Presumption experiment of supply rate fulfilment using tracer gas—verification on the cylinder house

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ABSTRACT
The purpose of this study is to estimate the accuracy of the Supply Rate Fulfilment (SRF) value measured by using tracer gas on a test house. The SRF is intended to evaluate quantity index and is defined as the ratio of the effective supply rate to the substantial required fresh air supply rate. The procedures to measure the SRF value with use of tracer gas techniques, which are constant concentration method and constant injection method, were shown. The SRF values of the each room in the test house were measured. These measured SRF values were compared to the theological values, which were calculated by the ΔP method and the airflow network model. The following are experimental results on the test house:
1. Whether or not the SRF values are fulfilled the SRF values itself were calculated.
2. The measured mean SRF values accorded with theological values.
3. The SRF value measured by tracer gas is useful in terms of practical standpoint.

INDEX TERMS
Ventilation performance; Tracer gas; Network model; House

INTRODUCTION
In buildings, rooms are connected complexly via openings such as doors or cracks. Therefore, the transferred airflow rates from other rooms cannot be ignored to estimate ventilation performance. Not only direct fresh air supply rate but also airflow rate from other rooms (called transferred air in this study) is considered assuming that they contain a certain quantity of fresh air, such as natural ventilation systems based on stack effect or whole house ventilation systems employing an exhaust fan. The Supply Rate Fulfilment (SRF) index (e.g. Sawachi *et al.*, 1998) is based on the quantity of fresh air rate or polluted levels in transferred air, hence this index is suitable for assessing ventilation performance. Previous works (Sawachi *et al.*, 1997) defined the procedures for estimating the SRF value by theological way and mentioned relations between tracer gas concentration and SRF value, where the concentration simply indicates SRF = 1.0 or SRF < 1.0 (means fulfilled or not). The purpose of this study is to estimate the accuracy of the SRF values, which are not only ‘fulfilled or not’ but also its value by using tracer gas on a test house in steady condition.

SUPPLY RATE FULFILMENT INDEX
Basic Point of SRF Index
The SRF is intended to evaluate the quantity index and is defined as the ratio of the effective supply rate S_i to the substantial required fresh air supply rate P_i' (shown in Eqn (1)). The SRF value ranges from 0 to 1 and SRF = 1 means the referenced room is fulfilled. The upper limit, SRF = 1, means the surplus fresh air can provide ventilation rate for other rooms. The S_i and the P_i' are calculated using the α_i (surplus fresh air supply rate contained in the transferred air exhausted which is derived by Eqn (2)). Equation (2) expresses the conservation law of α_i. If all airflow rates in a building were known α_i can be calculated. The maximum value of α_i is

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1.0, which means equal to outside air, and if the value indicates negative it means no fresh air quantity. The viewpoints of S_i and Pi' resemble the purging flow rate (e.g. Etheridge and Sandberg, 1996); however, S_i and P_i' are used in perfect mixing situation. Furthermore, S_i relies on only the positive fresh air supply rate whereas at the same time P_i' is based on required fresh air supply rate and negative fresh air supply rate.

$$SRF_i = \frac{S_i}{P_i - \sum_{j=1}^{n} \min(0, \alpha_j \cdot Q_{ij})} = \frac{S_i}{P_i'} \tag{1}$$

$$A_i + \sum_{j=1}^{n} \alpha_j \cdot Q_{ij} - \alpha_i \cdot (\sum_{j=1}^{n} Q_{ji} + B_i) - P_i = 0 \tag{2}$$

$$S_i = A_i + \sum_{j=1}^{n} \max(0, \alpha_j \cdot Q_{ij}) - \sum_{j=1}^{n} \max(0, \alpha_i \cdot Q_{ji}) - \max(0, \alpha_i \cdot B_i) \tag{3}$$

where

- A_i direct fresh air supply rate, the rate of air that is supplied directly to room i [m^3/h]
- B_i rate of air exhausted directly to the outside from room i [m^3/h]
- P_i required fresh air supply rate for room i [m^3/h]
- P_i' substantial fresh air supply rate of room i [m^3/h]
- Q_{ij} transferred airflow rate, rate of air flowing from room j to room i [m^3/h]
- S_i effective fresh air supply rate of room i [m^3/h]
- n number of rooms
- α_i surplus fresh air supply rate contained in the air exhausted from room i

