Measurement for Exterior Wall Airtightness of High-Rise Buildings Using Stack Effect/Individual Air Conditioning and Outdoor Air Entering through Entrance Doors

技研側から追加など

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1. Backgrounds and objectives

Backgrounds and Objectives (1)

- A simple test method of airtightness that uses buoyancy caused by stack effect in a high-rise building was developed in 1980s in Japan.
- When doors are opened near the ground floor or the rooftop, it is the same as pressurizing or depressurizing the building with a blower.
- The amount of airflow in and out of an open door or window at this time corresponds to the amount of air supplied and exhausted by the blower.
- Based on these results, the equations for the inflow and outflow volumes at the exterior wall can be formulated to estimate the airtightness of the exterior walls.
- Through the activities of Technical Committee of AIJ, we calculated the amount of air leakage at the exterior walls of 3 model buildings (low-rise, middle-rise, and high-rise buildings) and developed equations that can manually calculate air infiltration rates.

Backgrounds and Objectives (2)

- We also developed a method to measure the airtightness of the exterior walls on a reference floor using individual air-conditioning systems for each floor, which began to be widely used in 2000s.
- This method is introduced and measurement results are discussed in this presentation.
- We also report measurement results for outdoor air volumes entering through entrance doors and resulting heating loads in a high-rise building in winter, considering large impacts of stack effect.

2. Simple test method of airtightness using buoyancy caused by the stack effect in a high-rise building

Test Method of Airtightness using Buoyancy by Stack Effect

Developed new method to measure wall airtightness using stack effect

- Generate 3 equations for 3 conditions by changing the opening status of doors/windows on top and ground floors.
- Airtightness of exterior walls on top floor (αA_R), standard floors (αA_T), and ground floor (αA_G) are calculated by solving the 3 equations. Here, αA stands for "equivalent opening area (cm^2/m^2)".
- Airtightness of exterior walls for 3 buildings were measured.

$$Q_i = (\alpha A)_G \sqrt{2g\gamma_o |\Delta P_G|} + \sum_{j=2}^{M-1} (\alpha A)_{T\cdot j} \sqrt{2g\gamma_o |\Delta P_j|}$$

$$Q_o = \sum_{j=M}^{N} (\alpha A)_{T\cdot j} \sqrt{2g\gamma_i |\Delta P_j|} + (\alpha A)_R \sqrt{2g\gamma_i |\Delta P_R|}$$

Since the values in the root mark, denoted by K_G, K_j, and K_R can be obtained as measurement results, and $Q_i = Q_o$ can be assumed, the above-mentioned equations will be

$$K_G (\alpha A)_G + \sum_{j=2}^{N} K_j (\alpha A)_{T\cdot j} - K_R (\alpha A)_R = 0 \qquad (1)$$

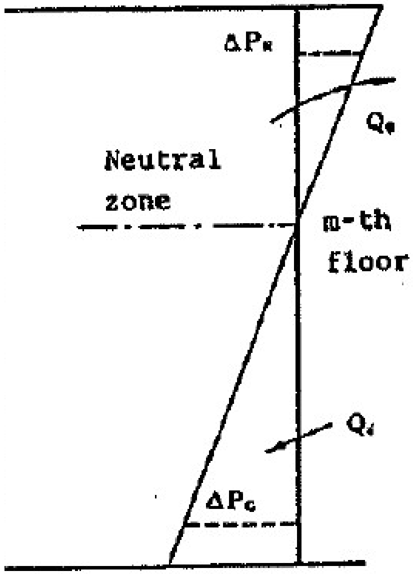


FIG. 2—Ordinary state.

Outline of Building A

- Middle-rise Office building of 9 floors with RC structure.

