Ventilation Performance of Natural Ventilation Building with Solar Chimney

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ABSTRACT

Because of the need of energy conservation and Business Continuity Planning (BCP), natural ventilation system, which basically does not use non-renewable energy, is attracting academic/practical attention. However, it is difficult to predict the natural ventilation performance even after completion of the building, because it is easily affected by unstable conditions, such as outdoor temperature and wind. The designing and controlling method of natural ventilation system is not yet sufficiently established. The designers are referring to the past cases, and are still designing it by rule of their thumb. In order to establish the designing and controlling method of this system, unclear phenomena has to be revealed, and the knowledge based on actual operation of the building has to be accumulated. The aim of this study is to establish the designing and controlling method of natural ventilation system for non-residential buildings. The performance of natural ventilation apparatus at an actual city hall with natural ventilation system is presented in this paper. The city hall consists of lower floors (1F – 3F), higher floors (4F – 7F) and three solar chimneys. Higher floors, which consist of office areas, are placed on the lower floors, and solar chimneys is placed alongside the higher floors, facing south. The lower floors, which is a large enclosure, consist of office areas and an atrium lobby at the middle. During the mid-season, the air flows into the building through the natural ventilation openings underneath the windows at the office areas, which open and close depending on the outdoor/indoor conditions, while the air flows out from the top of solar chimneys. Air flow rate was chosen to be the index of natural ventilation performance. The measurement was conducted in fall 2017, and the flow rate through the solar chimneys was obtained by three methods, i.e., airflow velocity measurement, tracer gas method, and measurement of pressure difference. As a result, referring the result of velocity measurement was the most reliable way of calculating the air flow rate. The velocity distribution was measured at solar chimneys in spring 2018. Additionally, vertical temperature distribution was measured in the solar chimneys, and velocity distribution measured at the natural ventilation opening of office areas. The measurement at holiday, which applied heating and lighting as heat load, showed a good agreement with the measurement at week day, whose heat load was from the real workers and heat sources, which means the measurement was reliable. Air change rate was approximately 10 times/h, and it was 1.5 times of the performance prediction result at designing phase. It was also shown that it is possible to estimate the air flow rate from the BEMS data if only the method has fixed. Moreover, the result shows that measured vertical temperature distribution inside the solar chimneys can be beneficial for estimating the flow patterns.

KEYWORDS

Natural ventilation, Flow rate, Mid-season, Solar chimney

1 INTRODUCTION

The aim of this study is to establish the method of designing and controlling natural ventilation system. In order to explore natural ventilation performance in actual buildings, the field measurement is performed in an environment-conscious city hall in the mid-season, and the result is compared with the prediction result of ventilation performance at designing phase in this paper. With the need of energy conservation and Business Continuity Planning (BCP) is on the rise, natural ventilation system, which basically does not use non-renewable energy, is attracting increasing attention. However, there are some hurdles that have to be cleared for installing natural ventilation system. Natural ventilation is easily affected by unstable conditions, such as outdoor temperature and wind. It is difficult to predict the natural ventilation performance even after the completion of the building, so the designing method is not yet completely established. The designers are referring to the past cases, and are still designing it by rule of their thumb *[1]*. In order to establish the designing and controlling method of this system, unclear phenomena has to be revealed, and more measurement data at actual buildings has to be accumulated. Measurement data on actual buildings is needed for validating models and analysis in order to predict natural ventilation performance *[2]*. Additionally, though the indices for assessing mechanical ventilation performance have been organized systematically to date *[3]*, the study on the most suitable method for assessing the natural ventilation performance is still not sufficient. The final goal of this study is to establish the designing and controlling method of natural ventilation system for non-residential buildings. The performance of natural ventilation apparatus in an actual city hall with natural ventilation system is presented in this paper.

2 NATURAL VENTILATION SYSTEM IN MID-SEASON

The city hall consists of lower floors (1F – 3F), higher floors (4F – 7F) and three solar chimneys. Higher floors, which consist of office area, are placed on the lower floors, and solar chimneys are placed alongside the higher floors facing south. The lower floors, which is a large enclosure, consist of office areas and an atrium lobby at the middle. As shown in Figure 1, in mid-season, outdoor air is allowed to flow into the building through the natural ventilation openings (Figure 2) underneath the windows of the office areas, which are opened and closed with the outdoor/indoor conditions, while the air flows out from the top of solar chimneys. One of the solar chimneys is for higher floors (Chimney H), and the other two are for lower floors (Chimney L). The two Chimney L are standing alongside the Chimney H, respectively at East side (Chimney LE) and West side (Chimney LW). Air of the lower floors goes into the Chimney L from the bottom of the Chimney L, which is always kept open to the atrium lobby. On the other hand, the bottom of the Chimney H is always kept close, air of higher floors goes into the Chimney H from the vent of the higher floors instead. All the solar chimneys are joined together at the solar chimney top, and the air is exhausted from the top exhaust vent. Schematic plan view of the target building is shown in Figure 3, and geometric data of the target building is given in Table 1.