Estimation Method for SRF Using Tracer Gas

In this study a constant concentration method (e.g. Roulet and Vandaele, 1991) was used for measuring the direct fresh air supply rate (A_i in Eqn (2)) and the constant injection method (e.g. Roulet and Vandaele, 1991) was used for presumption of the SRF value. The tracer gas injection rates are determined by Eqn (4). This means only one σ_c should be derived for all rooms and this value is determined by Eqn (4)′. The convergent tracer gas concentration of each room indicates the SRF value equals 1.0 or less than 1.0 (shown in Eqns (5) and (6)). The method to calculate the SRF value when it indicates less than 1.0 is the following. The α_i is related with σ_i as defined in Eqn (7). If the mean surplus fresh air supply rate contained in the air supplied into room i ($\overline{\alpha_i}$) is known then the SRF_i can be calculated by using Eqns (9) and (10). The tracer gas concentration and the tracer gas of room i are related, as shown in Eqn (11) in steady condition. The A_i and the Q_{ij} in Eqn (8) are given when the numbers of upstream rooms are less than 2 by using equation (11). Therefore, the $\overline{\alpha_i}$ value can be calculated by Eqn (8). Additionally, lack of substantial fresh air supply rate Q_{Li} can be calculated by Eqn (12).

$$P_1 : P_2 : P_3 : \cdots : P_n = q_1 : q_2 : q_3 : \cdots : q_n \tag{4}$$

$$\sigma_c = \frac{q_i}{P_i} \tag{4'}$$

$$\sigma_i \le \sigma_c \Leftrightarrow SRF_i = 1 \tag{5}$$

$$\sigma_i > \sigma_c \Leftrightarrow SRF_i < 1 \tag{6}$$

$$\alpha_i = 1 - \frac{\sigma_i}{\sigma_c} \tag{7}$$

$$\overline{\alpha_i} = \frac{A_i + \sum_{j=1}^{n} \max(0, \alpha_j \cdot Q_{ij})}{A_i + \sum_{j=1}^{n} Q_{ij}} \tag{8}$$

$$d_i = \frac{\sigma_c}{\sigma_i} \tag{9}$$

$$SRF_i = d_i \cdot \frac{1}{d_i + (1 - d_i) \cdot \frac{1}{\overline{\alpha_i}}} \tag{10}$$

$$0 = q_i + \sum_{j=1}^{n} Q_{ij}(\sigma_j - \sigma_i) - A_i \sigma_i \tag{11}$$

$$Q_{Li} = (1 - SRF_i) \cdot P_i' \tag{12}$$

where

- Q_{Li} lack of substantial fresh air supply rate for room i [m^3/h]
- d_i rate of concentrations of room i
- q_i tracer gas injection for room i [mg/h]
- $\overline{\alpha_i}$ mean surplus fresh air supply rate contained in the air supplied into room i
- σ_c concessionary tracer gas concentration [mg/m^3]
- σ_i convergent tracer gas concentration of room *i* [mg/m^3]

EXPERIMENT ON THE CYLINDER HOUSE

The Cylinder House

The experiments for presuming the SRF values were performed on a test house called the cylinder house, which has two storeys (Figures 1 and 2), in the Building Research Institute, Japan. The cylinder house is located in an artificial climate chamber and its external walls have cylinders to vary its airtightness. Valuable and pressure difference gauges are installed in the external walls of each room to measure internal–external pressure differences. The ΔP–Q characteristics of the cylinders are known. There is a negligible leakage area on the walls without the cylinders; therefore, the direct supply air rates can be calculated by pressure. The method to calculate the airflow rate using the pressure is called the ΔP method in this study. Electric heating panels can control the internal temperature of each room.

