infiltration from outdoor arises. Airflow rate of ventilation system and compact fans was controlled by transformers [Note 1]. All room temperature was set to 20 °C by means of air-conditioning.

Measurement item and method
(1) Discharge quantity of CO₂ estimated by the heart rate [Note 2]
One subjected person put on a portable heart rate monitor and moved following each case of the experiment under various behaviour patterns. The access to 2nd floor from 1st floor and is through an external staircase. Discharge quantity of CO₂ was estimated based on measured heart rate referring to literatures on exercise physiology (Ikai, 1985 Nakani, 1993 Nakayama, 1985). Heart rate was measured by 5 seconds.

(2) CO₂ concentration
Portable CO₂ sensors were set at center of each room (Fig.2) and outdoor. CO₂ concentration was measured by 1 minute.

(3) Occupancy
Infra-red sensors for occupants were set at corner of each room. Infrared change was detected by 1 minute. Perceptible area is 110 degree (two-dimensional

Table 1. Equivalent leakage of the house envelope

<table>
<thead>
<tr>
<th>Zone</th>
<th>Equivalent leakage area of the house envelope (A,cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E</td>
<td>131.9</td>
</tr>
<tr>
<td>1W</td>
<td>37.9</td>
</tr>
<tr>
<td>2E</td>
<td>34.4</td>
</tr>
<tr>
<td>2W</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Fig.2. Floor plan and location of measuring points

Fig.3. Concept of the ventilation system
angle) and 15 m (distance).

(4) Airflow rate at each inlet of supply air, outlet of exhaust air and compact fans between rooms
It was measured by the airflow meter 3 times before and after each experiment respectively.

(5) Outdoor airflow rate entering the rooms
It was measured by using the constant concentration tracer gas method. SF6 was used as a tracer gas.
The gas injection was controlled so that the indoor SF6 gas concentration was maintained at 5 ppm.
The test equipment consisted of a B&K 1302 multi-gas monitor and two B&K 1303 multi-point samplers and dosers.
Diverged type of gas tube and compact fans were used (except 'Case5') to ensure that injected gas could be distributed sufficiently.

(6) Indoor and outdoor temperatures
These were measured by measuring function of the portable CO2 sensors for temperature and small data loggers with sensor in 1 minute interval.

(7) Outdoor wind velocity and direction
Wind sensor was set at a height of 8m and measured in 10 minutes interval.

(8) Input data for calculation by system identification theory
CO2 concentration, discharge quantity of CO2 and human occupancy were input into SPI-D-C, system identification calculation program (Okuyama, 1984), as parameters for estimating ventilation rate.

(9) Experiment period
Each experiment was carried out in six hours. The measurement period was from 9/2/2007 to 26/2/2007 [Note 3].

Experimental condition
In line with the actual state of residence, various behaviour patterns of a human being were included in the experiment. Summary of experimental cases and behaviour patterns are shown in Table 2. 'Case1' was set as the standard condition. More than two CO2 concentration peaks accompanying human occupancy were observed. In addition, all rooms were occupied by the subject. These were set for increasing accuracy (Ohta, 2004). 'Case2' was observed only one CO2 concentration peak. 'Case2-a' was occupied in 45 minutes of each room while 'Case2-b' was 90 minutes in each room. 'Case3' was the case for "not staying room (1W)". 'Case4' was the case with short period of "window opening".

<table>
<thead>
<tr>
<th>Case</th>
<th>Experiment period</th>
<th>Behaviour pattern</th>
<th>Total staying time</th>
<th>Concentration peak</th>
<th>Not staying room</th>
<th>Window opening</th>
<th>Mixing indoor air</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2/9 10:00~16:22</td>
<td>A</td>
<td>6h</td>
<td>2 (each room)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2-a</td>
<td>2/9 10:00~13:10</td>
<td>A</td>
<td>3h</td>
<td>1 (each room)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2-b</td>
<td>2/10 10:00~16:13</td>
<td>B</td>
<td>6h</td>
<td>1 (each room)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>2/11 10:00~16:18</td>
<td>C</td>
<td>6h</td>
<td>2 (each room)</td>
<td>Have</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>2/18 10:00~16:22</td>
<td>A</td>
<td>6h</td>
<td>2 (each room)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>2/26 10:00~16:15</td>
<td>A</td>
<td>6h</td>
<td>2 (each room)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2. Summary of experimental cases and behaviour
Assuming winter cross ventilation, the window was opened for 15 minutes two times. 'Case5' was the case that indoor air was not mixed at all. All compact fans for mixing indoor air were stopped including those of constant concentration tracer gas method. In addition, all air-conditioners were also stopped.

RESULTS AND COMPARISON

The result of airflow rate between rooms and total air change rate are compared and shown in Table 3.

Case1 (Standard condition)
The measurement results are shown in Fig.4. The average of CO2 discharge quantity was 16.3[l/h]. The air change rate was generally found stable. Fig.5 shows the estimated results from system identification calculation and measurement results from airflow meter and constant concentration tracer gas method (hereafter, Measured airflow rate). The estimated value of the total air change rate was 14.5% less than that of measured value. Outdoor airflow rate was slightly under-estimated. However, good agreement was generally obtained. Occurred error may be due to:

a) Occurred error in the system identification calculation,
b) Different discharge quantity of CO2 from the actual value.