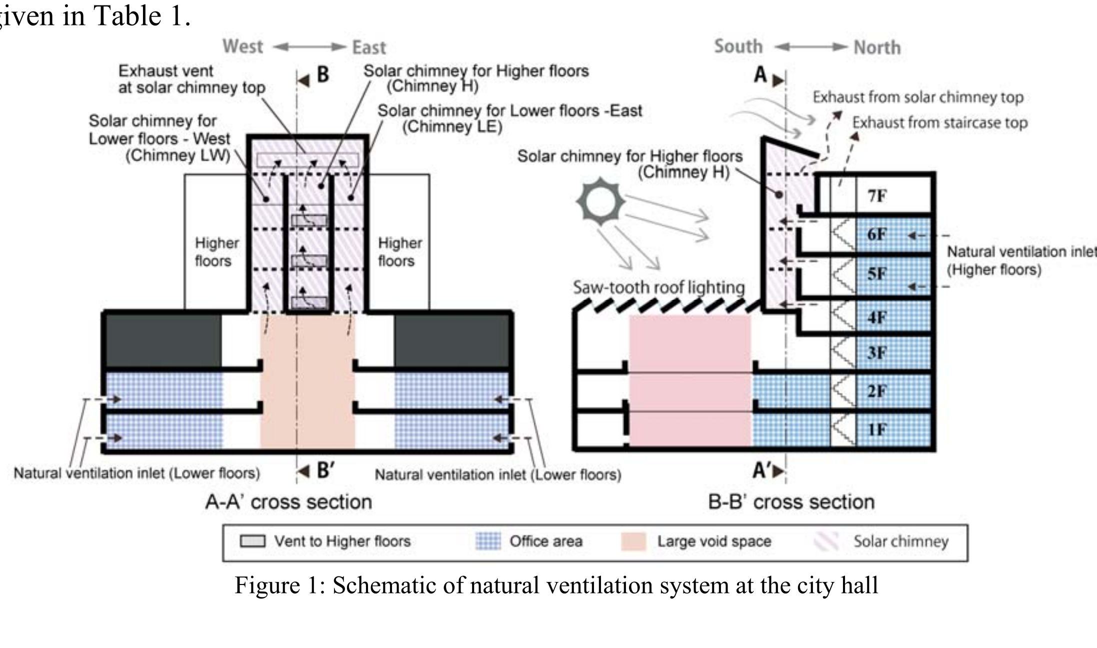

Figure 1: Schematic of natural ventilation system at the city hall

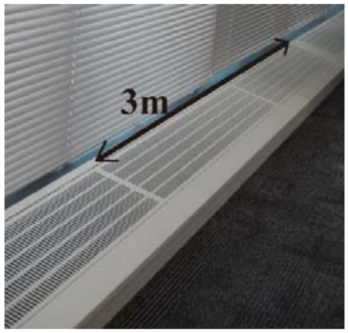

Figure 2: Natural ventilation opening points

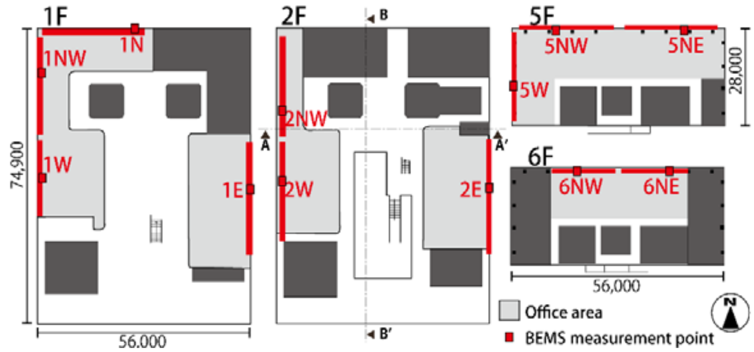

Figure 3: Schematic plan view and BEMS velocity measurement

Table 1: Geometric data of the target building

Measurement point		Area[m²]	Height[m]
Office area	6F	449	2.7
	5F	873	2.7
	2F	1,053	3.0
	1F	1,238	3.5
Solar chimney	Chimney H	6.3 * 1.7 = 10.7	Approx. 18.0
	Chimney LE, LW	5.2 * 1.7 = 8.84	

3 MEASUREMENT METHOD

For assessing ventilation performance of the target building, the field measurements were conducted in the fall of 2017 and the spring of 2018, respectively. The meteorological data is shown in Table 2. Measurement equipment and measurement cases are summarized in Table 3 and Table 4, respectively.