The Artificial Climate Chamber

The air temperature in the artificial climate chamber can be controlled from –10 to 40°C and the chamber has ventilation fans to exchange the air at a rate of 400 m^3/min; therefore, the concentration of tracer gas can be low when it is discharged from the cylinder house.

Tracer Gas Techniques

Through tubes the tracer gas was injected and sampled at point X in Figure 1. Small fans were installed at the front of the injection point for good mixing of the gas into the air. The analyser and tracer gas-injecting pump were set outside the artificial climate chamber and the two tracer gas techniques were operated by using those instruments.

Experimental Conditions

The experimental conditions are four cases shown in Table 1. These conditions were decided in order to provide four different transferred airflow aspects. Two patterns of exhaust air rate were provided (Figure 3) while setting values of P_i as shown in Table 2. The rooms were connected via door undercuts simulating openings. The conditions were kept steady state.

Method of Verification
The measured parameters (SRF, α, A and Q_L) by tracer gas were compared to the values by using the ΔP method or the multi-zonal airflow network model. In this study, the values, which are calculated by the ΔP method and the network model, are considered as theological values.

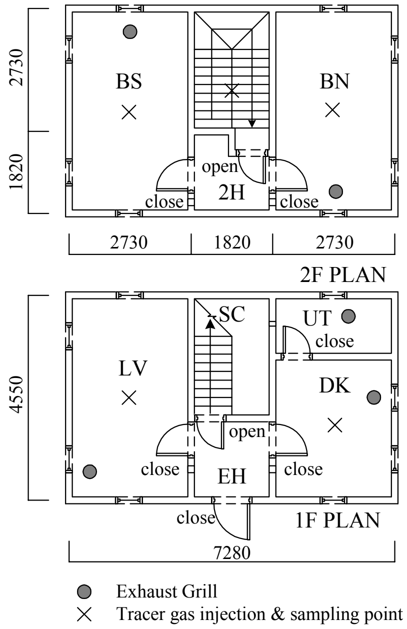
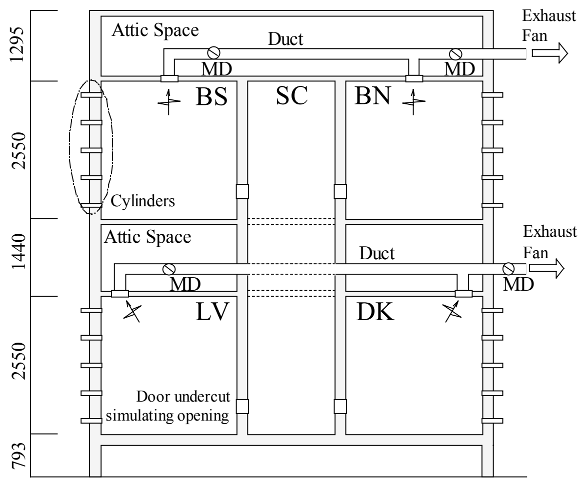


Figure 1 Plan of the cylinder house.



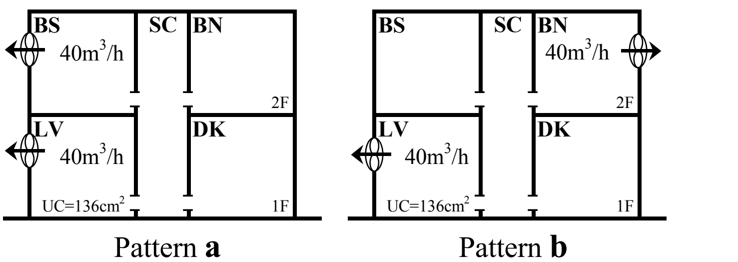
This figure only shows the exhaust ducts used in this study. The cylinder house has supply air ducts (and supply funs) in the same attic space too.

Figure 2 Section of the cylinder house.

Table 1 Experimental conditions

Experiment CASE	Fan setting pattern (shown in Figure 3)	Air tightness (setting leakage area /floor area) [cm^2/m^2] at 9.80665 Pa	Setting temperature [°C]		
			External*	Internal **	Temperature difference
01	a	5	5	20	15
02	b				
03	a	2			
04	b				

*Artificial climate chamber **Cylinder house



UC: door undercut effective leakage area at 9.80665[Pa]
This figure shows exhaust air flows using ducts and fans as exhaust fans

Figure 3 Fan setting patterns.

