Effective flow area estimation test using CO2

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Abstract

We developed a method for estimating effective flow areas not only in the external wall of a house but also in the internal walls between rooms using only one type of tracer gas. This method is based upon the following hypotheses: (1) the temperature and tracer-gas concentration in the room is homogenous, (2) the air in the room is in a windless state, (3) there is no error in the measurement of tracer-gas concentration. However, we know that in reality, these hypotheses are not entirely true. To check the effects of discrepancies between the hypotheses and actual conditions on the estimated results, we set up a miniature model experiment. As a result of this experiment, it was clarified that the present estimation method yields a reasonable estimate of the discharge coefficient even when there is a certain amount of discrepancies between the hypotheses and actual conditions.

Keywords: Effective flow area, Air leakage area, Discharge coefficient, Estimation, Newton’s method, experiment, miniature model.

Introduction

To quantify air flow rate through leakage area in a wall under any conditions, it is necessary to determine the effective flow area in the wall. Practical method exists for estimating effective flow area on the basis of the relation between pressure difference and air flow rate [1]. However, this method has mostly been used to estimate effective flow areas in the external walls of a house and not those in the internal walls between rooms.

We developed a method for estimating effective flow areas not only in the external wall of a house but also in the internal walls between rooms using only one type of tracer gas [2]. The effective flow area is calculated by multiplying the discharge coefficient of the wall and the area of the wall. Therefore, if the discharge coefficient is known, we can obtain the effective flow area. The theoretical basis of the estimation method is as follows. The discharge coefficients and the pressure in the rooms - which are unknown variables - are determined using a set of equations, which are balance equations for mass and tracer-gas concentration in the rooms. Here, mass and tracer-gas concentration balance equations are considered so as to include the same number of unknown variables as the number of equations. These equations form a nonlinear system, which can be solved using Newton's numerical method.

This method is based upon the following hypotheses: (1) the temperature and tracer-gas concentration in the room is homogenous, and (2) the air in the room is in a windless state (still). However, we know that in reality, the above hypotheses are not entirely true. Further, it is possible that measuring errors may affect the estimated effective flow areas. To check the effects of discrepancies between the hypotheses and actual conditions on the estimated results, we set up a miniature model experiment.

Experimental setup

Figures 1 shows the diagram of the miniature model used in the experiment. The experiment was carried out in an experimental room. The airflow inside the experimental room was maintained under quiet conditions. The miniature model had four cubic rooms, each with sides 0.4-m long. In each internal wall, i.e., a wall between rooms, and external wall, i.e., a wall separating a room from the external environment, 25 holes with a diameter of 6.5 mm were bored such that there were five holes in the vertical and horizontal directions; neighboring holes were separated by a distance of 0.065 m. The discharge coefficients of the walls in which holes had been bored were estimated using the effective flow area estimating method [2]. Here, the discharge coefficient of a wall is defined as shown in Equation 1. We assume that the air flow rate is proportional to the square root of pressure difference across an opening as long as there is no vertical distribution of pressure difference. The effective flow area was calculated by multiplying the discharge coefficient of the wall and the area of the wall.

$$\alpha_w = \frac{\sum_{i=1}^{25} \alpha_i A_i}{A_w} \qquad \text{(Eq. 1)}$$

where:

α_w : discharge coefficient of a wall (-), $\left(= \frac{Q_0}{A_w} \left(\frac{\rho}{2} \right)^{0.5} (p_r)^{a-0.5} \right)$ [1],

Q_0 : air leakage coefficient (m^3/(s Pa^a)) [1],

a : air flow exponent (-) [1],

p_r : reference pressure difference (Pa) [1], (in Japan, 9.8 Pa),

α_i : discharge coefficient of hole “i” (-),

A_w : area of wall (m^2),

A_i : opening area of hole “i” (m^2).

CO_2 was used as the tracer gas. Figure 2 shows the location of the heating element (Nichrome wire), the location of the mixing fan, the point at which the CO2 was supplied, and the points at which temperature and the CO2 concentration were measured. The fans were installed to maintain uniform temperature and CO_2 concentration distributions in each room.