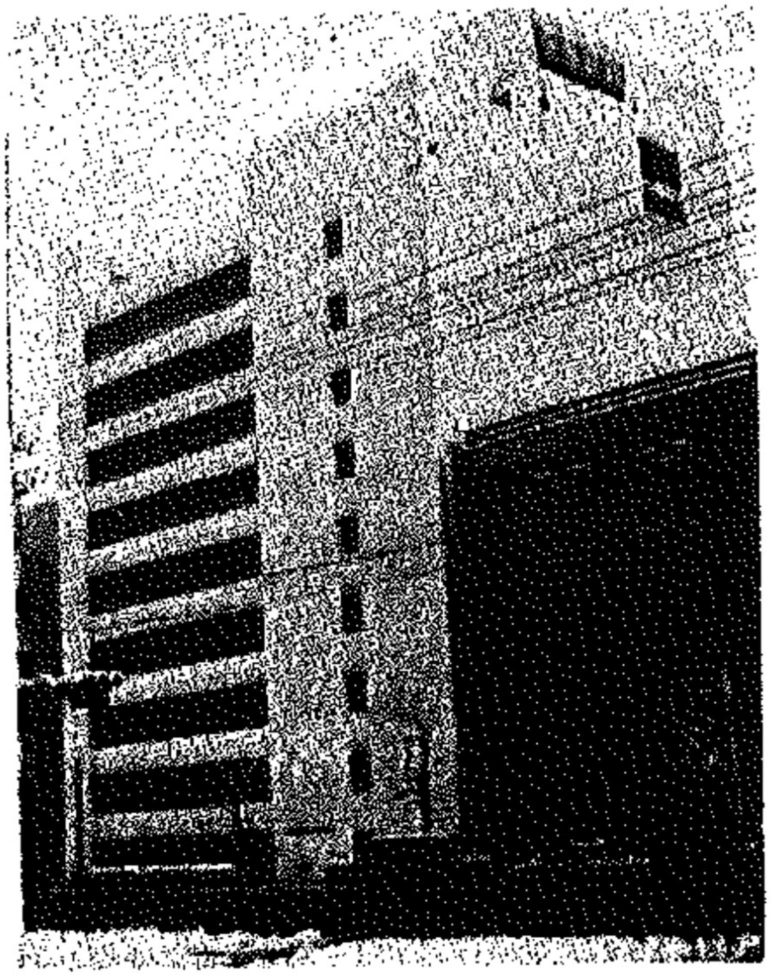


FIG. 5—*External appearance (Building A).*

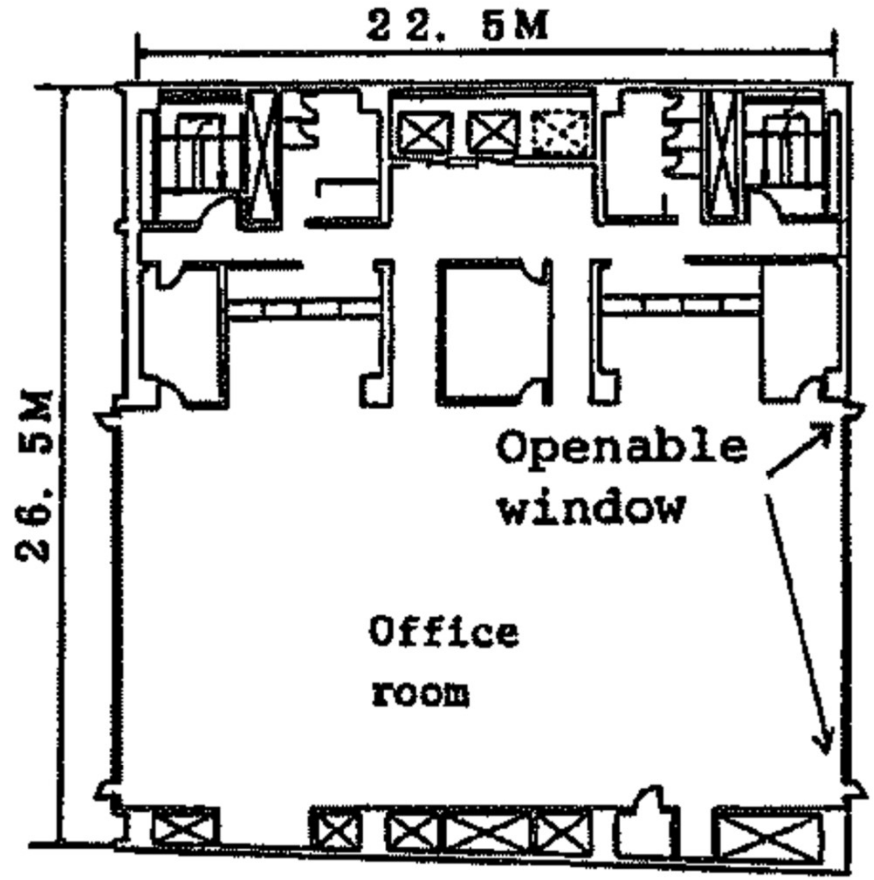


FIG. 6—*Plan of typical floor.*

Measurement Results for Building A

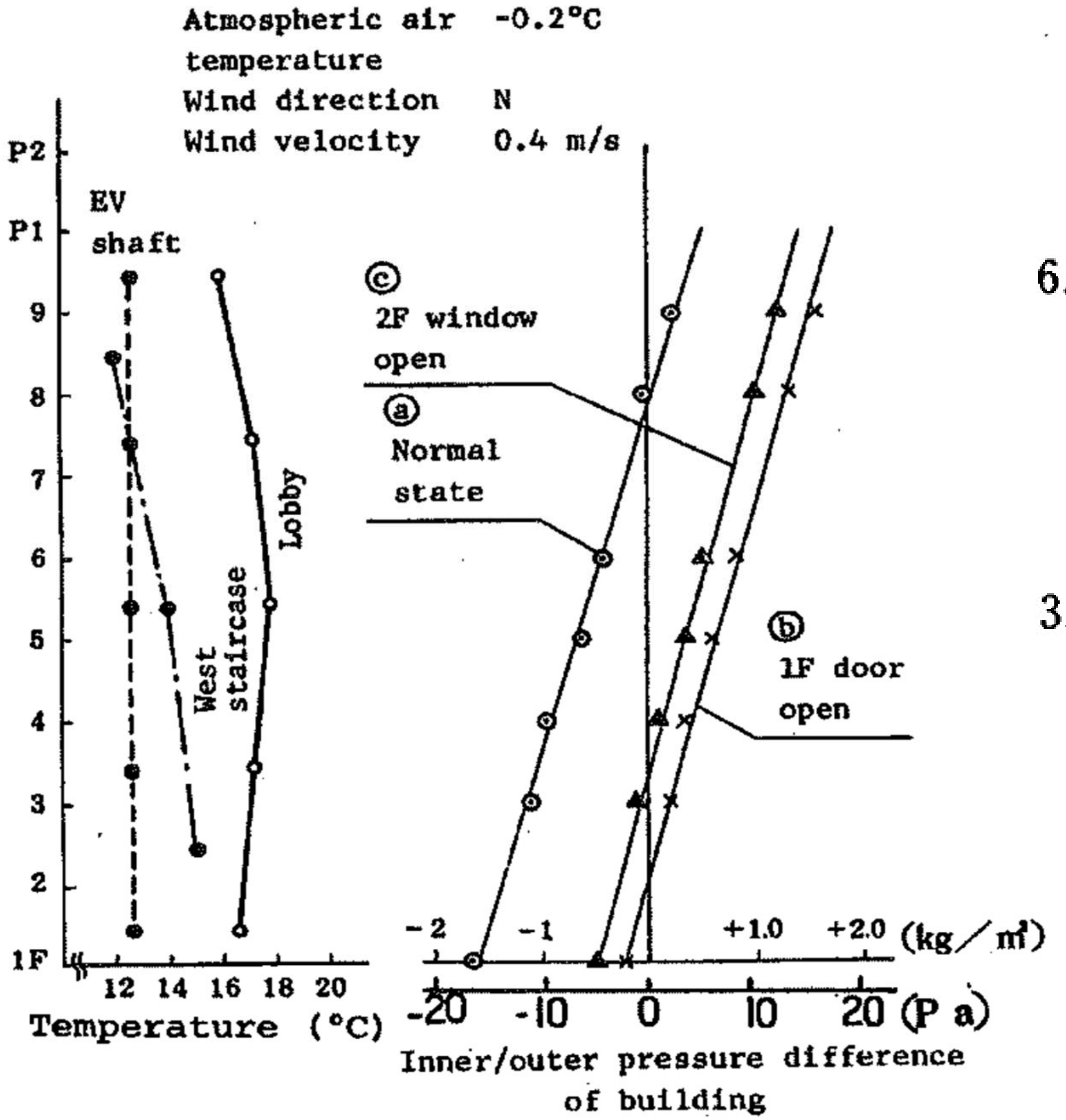


FIG. 7—*Measured results.*

$$6.37(\alpha A)_G + 20.20(\alpha A)_T - 3.66(\alpha A)_R = 0 \quad \cdots\cdots (4)$$

$$32.30(\alpha A)_T - 6.53(\alpha A)_R = 2.33 \quad \cdots\cdots (5)$$

$$3.26(\alpha A)_G - 21.64(\alpha A)_T - 6.09(\alpha A)_R = -1.83 \quad \cdots\cdots (6)$$

- αA_T can be calculated by these equations.

Process of Calculating Airtightness of Building A

TABLE 1—*Process of calculating coefficient K of Eq 4.*

Floor No.	Height*1 (m)	ΔP*2 (kg/m^2)	γ*3 (kg/m^3)	$Sign(\Delta P)\sqrt{2g\gamma\vert\Delta P\vert}$*4	K
R	31.6	(0.56)*5		3.662	K_R=3.66
9	28.2	0.32	1.222	2.771	
8	24.8	0.05		1.097	
7	21.4	(-0.14)	1.293	-1.884	K_T=-20.20
6	18.0	-0.33		-2.891	
5	14.6	-0.53		-3.667	
4	11.2	-0.88		-4.725	
3	7.8	-1.03		-5.113	
2	4.4	(-1.32)		-5.788	
1	1.0	-1.6		-6.368	K_G=-6.37

*1 Height from the ground level to 1 m above the floor
*2 External wall pressure difference (inside vs. outside)
*3 Specific weight of air When ΔP>0: Indoor air (15.7°C)
When ΔP<0: Outside air (0.1°C)
*4 Sign (ΔP) = (1, ΔP>0)
(-1, ΔP<0)
*5 Figure in parentheses shows estimated value and others are measured values.

Outline of Building B

- High-rise office building of 17 floors with steel structure and precast concrete curtain walls.