Table 2 Setting value of P_i

Room	P_i [m^3/h]
LV, BN	40
DK, BS	20
SC	0

RESULTS
The tracer gas injection and concentrations of CASE01 are shown in Figure 4 as an example. The α, SRF and other parameters were calculated by using data wherein the concentrations of tracer gas were considered as convergent. The measured and theological SRF values of each room are shown in Figure 5, which shows that every method gave the same result whether fulfilled or not (SRF = 1.0 or SRF < 1.0). The values are almost equivalence even when they

indicate less than 1.0. Figure 6 shows scatter charts of the measured A_i, α_i, SRF_i and Q_{Li} compared with the theological values. Table 3 shows the mean differences of the parameters as the basis for the tracer gas method. The coefficients of correlation R among three methods in each graph indicate high correlation (Figure 6) and the mean differences of those methods are not large (Table 3). This means that the tracer gas method shows useful values in terms of a practical standpoint.

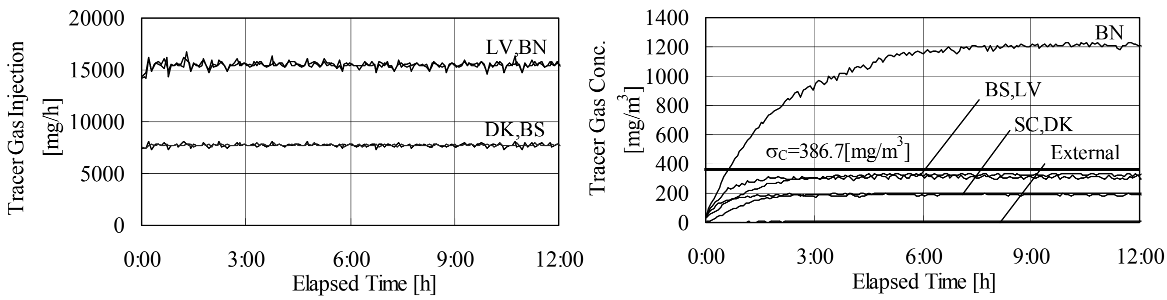


Figure 4 Tracer gas injections and concentrations of constant injection method (CASE01).

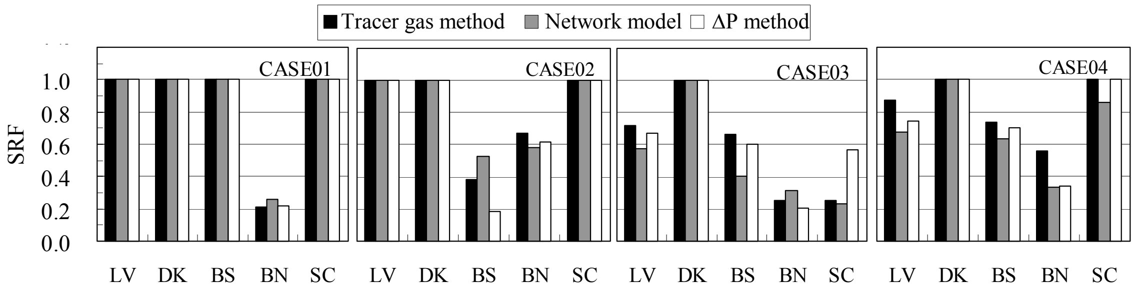


Figure 5 SRF values of each room.