Heat generation and the supply of CO2 were carried out under the three conditions listed in Table 1.

The temperature in each room was measured using T-type thermocouples at heights of 0.02 m, 0.20 m, and 0.38 m at the center of each room. The CO_2 concentration in each room was measured using Non-dispersive infra-red analyzers. The CO_2 concentration at a height of 0.20 m was measured throughout each experiment and that of 0.02 m and 0.38 m was measured just before the end of each experiment, the condition of which is listed in Table 1. The repeatability of the analyzers for full scale (volume standard concentration 5,000 ppm) was ±80 ppm. In each room, one such device was used to measure the CO_2 concentration; thus, four measuring devices were used in total. A plastic tube with a diameter of 6 mm, through which air flowed at a rate of 0.5 l/min, was used for aspiration of air during the measurement of the CO_2 concentration; the circulated air reached its original location after the measurement process was completed. The CO2 concentration of the external air was measured both before and after the CO2 concentration inside the room had been measured. The measured temperatures and concentrations were recorded by a data logger at 1-s intervals.

Results

Figure 3 depicts the changes in temperature and CO_2 concentration at height of 0.2 m under three conditions. The temperature in a room is represented by the average of the values measured at the three measuring points in that room.

The final values of the changes in temperature and concentration, as shown in Figure 3, were considered to be their steady-state values. (We considered that the steady state had been achieved when the change in concentration was less than 30 ppm for 3 min.) These values are listed in Table 2. This table also includes the temperature and concentration values under steady-state conditions at the three heights. The difference between the temperatures observed at the high and low points was 2.9–8.1℃ in the heated rooms and 0.1–1.6℃ in the other rooms. Further, the difference between the concentrations at the high and low points ranged up to 120 ppm (mass standard).

These average temperature of the three heights, average concentration of the three heights, and the volume of CO_2 supplied in each room, as well as the width and height of each wall were input into the program that uses the effective flow area estimation method [2], and the discharge coefficient of each wall was estimated. The allowed values of errors that satisfied the mass and concentration balance equations were respectively set to 2.0×10^{-5} kg/s and 8.0×10^{-9} kg/s.

Table 3 lists the estimated discharge coefficient of each wall. The validity of these discharge coefficients was verified by using the method described below. The change in CO_2 concentration in each room was simulated by inputting information into an airflow network calculating program [3]; the information that was input included the above-mentioned discharge coefficients, the dimensions of the miniature model, the volume of CO_2 supplied, and the changes in the temperature in each room. The validity of the estimated discharge coefficients was evaluated by comparing the calculated concentration change with the measured concentration change.

Figure 4 shows the calculated and measured values of the changes in CO_2 concentration. Since the calculated and measured values are roughly equal under all conditions, it is confirmed that the estimated values of the discharge coefficients that are listed in Table 3 are approximately correct.

Summary and conclusions

We developed a method for estimating effective flow areas not only in the external wall of a house but also in the internal walls between rooms using only one type of tracer gas [2]. This method assumes that the distribution of temperature and tracer-gas concentration in the room is completely uniform, the airflow inside the room is maintained under quiet conditions, and there are no errors in the measurement of temperature and concentration. To check the effects of discrepancies between the hypotheses and actual conditions on the estimated results, we set up a miniature model experiment.

As a result of this experiment, it was confirmed that the values of the discharge coefficients of the walls that were estimated by this method can be used to explain the experimental values of the changes in the CO2 concentration. Thus, it was clarified that the present estimation method yields a reasonable estimate of the discharge coefficient even when there is a certain amount of error in the measurement of concentration and the distribution of temperature, the concentration in the room is not perfectly uniform, and the air in the room is not in a quiet state. Further investigation is required to quantify the errors in the estimated discharge coefficient values; these errors may be caused by concentration measurement errors, nonuniform temperature and concentration distributions, and air circulation in the room.