Table 2: Meteorological data

Season	2017 Fall			2018 Spring		
Date	10/8 Sun.	10/9 Mon.	10/10 Tue.	4/21 Sat.	4/22 Sun.	4/23 Mon.
Time	15~22	9~20	9~12	16~20	9~20	9~11
Weather	Cloudy	Sunny	Sunny	Sunny	Sunny	Cloudy
Wind velocity [m/s]	1.34	2.07	3.45	5.82	3.34	4.03
Wind direction	S	S	NW	E	SE	SE
Solar radiation [W/m²]	280	303	287	76	311	460
Temperature[°C]	23	25.5	25.6	21.1	21.9	20.1
Humidity [%]	84.8	77.5	78.3	70.8	57.7	69.3

Weather data was from AMeDAS and all the other data was from BEMS (time average in measurement time)

Table 3: Measurement equipment

Date	Measurement point	Measurement topic	Equipment	Data logger	Measurement interval
2017 10/8 ~ 10/10	Solar chimney	CO_2 concentration	LumaSense 1412i	PC	Approx. 8 min.
		Velocity	Tohnic MONITOR-N	CADAC3, Keyence NR2000	1 sec.
		Differential pressure	Halstrup P26	Keyence NR2000	1 sec.
2018 4/21 ~ 4/23	Natural ventilation opening	Airflow velocity	KANOMAX Model 6501	10 sec. average	-
	Solar chimney	Airflow velocity	KANOMAX Model 1560	PC	1 sec.
		Temperature	(Module 1504, 0965-09 probe)	CADAC3	10 sec.

Table 4: Measurement conditions

Season			2017 Fall			2018 Spring						
Case			A	B	C	0a	0b	1	2	3	4	5
Natural ventilation opening	Higher floors	6F	●	●	●	●	●	○	●	○	●	●
		5F	○	○	○	●	●	○	○	○	○	●
	Lower floors	2F	○	●	○	●	●	○	○	●	●	○
		1F	●	●	●	●	●	○	○	●	●	○
Void top			○	○	○	●	○	○	○	○	○	○
Staircase top			○	○	●	●	●	●	●	●	●	●

○: Opened, ●: Closed

3.1 Air flow rate through solar chimneys

3.1.1 Method for estimating air flow rate

In order to study the method of estimating air flow rate through the solar chimneys, tracer gas measurement, velocity distribution measurement and differential pressure measurement were conducted in fall of 2017. The measurement points are illustrated in Figure 4.

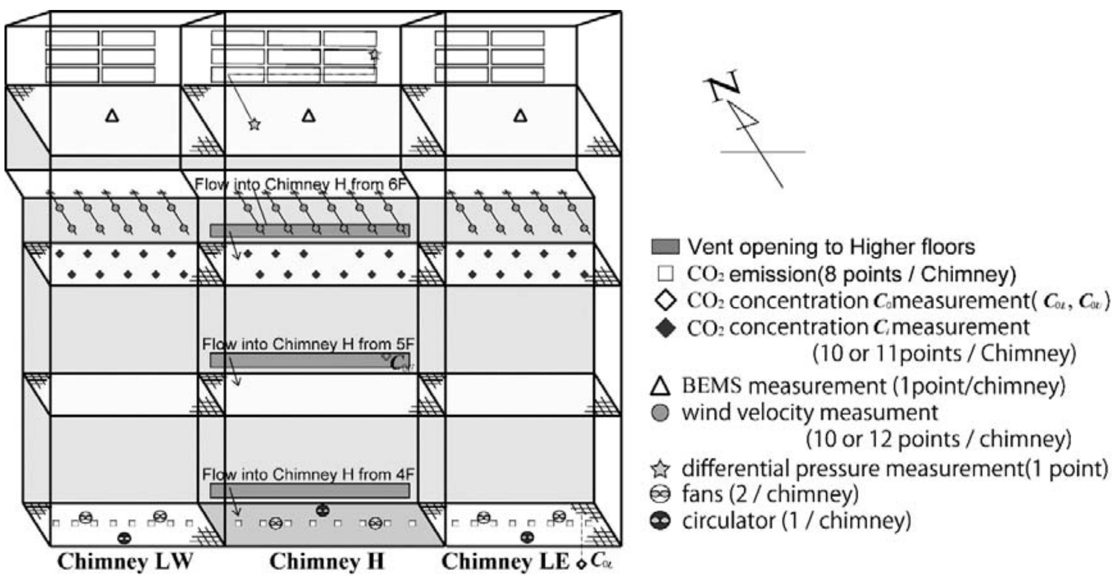

Figure 4: Measurement points at solar chimneys

Methods of estimating air flow rate through the solar chimneys use each of the equations below.