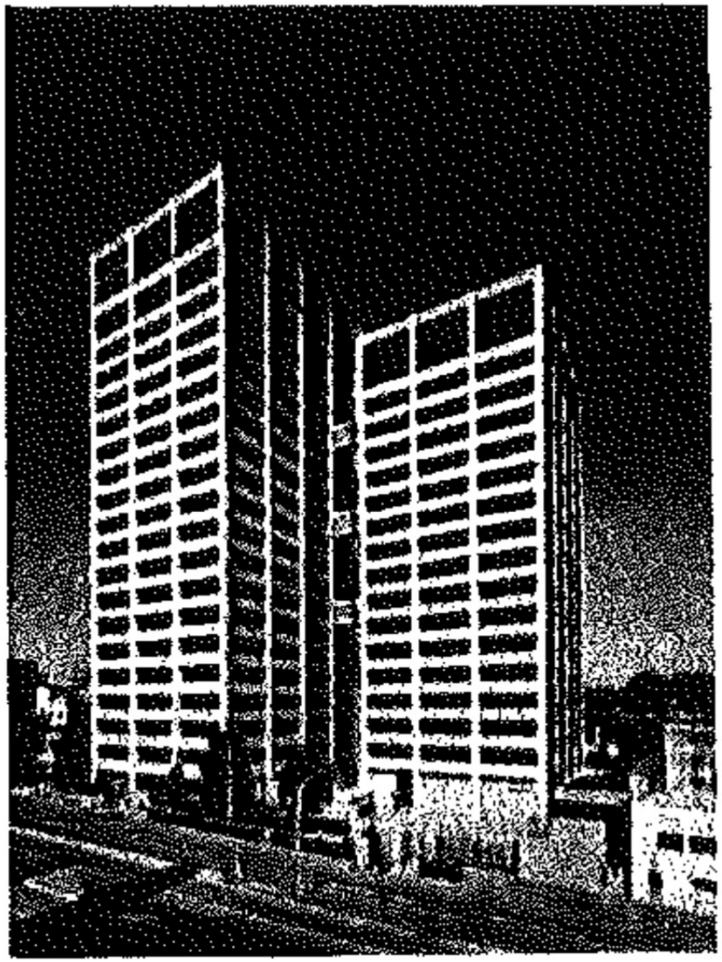


FIG. 8—*External appearance (the building on the right).*

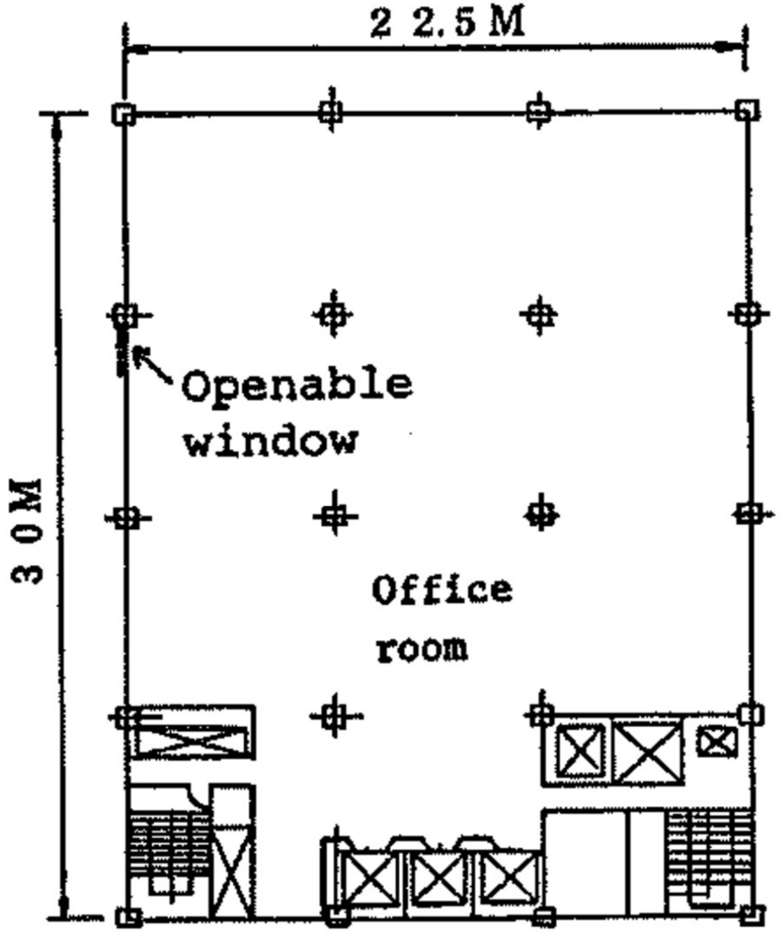


FIG. 9—*Typical floor of Building B.*

Measurement Results for Building B

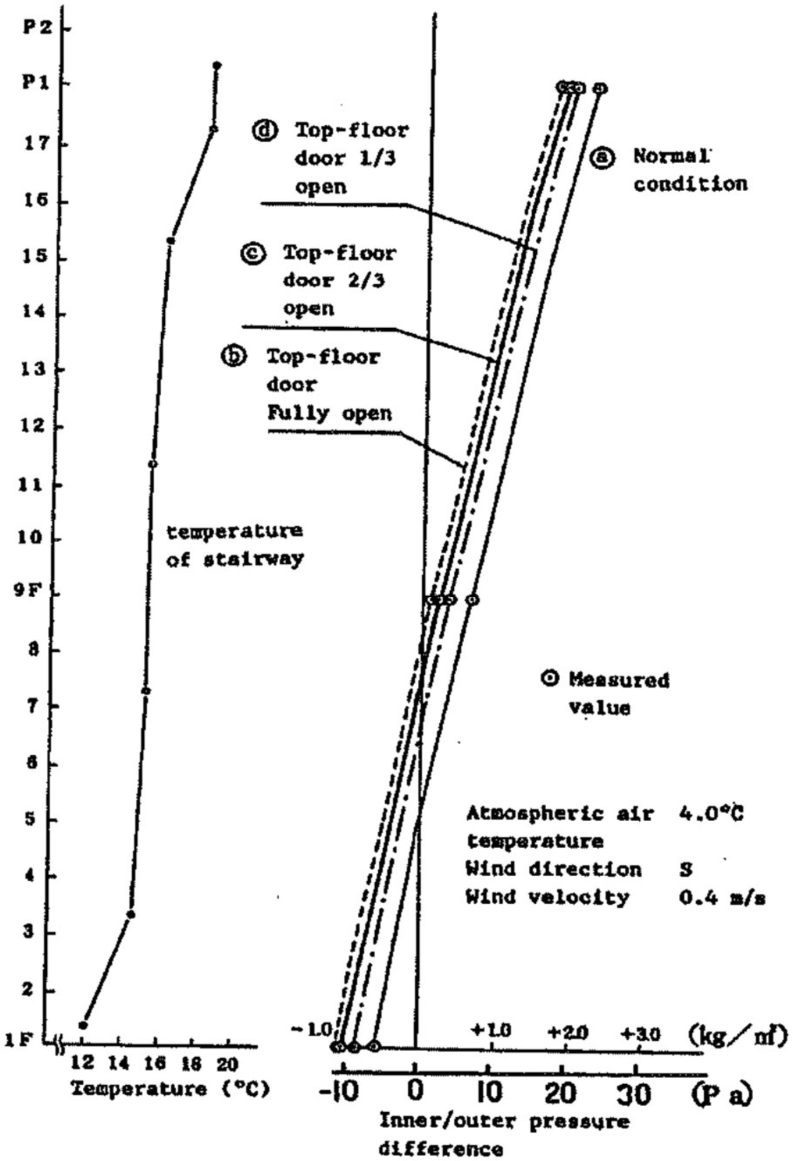


FIG. 10—*Measured result of Building B.*

$$5.27(\alpha A)_G - 12.24(\alpha A)_T = 4.00 \quad \cdots\cdots (7)$$

$$5.07(\alpha A)_G - 19.66(\alpha A)_T = 2.82 \quad \cdots\cdots (8)$$

$$4.69(\alpha A)_G - 28.26(\alpha A)_T = 1.85 \quad \cdots\cdots (9)$$

- αA_T can be calculated by these equations.

Outline of Building C

- Super-high-rise office building of 55 floors with steel structure and metal curtain walls.