Acknowledgments

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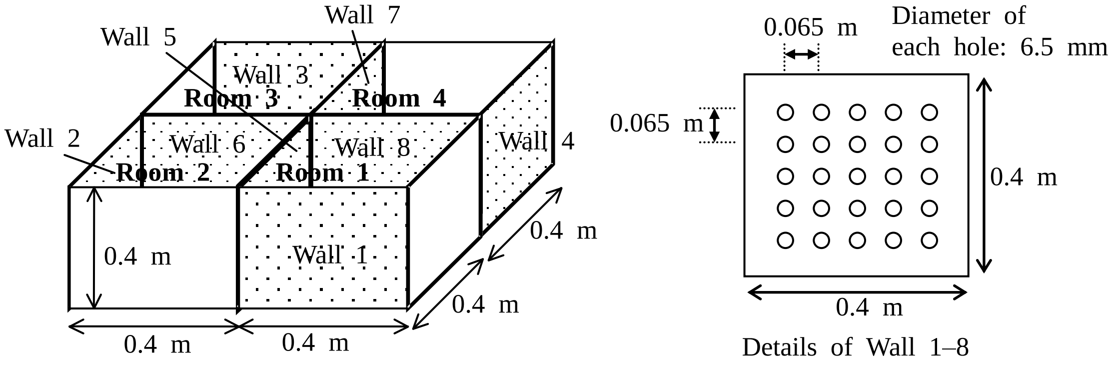


Fig. 1 Diagram of miniature model

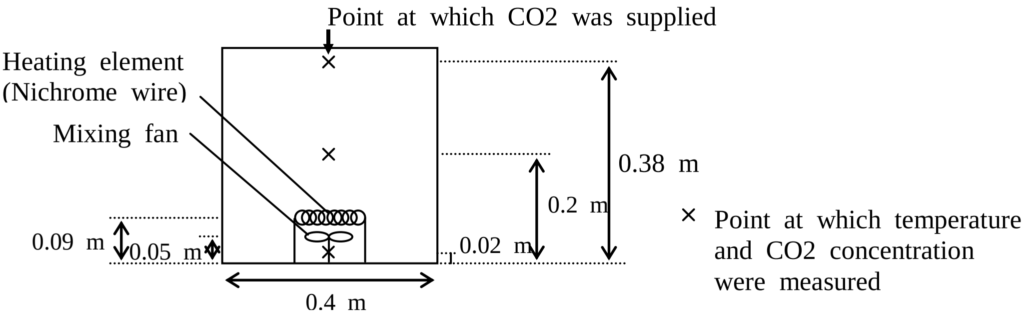
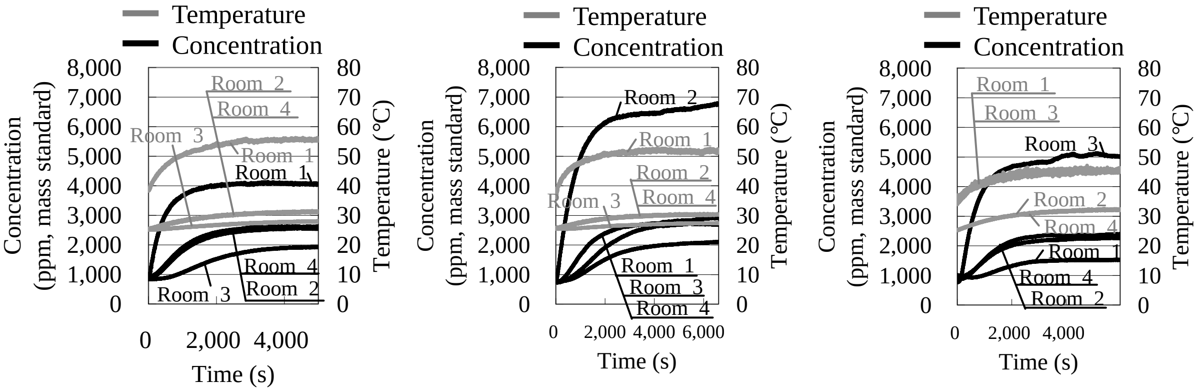
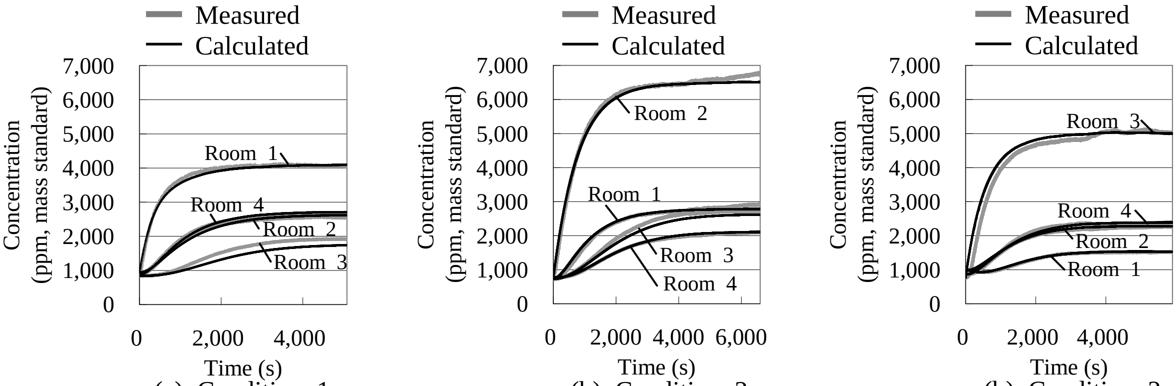