I) CO_2 concentration (C_i) distribution measurement (each solar chimney)
(Steady tracer gas method with complete mixing assumption)

$$Q_C = \frac{M}{\frac{1}{N_C}\sum_{i=1}^{N_C}(C_i - C_0)\times 10^{-6}} \tag{1}$$

where, $M = 1.0\times10^{-3}$ m^3/s for Case A, $M = 0.5\times10^{-3}$ m^3/s for Case B and C, $N_C = 11$ for Chimney H and $N_C = 10$ for Chimney L.

II) Airflow velocity (v) distribution measurement (each solar chimney)

$$Q_v = \frac{1}{N_v}\sum_{i=1}^{N_v}(v_i \times A_V) \tag{2}$$

where, $A_V = 10.7$ m^2 for Chimney H, $A_V = 8.84$ m^2 for Chimney L, $N_C = 12$ for Chimney H and $N_C = 10$ for Chimney L.

III) Differential pressure (Δp) measurement (all the solar chimneys together)

$$Q_p = C_D A_{VT} \sqrt{\frac{2}{\rho}|\Delta p|} \tag{3}$$

where, A_{VT} = 29.2 m^2 and C_D = 0.447[-].

Example result of airflow velocity and CO_2 concentration distribution are shown in Figure 5. The sketch of the graphs of airflow velocity and CO_2 concentration are apparently not identical, i.e. the both are not sufficiently uniform. It shows that inside of solar chimney, the air was not mixed enough for applying the complete mixing assumption.

The air flow rate estimated by differential pressure shown in Table 5 indicate that in Case B, which is a case that the air flow rate of Chimney H is greater than that of Chimney L, Q_p might have been overestimated. Only one differential pressure gauge was placed at Chimney H, which might have overlooked the differential pressure distribution, so more differential pressure gauge should be placed for reliable measurement. Moreover, it was not sure if the measured pressure difference was appropriate, because one end of the pressure tube was placed just outside front of the exhaust window, but the other was placed at height 2300mm lower than the opening in the chimney, which may ignore the pressure loss due to the impingement and bend that occurs at the chimney top before outflow. Thus, it seems that using the result of airflow velocity measurement is the most effective way of estimating the flow rate through a large area of cross section, compared to the results of tracer gas and differential pressure.

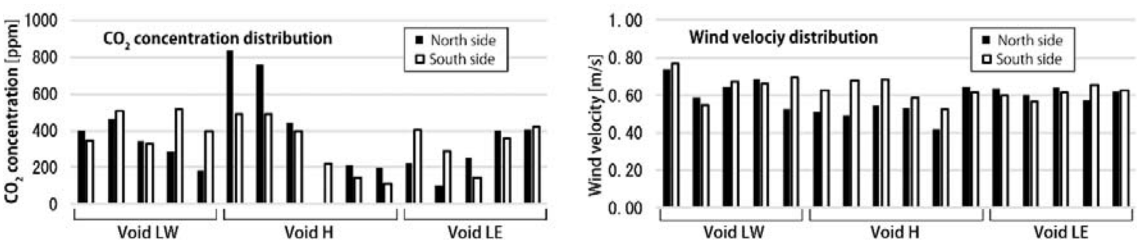

Figure 5*: CO_2 concentration distribution (left) and airflow velocity distribution (right) at solar chimneys

*In case A, velocity measurement and CO_2 concentration measurement couldn't be operated on the same day, due to technical troubles. Velocity distribution was measured on October 9th PM, CO_2 concentration in Chimney LW and H was measured on October 8th and it in Chimney LE was measured on October 9th AM.

Table 5*: Results of three methods for estimating flow rate through solar chimneys

Case	Solar chimney	Flow rate Q [m^3/s]			ACH [1/h]		
		Q_C	Q_v	Q_p	I	II	III
A	Lower	6.0	11.1	-	6.8	12.6	-
	Higher	2.6	6.1	-	4	9.3	-
	Total	8.6	17.2	15.5	5.6	11.2	10.1
B	Lower	-	6.5	-	-	7.4	-
	Higher	5.4	7.1	-	8.3	10.9	-
	Total	-	13.6	18.7	-	8.9	12.2
C	Lower	-	9.0	-	-	10.3	-
	Higher	4.6	6.1	-	7.0	9.3	-
	Total	-	15.6	15.6	-	10.2	10.2

Each of the Q_C, Q_v *and* Q_p stands for the air flow rate estimated by CO_2 concentration measurement, velocity measurement and differential pressure measurement.