Case2 (One CO2 concentration peak)

Case2-a (45 min per room)

Regarding case2-a, half of the data from case1 were used as the input for the SPID-C calculation. The measurement results are shown in Fig.6. Only one CO2 concentration peak was observed in each room. The estimated results from system identification calculation and measured airflow rate are compared and shown in Fig.7. The estimated value of the total air change rate was 24.6% less than that of measured value. The error was almost as much as Case2-a. However, little error of airflow rate between rooms was generally found in comparison to Case2-a.

Case2-b (90 min per room)

The result of airflow rate between rooms and total air change rate are compared and shown in Table 3.

Large discrepancy was observed at Case2-a. Half of the data from case1 were used as the input for the SPID-C calculation. The measurement results are shown in Fig.4. The average of CO2 discharge quantity was 16.3[l/h]. The airflow rate between rooms was generally found in comparison to Case2-a. However, little error of airflow rate between rooms was generally found in comparison to Case2-a.

Fig.4. Measurement results of Case1

Fig.5. Comparison of measured results and estimated results (Case1)
Case3 (Not staying room)
The measurement results are shown in Fig.8. CO₂ concentration of 1W was almost constant, 400ppm due to the absence of the occupant. The estimated results from system identification calculation and measured airflow rate are compared and shown in Fig.9. The estimated value of the total air change
rate was 14.9% more than that of measured value. Large variance was obtained at Outdoor \(\rightarrow 1W\) between 1W and 1E with airflow rate between rooms. Huge error was arisen with 1W (Not staying room) as a result.

**Case4 (Short period of window opening)**

The measurement results are shown in Fig.10. CO\(_2\) concentration in 2E dropped considerably when the window was opened, as a result air change rate increased up to 2.5[1/h]. The estimated results from system identification calculation and measured airflow rate are compared and shown in Fig.11.

![Fig.10. Measurement results of Case4](image)

![Fig.12. Measurement results of Case5](image)

![Fig.13. Comparison of measured results and estimated results (Case6)](image)
The estimated value of the total air change rate was 32.5% less than that of measured value. Large difference was found at Outdoor → 2E; between 1E and 2E with airflow rate between rooms. Huge error was arisen with 2E (the room that window was opened) as a result.

**Case5 (Indoor air is not mixed at all)**

The measurement results are shown in Fig.12. The CO₂ concentration and air change rate were generally found unstable due to the stopped fans. Indoor temperature changed responding to outdoor temperature due to the stopped air-conditioners. The estimated results from system identification calculation and measured airflow rate are compared and shown in Fig.13. The estimated value of the total air change rate was 18.3% less than that of measured value. The error was similar to that of Case1. However, the error of airflow rate between rooms was more in comparison to Case1, especially at Outdoor → 1E and 2E → 2W.

**COMPARISON BETWEEN EACH CASE**

Case1 generated the least error in term of total air change rate while the biggest error was found in Case4 (cf. Table 3). With a few exceptions (at Outdoor → 1W, 1E → 2E, between 2W and 2E), Case1 generated the least error with airflow rate between rooms (cf. Table 3). Comparing between each case, following conditions were found to be necessary for estimation accuracy.

a) More than two CO₂ concentration peaks accompanying human occupancy would occur.
b) Stay as long time as possible.
c) All rooms need to be occupied more than once during measurement period.
d) All windows have to be closed.
e) Indoor air should be mixed sufficiently.

**CONCLUSIONS**

1) Measured airflow rate and estimated results from system identification calculation showed relatively good correspondence as a result of experiment in a controlled-environment full-scale test house.

2) The impact on estimation accuracy made by occupant behaviour was investigated.
NOTES

[Note 1]
1) Controlled air change rate by forced supply and exhaust ventilation systems
1W, 2W: The airflow rate was controlled to be around 0.5[^1/h] converted to air change rate of each zone.
2E: 0.4[^1/h] air change rate.
1E: Only exhaust ventilation was installed and the air change rate was controlled to be around 0.5[^1/h].
2) Controlled airflow rate of compact fans between rooms
1st floor: The air change rate was controlled to be around 0.5[^1/h].
Opening between 1st and 2nd floor: 0.5[^1/h] air change rate of 1E.
2nd floor: 0.5[^1/h] air change rate of 2W.

[Note 2]
The relationship between \(O_2\) intake of male per person \(Y[^l/h]\) and heart rate \(X[^bpm]\) is defined as following,
\[Y = 1.848X - 124.02\]
Next, 0.85 is multiplied as the gas exchange ratio. Gas exchange ratio is defined as the ratio of \(CO_2\) discharge quantity to \(O_2\) intake.
The bottom line of \(CO_2\) discharge quantity was set to 11.2[^l/h] per person.

[Note 3]
Six hours measurement per one operation was conducted in previous experiment carried out by Tukidate et al (Tukidate, 2004). Burden of occupant was taken into consideration. Based on this case, same time setting was carried out in the current experiment.

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