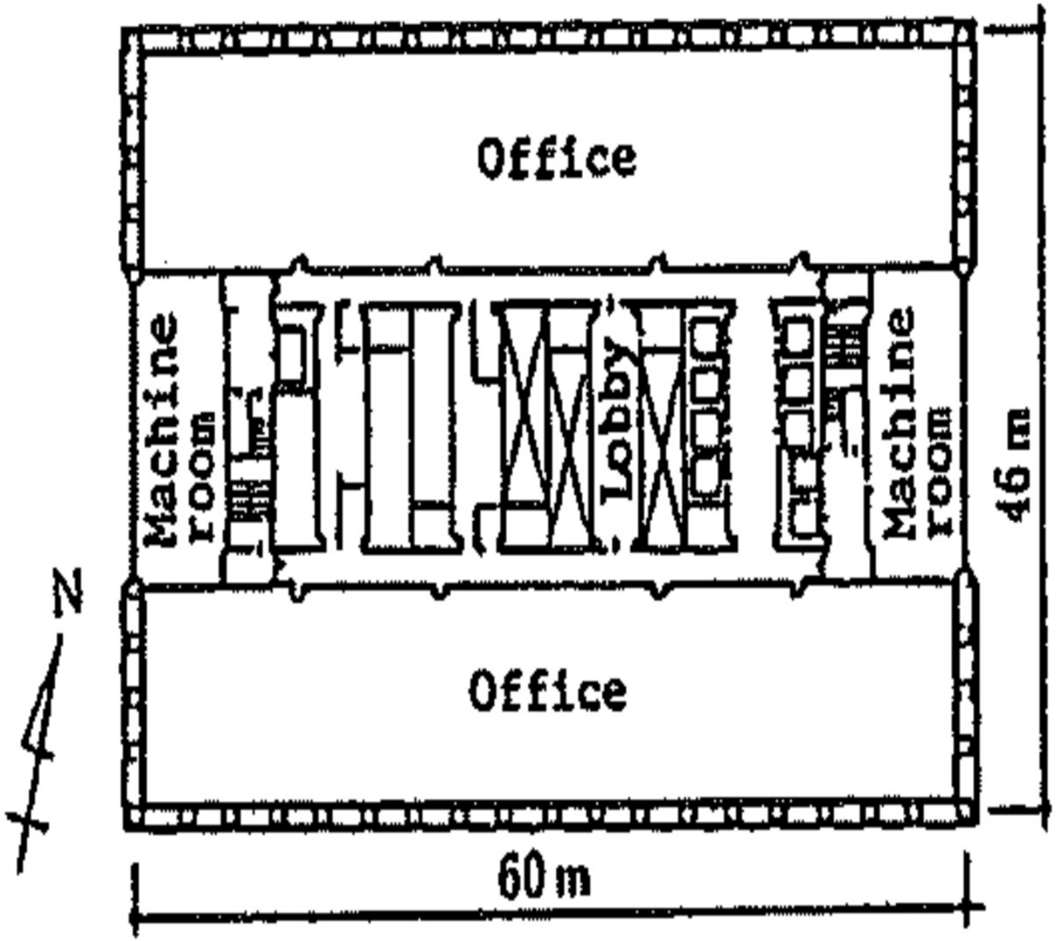


FIG. 11—*Plan of typical floor of Building C.*

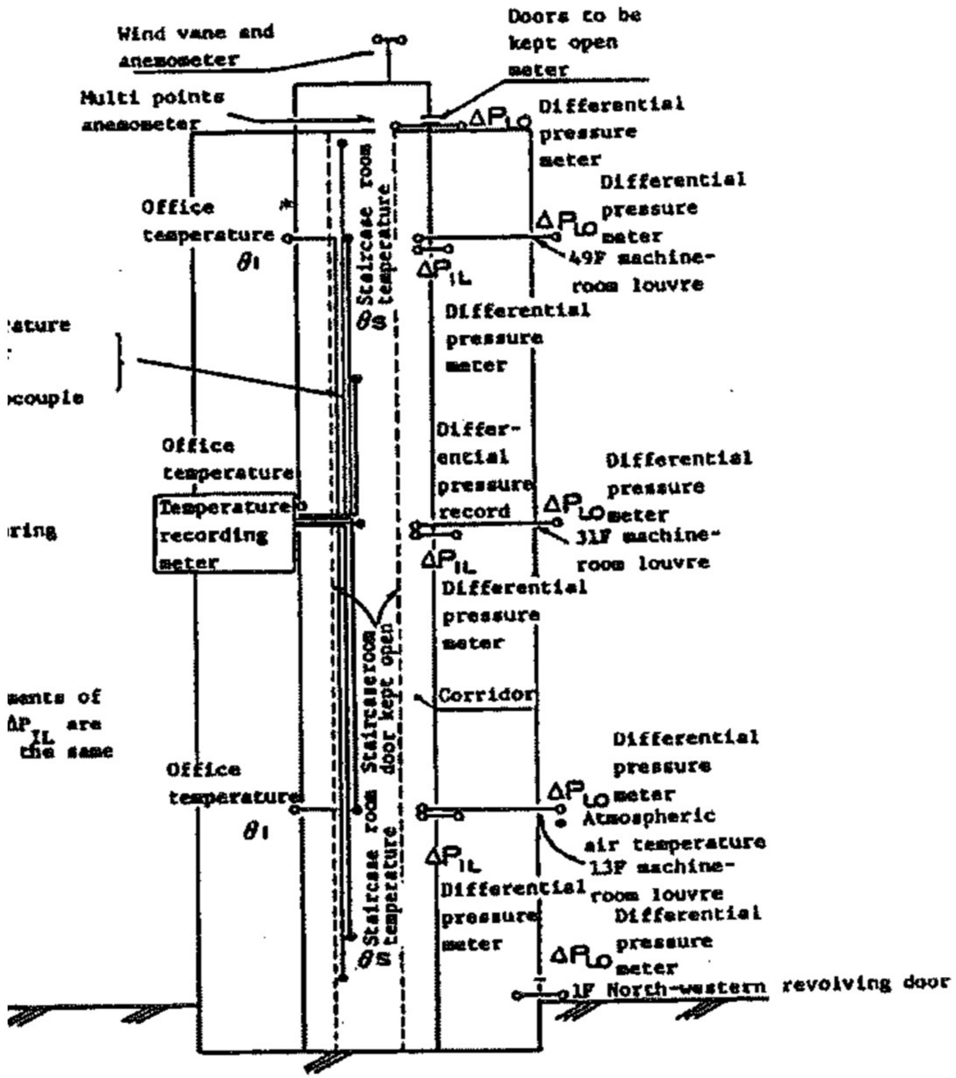


FIG. 12—*Measuring instrument layout diagram of Building C.*

Measurement Results for Building C

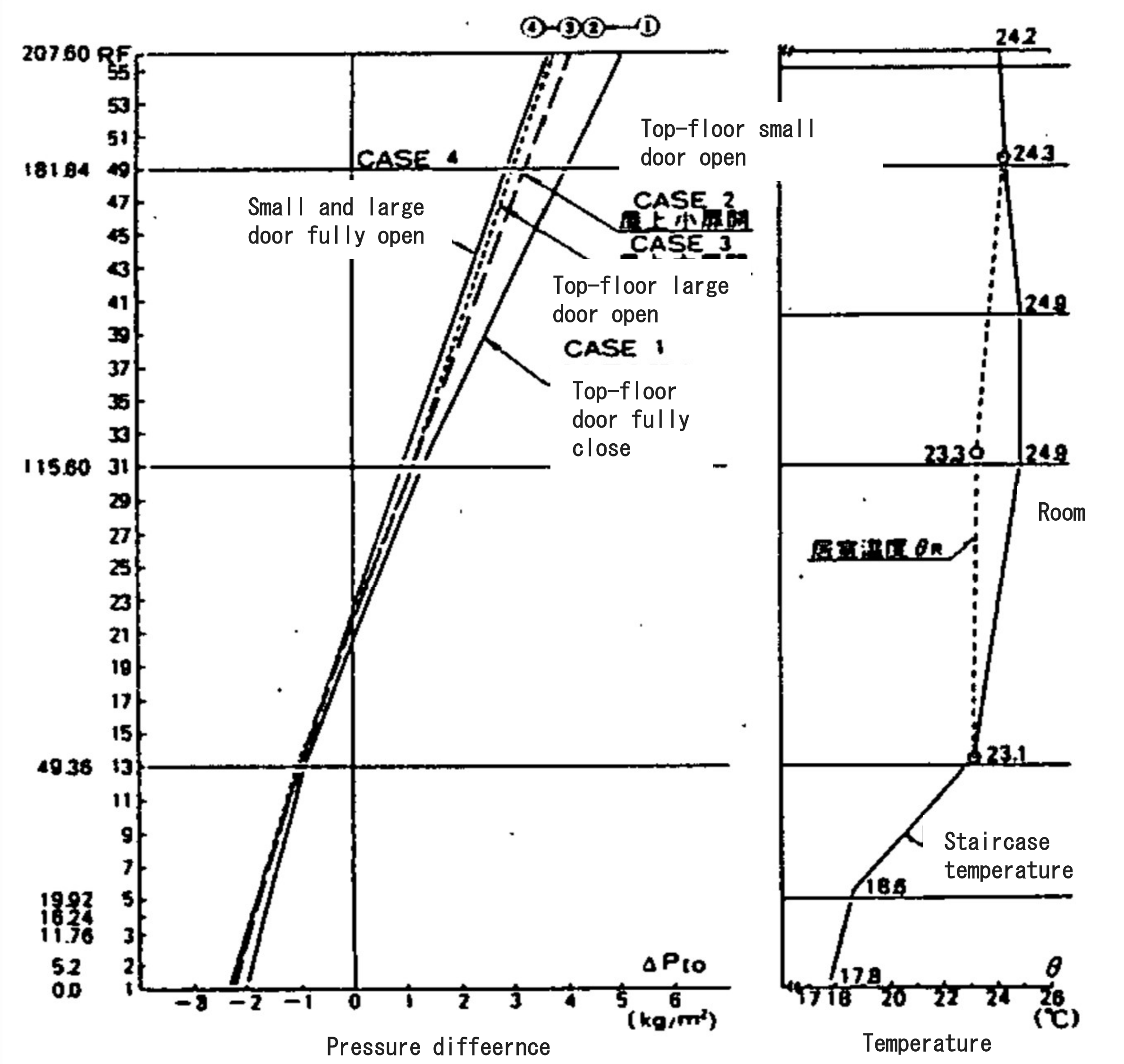


FIG.-21 Pressure fluctuations due to top-floor entrance/exit door kept open

CASE 2 より

$$14.55(\alpha A)_G - 127.16(\alpha A)_T - 9.75(\alpha A)_R = 13.22 \quad \cdots\cdots(12)$$

CASE 3 より

$$14.57(\alpha A)_G - 118.91(\alpha A)_T - 9.36(\alpha A)_R = 15.63 \quad \cdots\cdots(13)$$

CASE 4 より

$$14.77(\alpha A)_G - 107.59(\alpha A)_T - 9.16(\alpha A)_R = 18.54 \quad \cdots\cdots(14)$$

- αA_T can be calculated by these equations.

Measurement Results for Airtightness of Exterior Walls

- Based on the measurements, airtightness of exterior walls are summarized as below.

Measured Airtightness of Exterior Walls

Building type	Equivalent Opening Area	
8 Floors, RC Structure, Aluminum Sash, Sliding Window	$0.5\ cm^2/m^2$	Tight
RC Structure, 9 Floors, Steel Sash, Fixed Window	$0.8\ cm^2/m^2$	Tight
Steel Structure, 55 Floors, Metal Curtain Wall, Fixed Window	$1.5\ cm^2/m^2$	Average
Steel Structure, 17 Floors, Precast Concrete, Steel Sash, Fixed Window	$2.8\ cm^2/m^2$	Loose

Categories of Airtightness of Exterior Walls

- Based on the measurements, airtightness of exterior walls are categorized as below.

Categories of Airtightness of Exterior Walls

Cast-in-place RC ·· ··· ···	Tight 、Average
Metal Curtain Wall ··· ··· ···	Average 、Loose
Precast Concrete Curtain Wall ···	Loose

Tight: Around 0.5 cm_2/m_2 or smaller

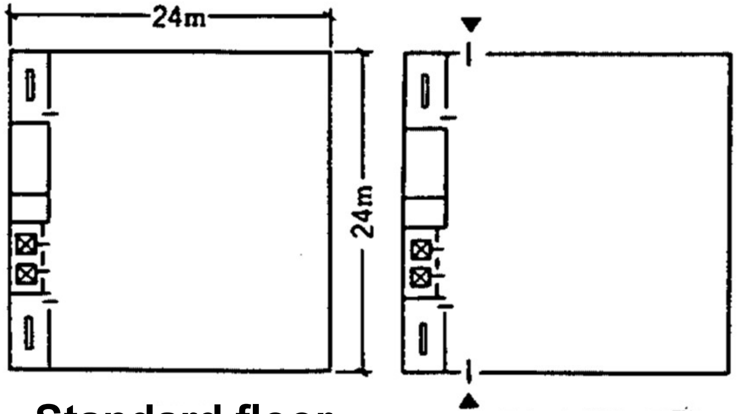
Average: Around 1.0 cm_2/m_2

Loose: Around 2.0 cm_2/m_2 or larger

3. Guideline for amount of air leakage at exterior walls made by Architectural Institute of Japan (AIJ)

Plans for Model Buildings A, B and C

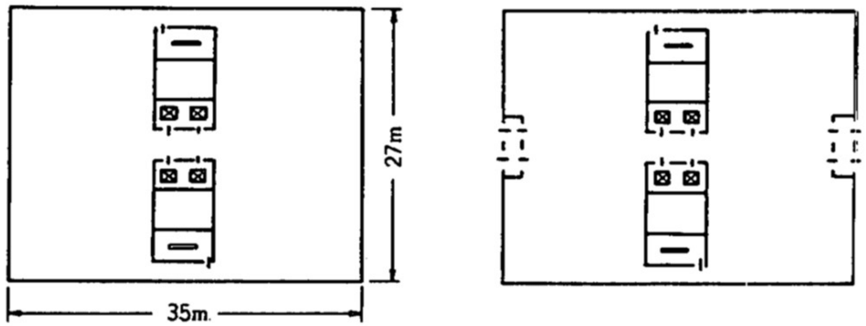
Calculated amount of air leakage at exterior walls for 3 model buildings



Standard floor

Entrance floor

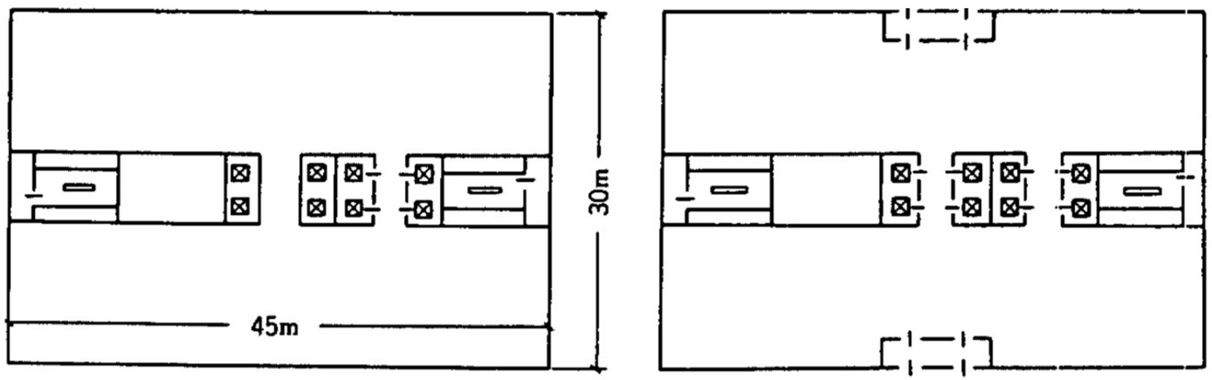
Building A (Low-rise building)



Standard floor

Entrance floor

Building B (Middle-rise building)