I: CO_2 concentration measurement, II: velocity measurement, III: differential pressure measurement

3.1.2 Velocity distribution measurement for estimating flow rate

According to the result of 3.1.1, the velocity distribution measurement was conducted for estimating the air flow rate through the solar chimneys in the spring of 2018 by using multi-point anemometer. Measurement points are shown in Figure 6. Apart from these measurement points, the anemometers used for BEMS (Building Energy Management System) were placed at GL+30,977mm whose cross-sectional area is approximately twice of that at multi-point anemometer measurement height. In order to estimate the air flow rate easily by using BEMS data, the flow rates estimated by BEMS and multi-point anemometer were compared. The relationship between the two measurement results were expressed by the following equation,

$$Q_m = K \times Q_{BEMS} \quad (4)$$

where, $K = K_1$, $Q_m = v_m \times A_V$ $(= 28.38\text{m}^2)$, $Q_{BEMS} = v_{BEMS} \times A_V{}'$$(= 74.25\text{m}^2)$, and v_m and v_{BEMS} were spatially averaged over the three solar chimneys.

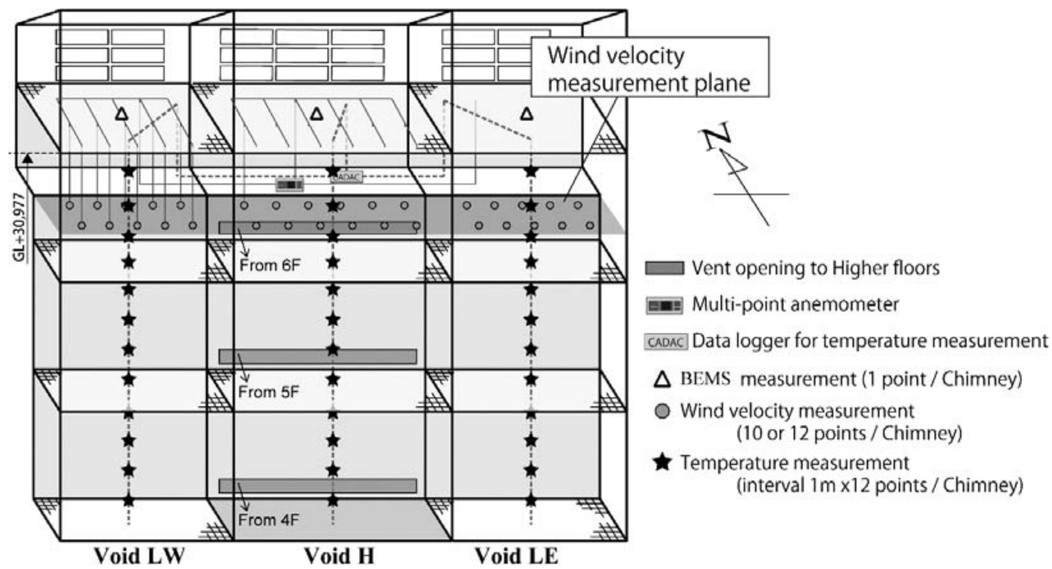

Figure 6: Measurement points at solar chimneys in spring 2018

3.2 Air flow rate through natural ventilation opening in office areas

BEMS sensors for measuring airflow velocity and temperature are placed at natural ventilation opening (Figure 2) in office area (Figure 3) of the building. Air flow rate through the opening was expected to be estimated easily by using the velocity measurement data of BEMS. The relationship between measured data and BEMS data were expressed by an Eq. (4), where, $K = K_2$, $Q_m = v_m \times (2 \times A_{duct})(= 0.39\text{m}^2)$, $Q_{BEMS} = v_{BEMS} \times A_{in}(= 0.22736\text{m}^2)$, v_m was spatially averaged over half a unit and v_{BEMS} was the result of BEMS. By postulating, symmetry that was seen in the preliminary measurement, the measurement was conducted over half of a unit for each measurement point. Measurement method is shown in Figure 7. Three anemometers were used for the measurement, one was for measuring temporal change of velocity, it was fixed at the centre of the measurement area as the reference point: the other two were for measuring velocity distribution. The results of velocity distribution measurement were normalized by the corresponding velocity of the reference point obtained simultaneously by the following equation:

$$v_m = v_d|_n \times \frac{\overline{v_t}}{v_t|_n} \quad (5)$$

where v_d is the velocity measurement data to obtain velocity distribution and v_t is the velocity measurement at the reference point.