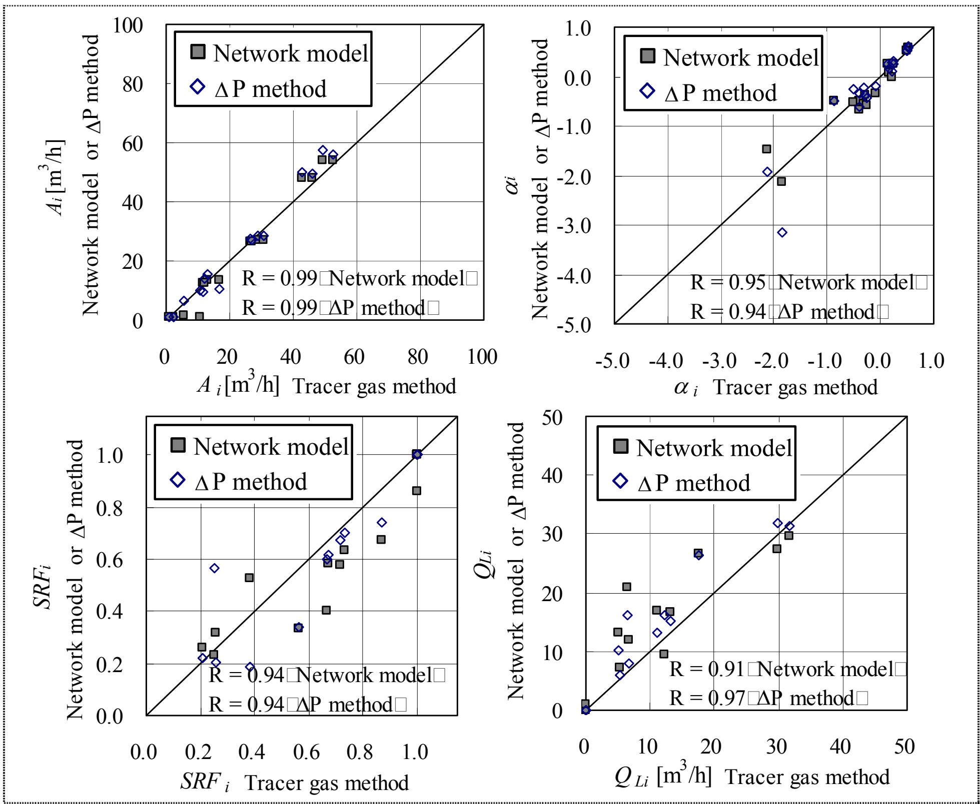


Figure 6 Scatter graphs comparing the values found by use of the tracer gas method to the use of ΔP method and network model.

Table 3 Mean differences of the parameters as the basis for the tracer gas method

Assortment term (n = number of data)		SRF_i		α_i		$Q_{L\,i}$	
		NM – TG	ΔP – TG	NM – TG	ΔP – TG	NM – TG	ΔP – TG
All data (n = 20)	**Mean**	**–0.05**	**–0.02**	**–0.03**	**–0.03**	**2.08**	**1.77**
	s.d.	0.10	0.10	0.23	0.33	4.29	3.00
Upstream room number = 1 (n = 7)	**Mean**	**–0.09**	**–0.09**	**0.03**	**0.05**	**3.32**	**2.86**
	s.d.	0.14	0.09	0.32	0.20	4.52	3.07
Upstream room number = 2 (n = 4)	**Mean**	**–0.04**	**0.08**	**–0.11**	**0.01**	**3.90**	**2.47**
	s.d.	0.07	0.16	0.14	0.08	7.15	4.93
SRF < 1 (n = 10)	**Mean**	**–0.08**	**–0.05**	**–0.05**	**–0.09**	**2.61**	**2.56**
	s.d.	0.14	0.15	0.32	0.46	4.38	2.80

NM – TG : Difference between the values using the airflow Network Model and the Tracer Gas method.
ΔP – TG : Difference between the values using the ΔP method and the Tracer Gas method.
s.d. : Standard deviation.

CONCLUSIONS

In this study, the accuracy of the measured SRF by the tracer gas method was estimated by comparing with the ΔP method and the network model. The following are conclusions on the experiment in steady condition:

1. The procedures that are used for calculating the SRF and the other parameters by the tracer gas method were shown.
2. Whether or not the SRF values are fulfilled the SRF values itself were calculated.
3. The measured mean SRF values accorded with theological values.
4. The SRF value measured by the tracer gas is useful in terms of a practical standpoint.

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