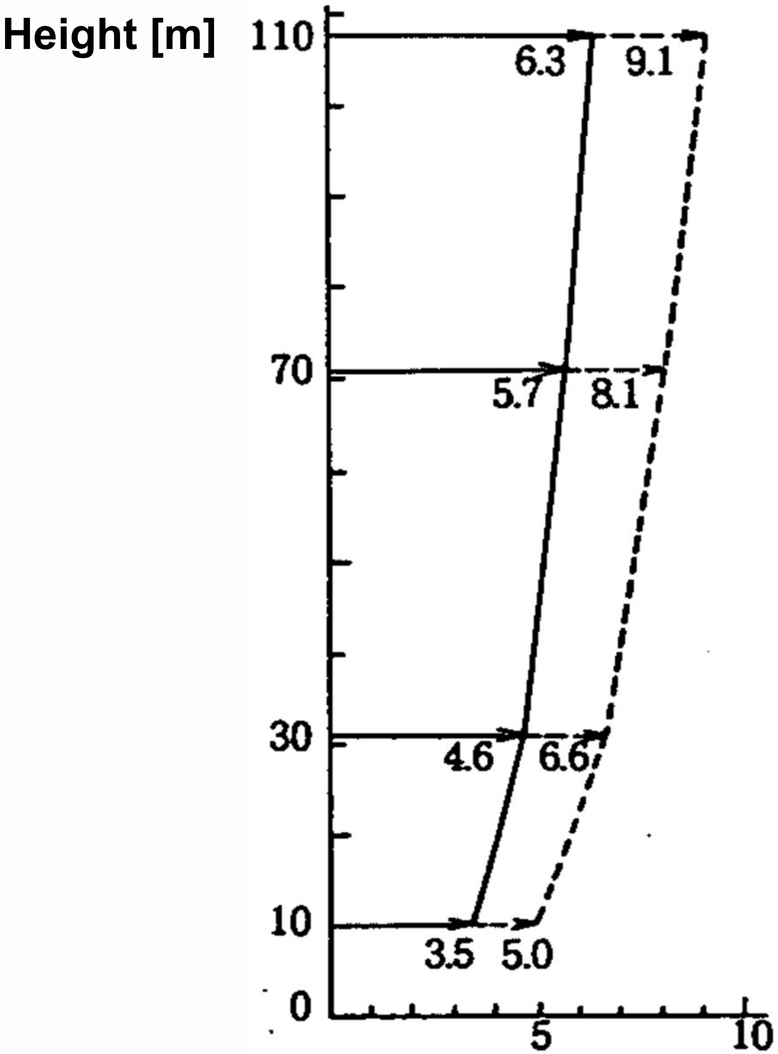
Standard floor

Entrance floor

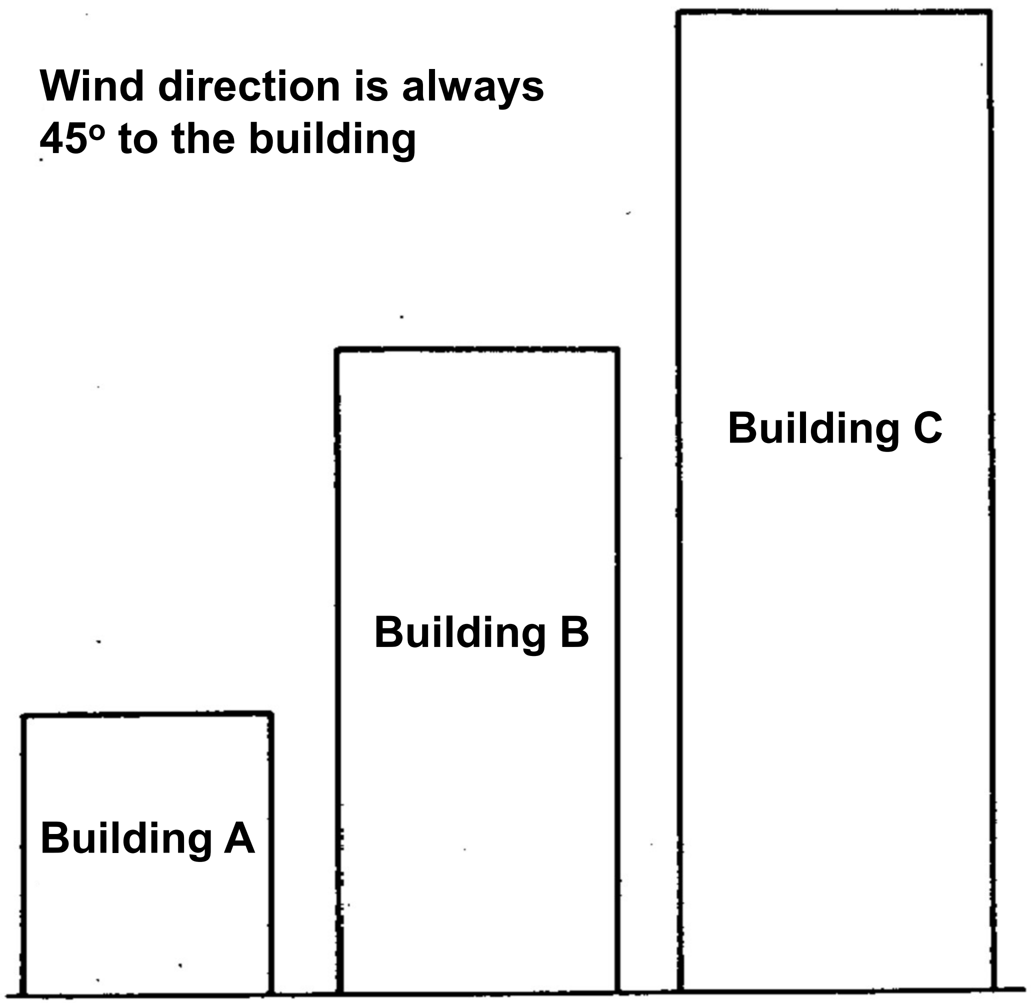
Building C (High-rise building)

Wind Velocity Setting for Simulations

- Vertical wind profile was assumed for 3 model buildings.



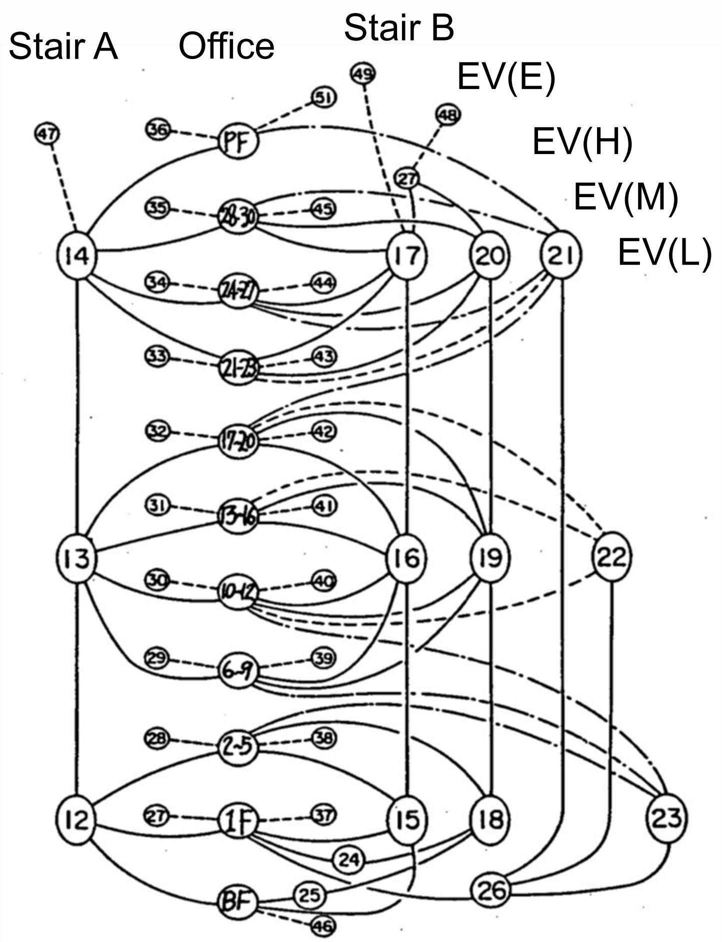
Wind velocity (m/s)



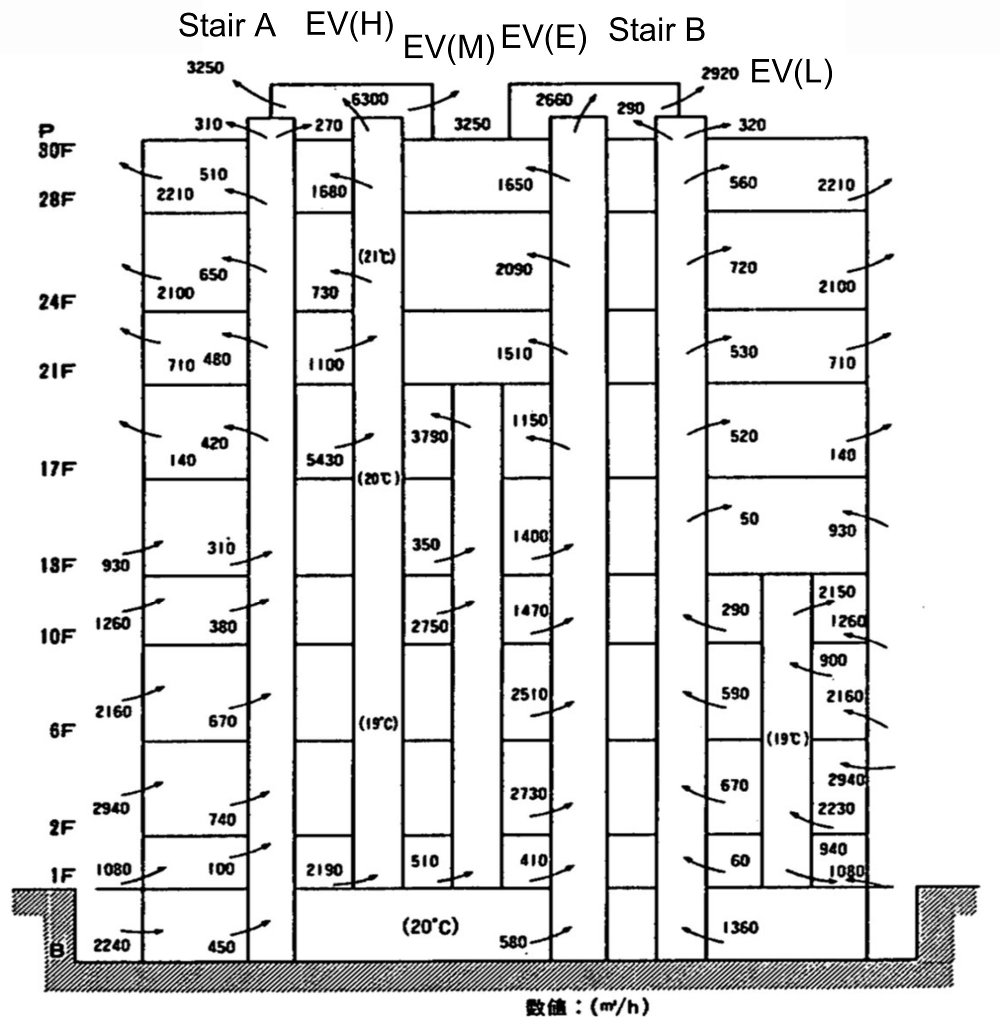
Scale of model buildings

Airflow Network Model for Building C

- Air leakage at exterior walls are calculated using airflow network model.