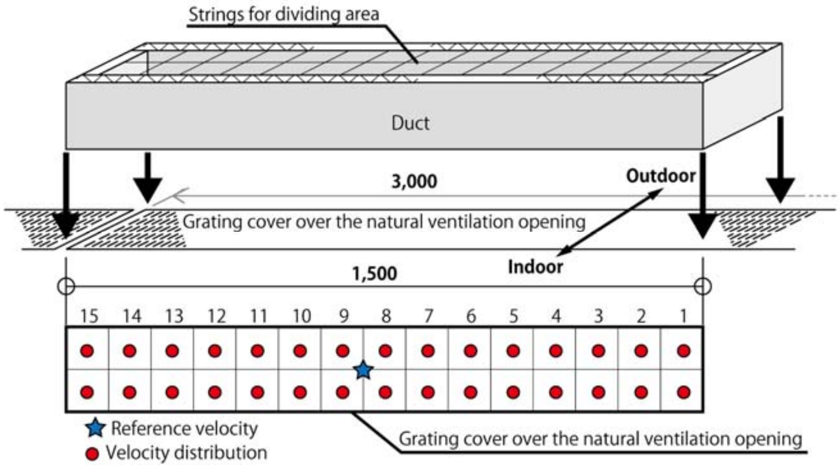

Figure 7: Method for estimating velocity distribution

3.3 Vertical temperature distribution in solar chimneys

The vertical temperature distribution within the solar chimney was measured in spring of 2018. As shown in Figure 4, thermocouples were hanged down from GL+31,000mm, and the temperature were measured every 1m till 12m down, which is approximately the height of solar chimney bottom. Measurement points were covered by aluminium sheet for avoiding the effect of solar insolation.

4 RESULTS AND DISCUSSION

4.1 Air flow rate through solar chimney

As an example, the velocity distribution of the solar chimney for Case 1 in April 22nd and 23rd are shown in Figure 8. It must be noted that: April 22nd was a holiday, thus occupants were almost not existing, and the heat loads were simulated by artificial lighting and heating; however, April 23rd was a week day, no additional heat load was added because were there existed the actual occupants. Sketches of airflow velocity distribution inside the chimney showed a good agreement, thus the measurement results on holiday are considered to be relatively reliable.

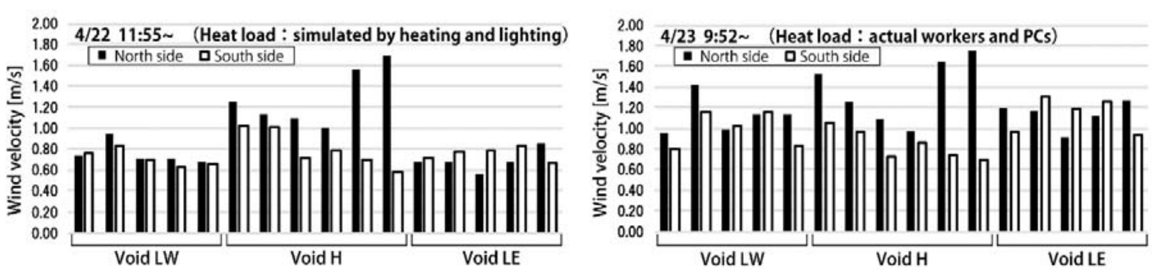

Figure 8: Comparison of velocity distribution in solar chimneys on holiday (left) and weekday (right)

All the estimated results of air flow rate are listed in Table 6. ACH seem to relatively high, which were approximately 0.5 times higher than that expected in the design phase. The result of velocity measured by multi-point anemometer was compared with BEMS data. K_1 was calculated for each case, and was determined to be 1.12 by averaging those results. However, it seems to be difficult to estimate the flow rate using this constant, due to the large cross-sectional area at the height of BEMS measurement point.