Fig. 2 Vertical cross section of a room



(a) Condition 1 (b) Condition 2 (c) Condition 3

Fig. 3 Changes in temperature and CO_2 concentration



(a) Condition 1 (b) Condition 2 (b) Condition 2

Fig. 4 Calculated and measured values of changes in CO_2 concentration

Table 1 Conditions for heat generation and supply of CO2

	Heating				Supply rate of CO2 (g/h)			
	Room 1	Room 2	Room 3	Room 4	Room 1	Room 2	Room 3	Room 4
Condition 1	heated	-	-	-	1.944	-	-	-
Condition 2	heated	-	-	-	-	1.944	-	-
Condition 3	heated	-	heated	-	-	-	1.944	-

Table 2 Values of the steady-state temperature and CO2 concentration

	Temperature (℃)				CO2 concentration (ppm, mass standard)			
	Room 1	Room 2	Room 3	Room 4	Room 1	Room 2	Room 3	Room 4
Condition 1 ave.	55.27	31.27	27.97	31.23	4,020	2,540	1,923	2,635
0.38 m height	59.3	31.8	28.0	31.7	4,068	2,555	1,925	2,650
0.20 m height	55.3	31.8	28.1	31.2	4,045	2,548	1,919	2,621
0.02 m height	51.2	30.2	27.8	30.8	3,948	2,517	1,926	2,634
Condition 2 ave.	51.80	30.37	27.33	30.27	2,928	6787	2,702	2,115
0.38 m height	51.3	30.4	27.3	30.6	2,937	6,839	2,683	2,118
0.20 m height	57.1	30.5	27.3	30.2	2,914	6,776	2,685	2,101
0.02 m height	47.0	30.2	27.4	30.0	2,931	6,748	2,738	2,126
Condition 3 ave.	45.37	32.27	45.77	32.10	1,524	2,249	5,009	2,395
0.38 m height	46.6	32.3	46.4	32.4	1,534	2,243	5,016	2,403
0.20 m height	45.8	32.4	50.0	32.1	1,521	2,262	5,015	2,386
0.02 m height	43.7	32.1	40.9	31.8	1,519	2,242	4,996	2,395

Table 3 Estimated discharge coefficients

Wall No.	1	2	3	4	5	6	7	8
Estimated value	0.002870	0.002047	0.002500	0.001858	0.002119	0.001529	0.001505	0.001727