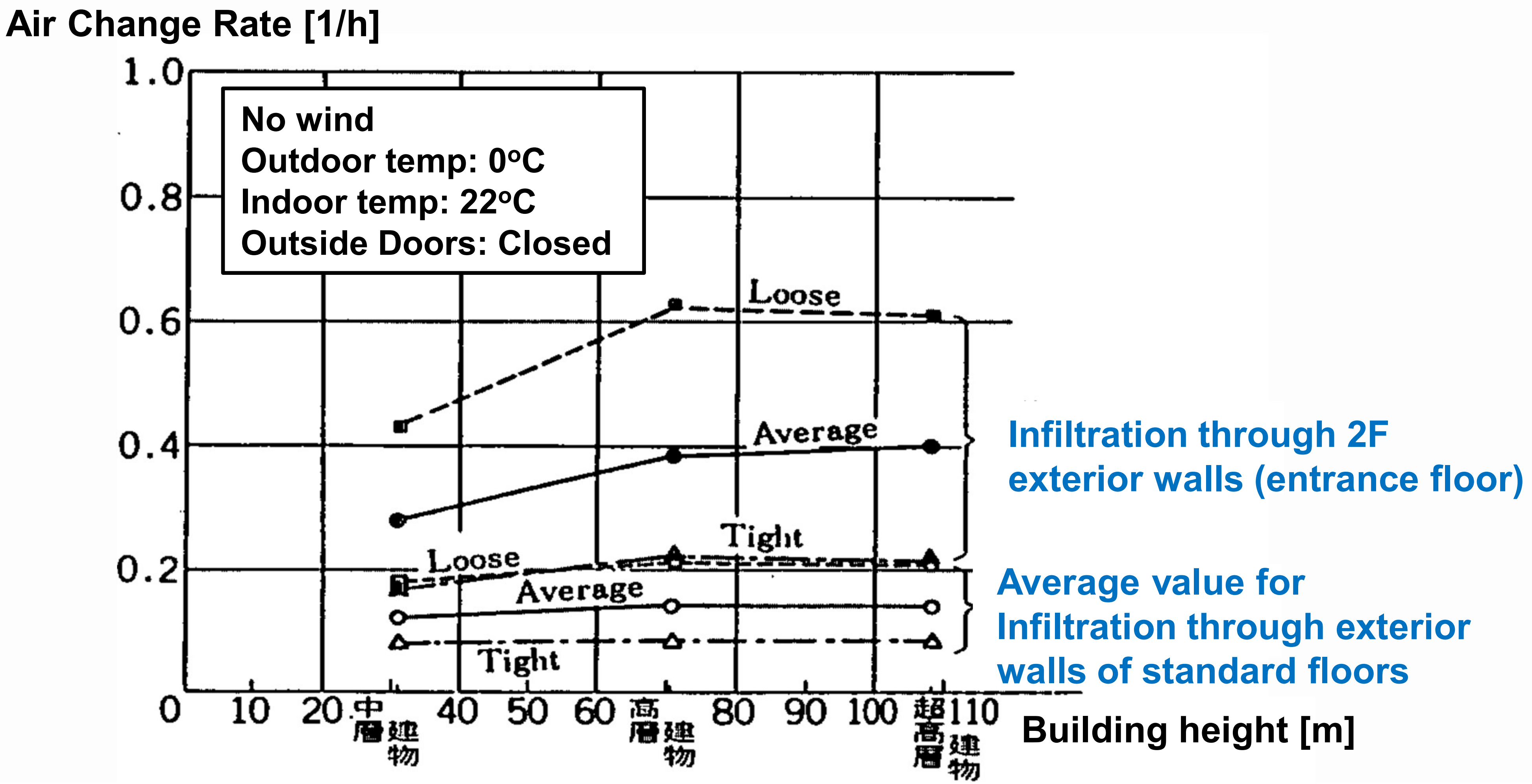
Airflow network model for Building C



Calculated results of air movement in Building C when there is no wind

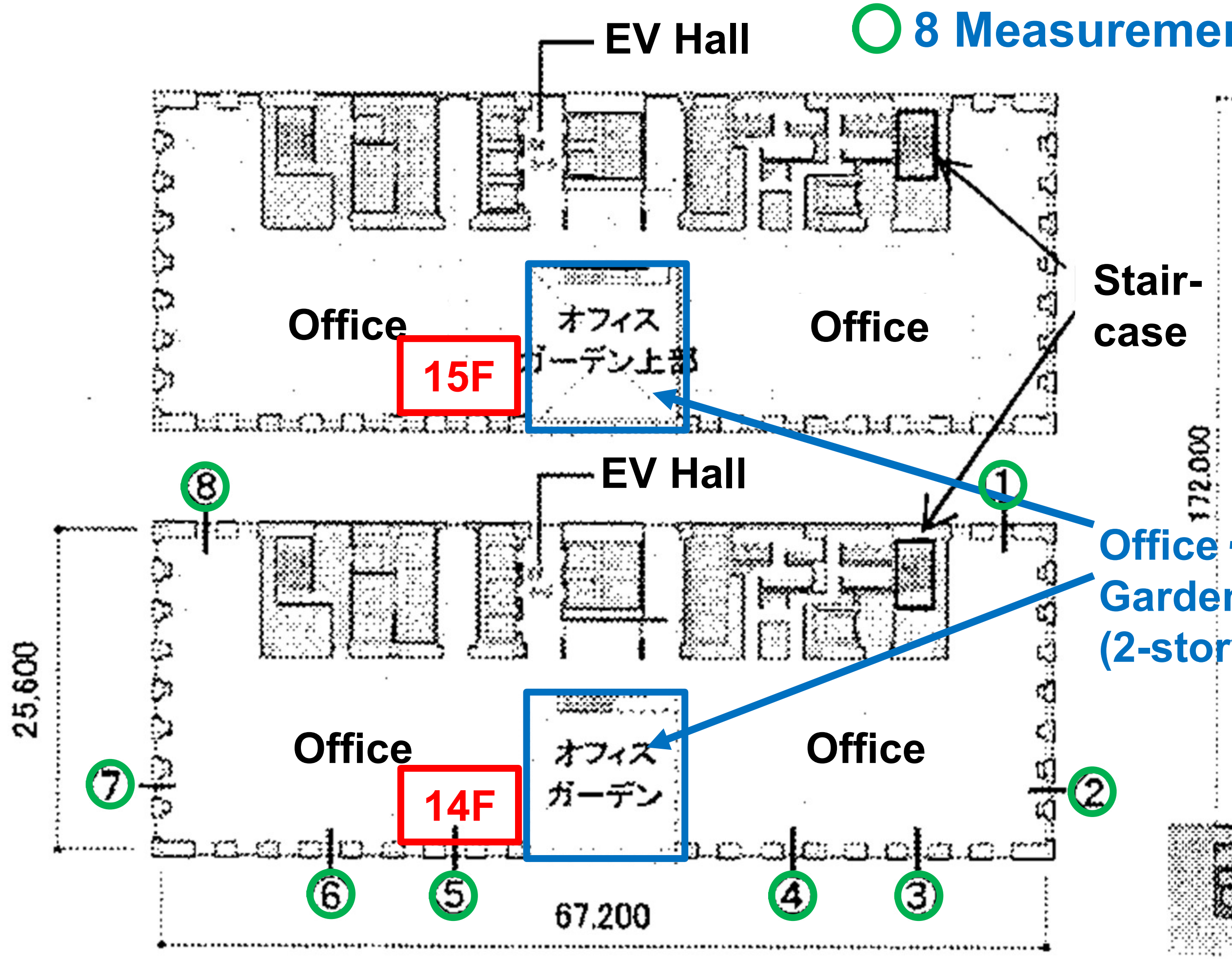
Air Change Rate by Infiltration through Exterior Walls of Standard Floors

- Infiltration through exterior walls for standard floors was evaluated by simulation.
- Results were summarized as Guideline for Calculating Cooling/Heating Loads of Society of Heating, Air-conditioning and Sanitary Engineers of Japan (SHASE).