Table 6: Measurement result at solar chimneys in spring of 2018

Measurement conditions			Time averaged velocity [m/s]				Air flow rate [*10^3 m^3/h]				K_1 [-]	ACH [1/ h]
			Multi-point anemometer			BEMS	Multi-point anemometer			BEMS		
Start	End	Case	L	H	Ave.	Ave.	L	H	$v_m * A_V$	$v_{BEMS} * A_V'$		Total
4/21 Sat.												
16:15	17:05	1	1.09	1.14	1.12	0.56	69.4	43.9	113.9	149.7	0.76	10.2
17:05	18:05	2	0.98	0.75	0.87	0.44	62.4	28.9	88.4	118.1	0.75	9.3
18:05	19:35	3	0.32	0.72	0.52	0.20	20.4	27.7	53.1	52.7	1.01	13.5
4/22 Sun.												
9:35	10:45	3	0.32	0.81	0.57	0.08	20.4	31.2	57.7	22.1	2.62	14.4
10:48	11:50	4	0.37	0.64	0.51	0.17	23.5	24.7	51.6	44.8	1.15	20.5
11:55	13:40	1	0.73	1.05	0.89	0.36	46.1	40.4	90.7	96.2	0.94	7.8
13:40	15:22	2	0.65	0.64	0.65	0.13	41.4	24.7	65.9	34.1	1.93	6.7
15:22	16:22	5	0.89	0.34	0.61	0.22	56.3	13.1	62.6	58.1	1.08	9.3
16:22	17:20	1	0.80	0.93	0.86	0.40	50.6	35.8	88.1	105.6	0.83	7.8
17:20	18:20	2	0.79	0.62	0.71	0.32	50.3	23.9	72.0	85.5	0.84	7.5
18:20	19:30	5	0.94	0.31	0.62	0.42	59.5	11.9	63.6	112.9	0.56	9.5
4/23 Mon.												
9:00	9:30	0a	0.22	0.20	0.21	0.05	13.7	7.7	21.2	13.4	1.59	-
9:30	9:52	0b	0.66	0.32	0.49	0.24	42.0	12.3	50.1	63.5	0.79	-
9:52	10:35	1	1.10	1.10	1.10	0.53	70.0	42.4	112.4	140.3	0.80	10.2

"Ave." stands for "Average"

4.2 Air flow rate through natural ventilation opening in office areas

Examples of velocity distribution at natural ventilation opening are shown in Figure 9. The result of K_2 was 1.022. Figure 9 shows that even the measurement points were same at plan view, the sketches of the graphs were not the same if the height is different. In addition, the planar difference of measurement point lead to the velocity difference. It was shown that easily estimating an accurate flow rate using BEMS data seem to be not realistic in this building, and measurement method has to be reconsidered. However, the K_2 is still expected to be contributed to the approximate calculation.

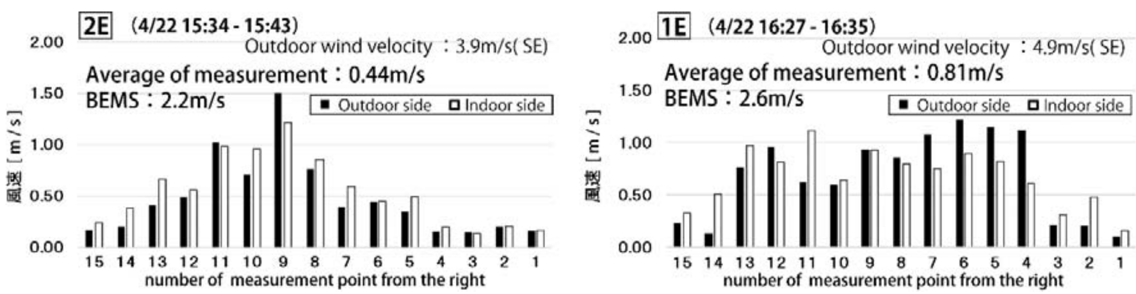

Figure 9 Examples of results on velocity distribution at natural ventilation opening

4.3 Vertical temperature distribution in solar chimneys

Results of vertical temperature distribution in solar chimneys on April 22nd are shown in Figure 10. Temperature difference between 1m and 12m below from GL+31.0m (Δt) is also shown in Figure 10. The temperature stratification is an important driving force of natural ventilation, thus vertical temperature distribution was expected to be stratified, which means, temperature at the top of the chimneys are higher than that at the bottom. However, from case 3 (9:35~) to case2 (13:40~), t_1 was lower than t_{12} in the Chimney H, while it was opposite in the Chimney L. Chimney L has obviously stratified temperature distribution, because air inflow to the chimneys was basically from the bottom of the chimney. On the other hand, opening to the Chimney H changes depending on the cases, so the airflow is not stable. Moreover, air at the bottom is stagnated and didn't change for the cases in spring of 2018, thus the temperature at the bottom is obviously high. Additionally, even Δt was smaller than 0 at Chimney H, the flow rate was still sufficient for natural ventilation. It is considered to be the result of solar chimney top's geometric feature that all the chimneys are joined together at the top, so the Chimney L helps Chimney H to pull up the air.