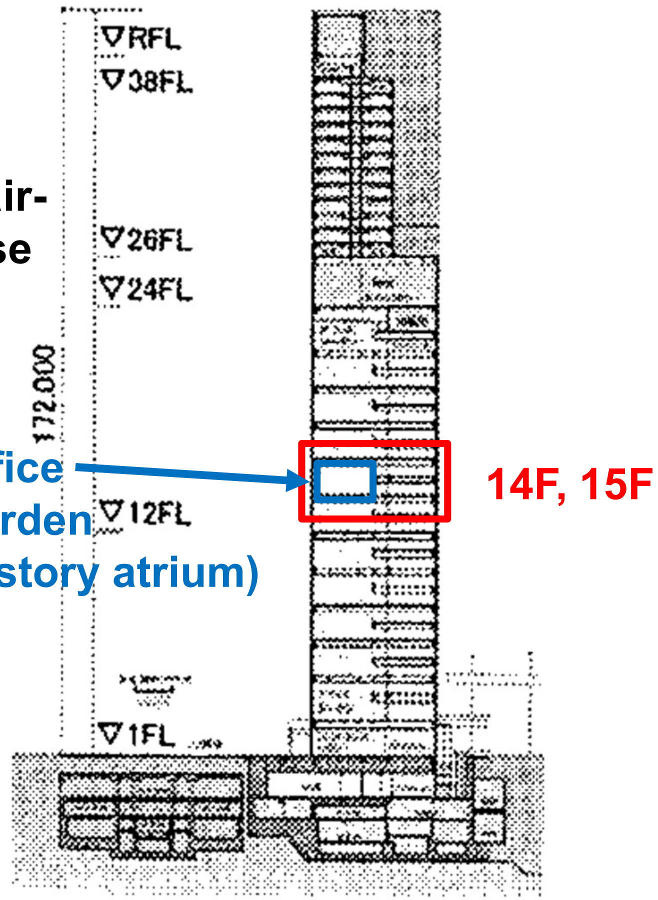


4. Method to measure the airtightness of the exterior walls using individual air-conditioning systems

Outline of Measured High-rise Building

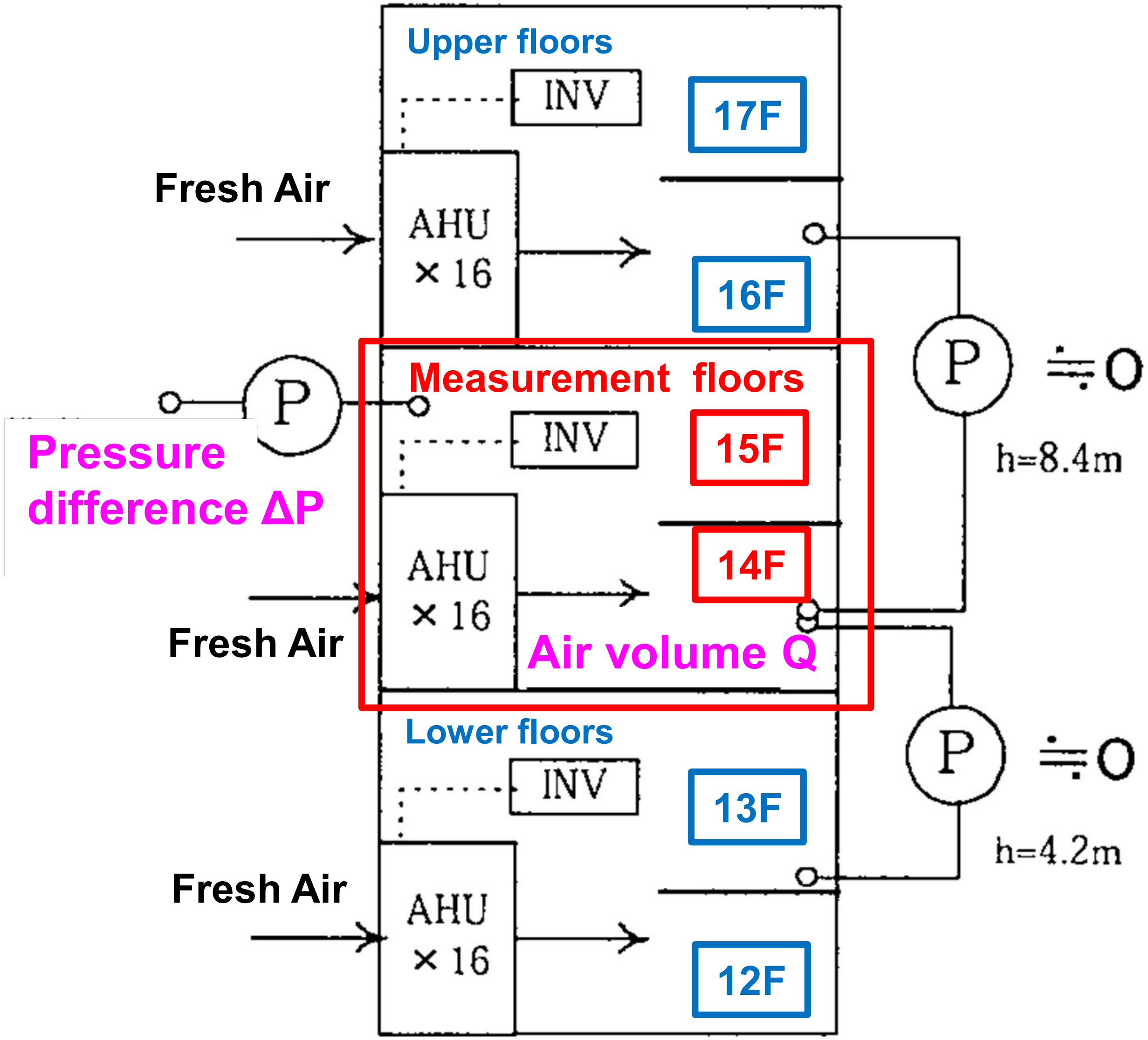


Plan of the standard floors (2 stories)



Section of the building

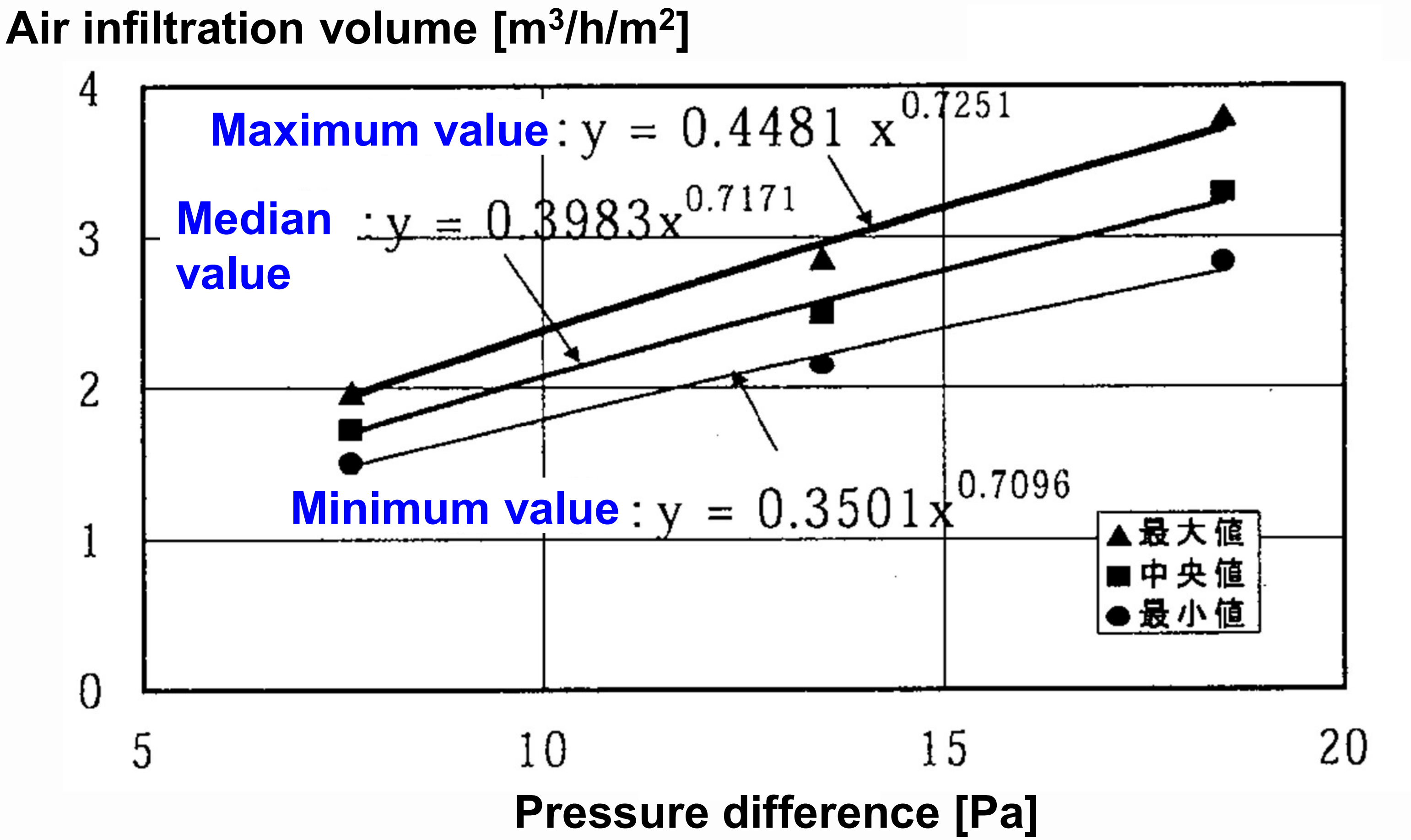
Outline of Pressurization System



- Pressurized air volume Q and pressure difference ΔP were measured by changing Q by controlling AHUs.
- Pressure difference between measurement floors and upper/lower floors were controlled to be nearly zero.

Pressure Difference vs. Air Infiltration Volume

- Pressure difference vs. air infiltration volume was clarified by this measurement.
- The results are equivalent to the airtightness of exterior walls of 1.25 to 1.67 cm²/m² ("Average").