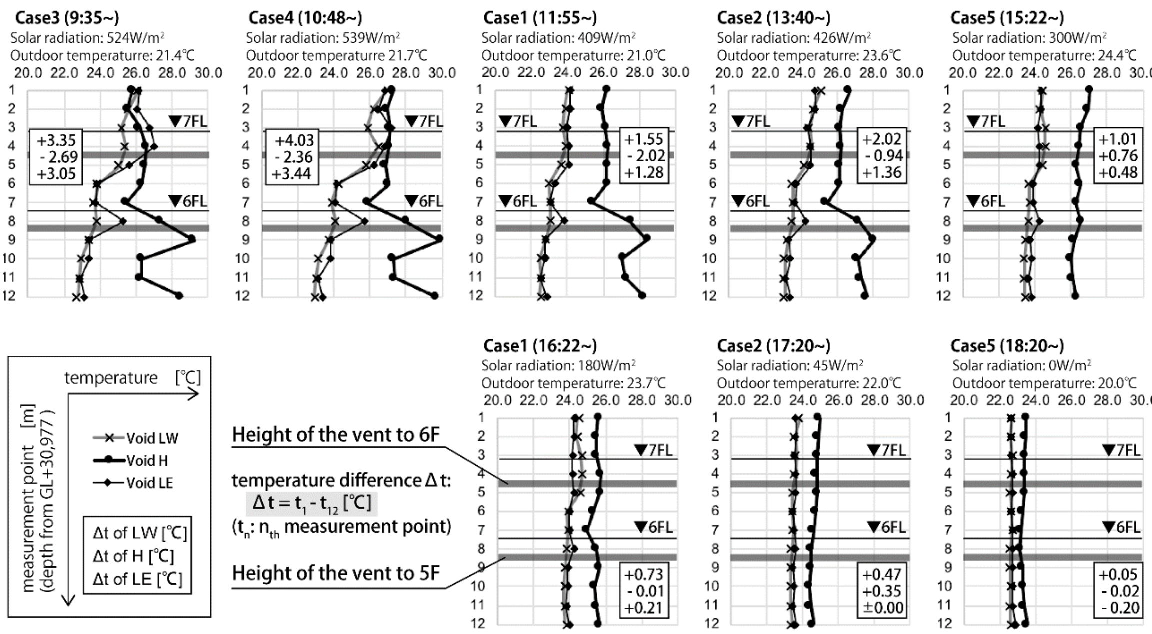

Figure 10: Vertical temperature distribution in the solar chimneys

5 CONCLUSION

Evaluation of natural ventilation performance in mid-season for an environment-conscious city hall is presented in this paper.

The main knowledge obtained in this study is summarized as follows:

- For estimating the air flow rate through an opening with a large cross-sectional area, it is considered that using the result of velocity measurement is the most effective way, compared to steady tracer gas method and differential pressure measurement.
- The actual measurement showed that the air change rate (ACH) was approximately 10 times/h, and it was 1.5 times of the predicted natural ventilation rate in the design phase.
- If a building has a lot of natural ventilation opening, it is difficult to estimate all the flow rate completely by measuring partial velocity. However, possibility of estimating approximate flow rate was indicated, by expressing relationship between BEMS velocity measurement result at a point and spatial average of velocity with a simple coefficient.

- The result of vertical temperature distribution in the solar chimneys obtained in this study showed that the smaller the velocity through the chimney L, the greater the temperature difference (Δt). However, the relationship between Δt and flow rate through solar chimney was not able to be expressed with single coefficient in this study.

Nomenclature

A_{duct}	Area of the duct for velocity measurement at natural ventilation opening [m^2]
A_{in}	Area of natural ventilation opening in office area [m^2]
A_V	Cross-sectional area of solar chimney at the height of multi-point anemometer probe [m^2]
$A_V{}'$	Cross-sectional area of solar chimney at the height of BEMS anemometer probe [m^2]
A_{VT}	Area of exhaust vent at top of solar chimney [m^2]
C_0	CO_2 concentration of inflow into solar chimney [ppm]
C_D	Discharge coefficient of exhaust vent at solar chimney top
C_i	CO_2 concentration at measurement point *i* [ppm]
K	Coefficient for expressing the relationship between actual flow rate and BEMS (K_1 for solar chimney and K_2 for natural ventilation opening)
M	CO_2 emission[m^3/s]
N_C	Number of measurement point for each solar chimney in tracer gas method [-]
N_v	Number of measurement point for each solar chimney in velocity measurement [-]
Δp	Differential pressure at solar chimney top
Q_C	Air flow rate through solar chimney estimated by tracer gas method [m^3/s]
Q_p	Air flow rate through solar chimney estimated by differential pressure measurement [m^3/s]
Q_v	Air flow rate through solar chimney estimated by velocity measurement [m^3/s]
v_{BEMS}	Velocity measured by BEMS [m/s]
v_d	Velocity at distribution measurement point [m/s]
v_i	Velocity at measurement point *i* [m/s]
v_m	Velocity measured in field measurement [m/s]
v_t	Velocity at the reference point [m/s]
ρ	Density [kg/m^3]

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