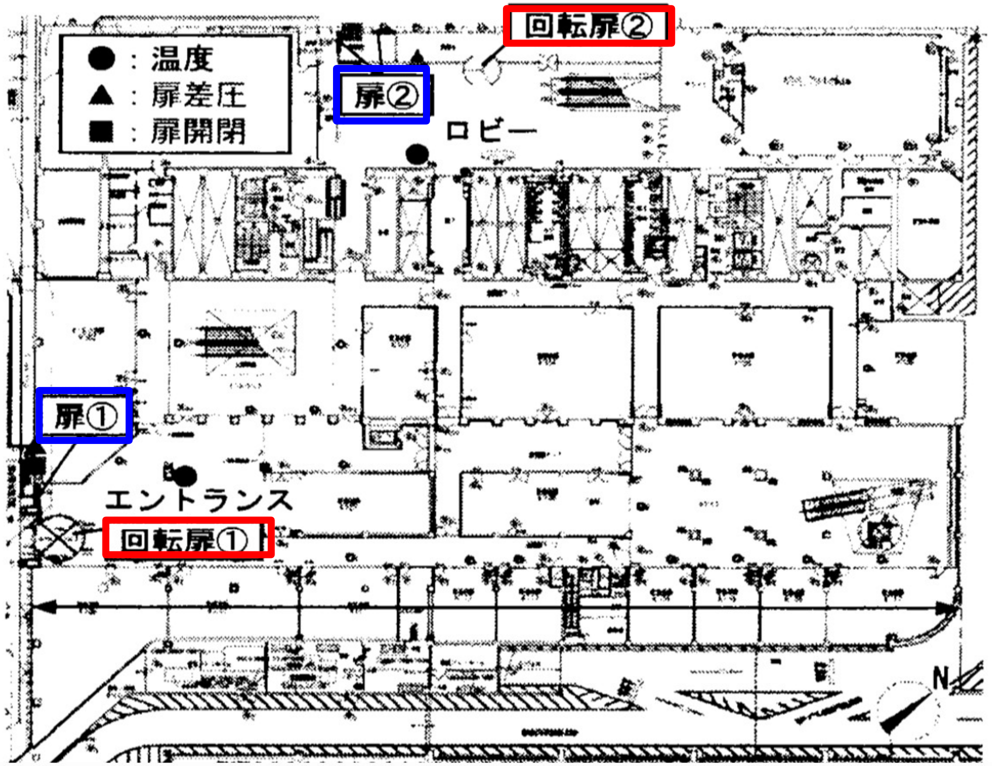


5. Measurements in a high-rise building for outdoor air volumes and heating loads through entrance doors in the winter

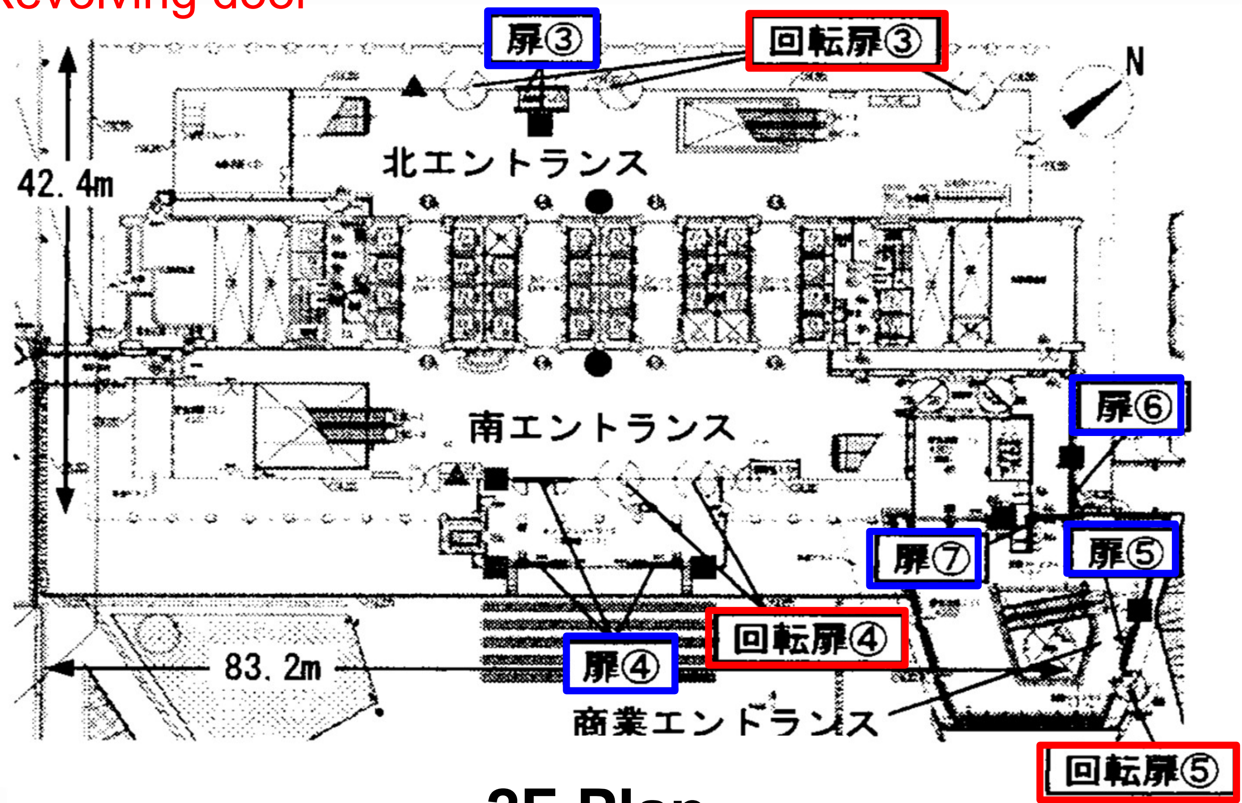
Outline of the Measurement

- Outdoor air volumes and heating loads through entrance doors were measured in a high-rise building in the winter (37 stories and 147m high).
- We compare the case when both automatic and revolving doors were normally operated and the case when opening doors were always used.
- Opening status of doors, pressure differences at entrance doors were measured.

Automatic door　Revolving door

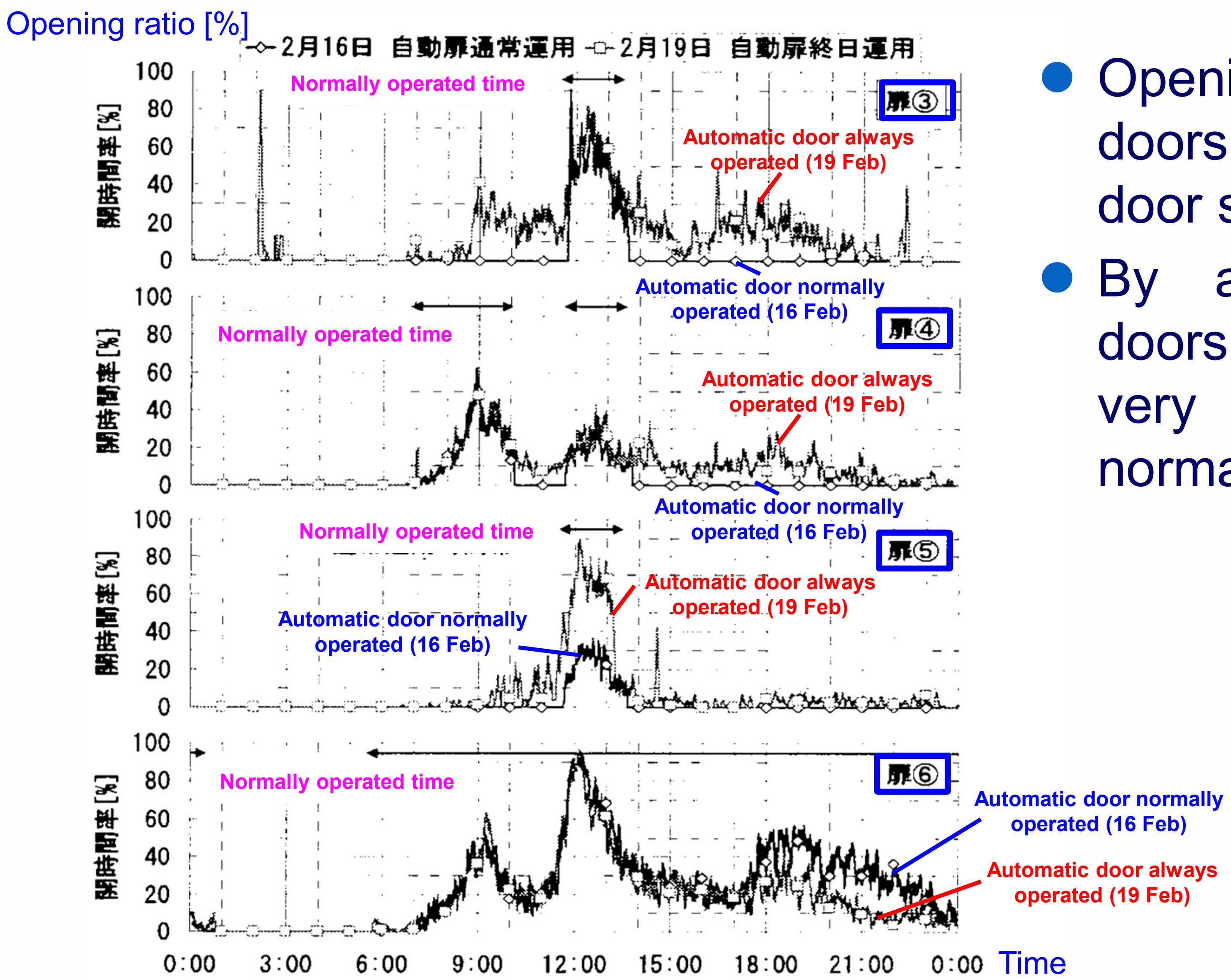


1F Plan



2F Plan

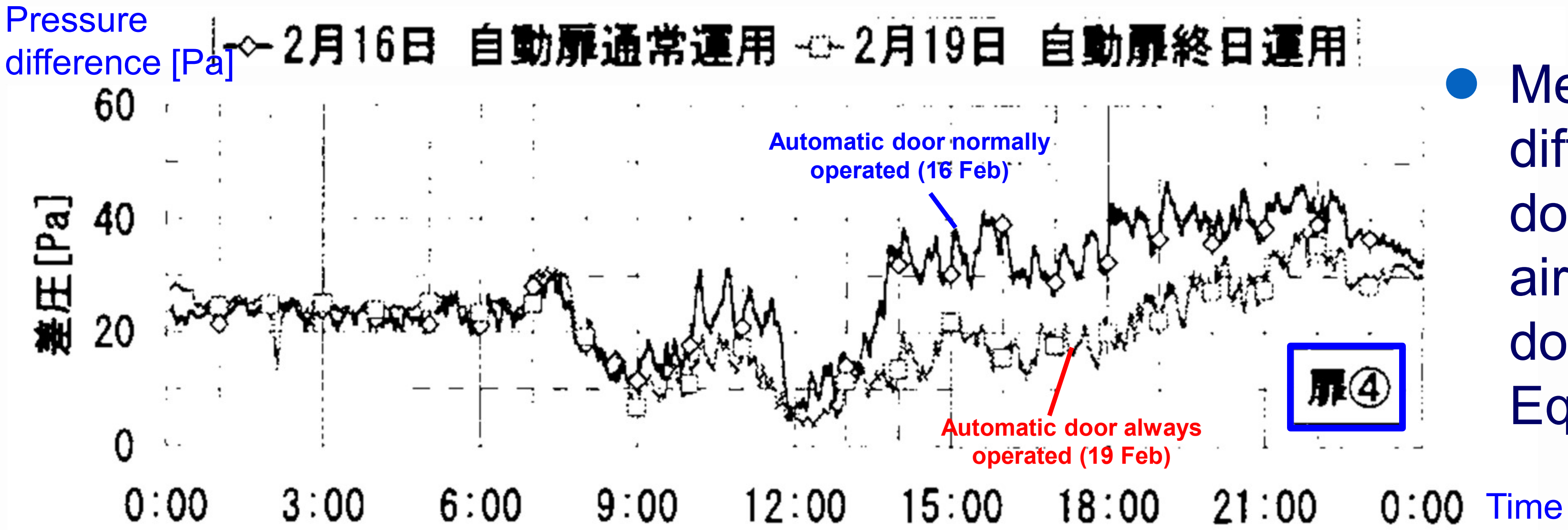
Measured Results for Opening Ratios for Entrance Doors



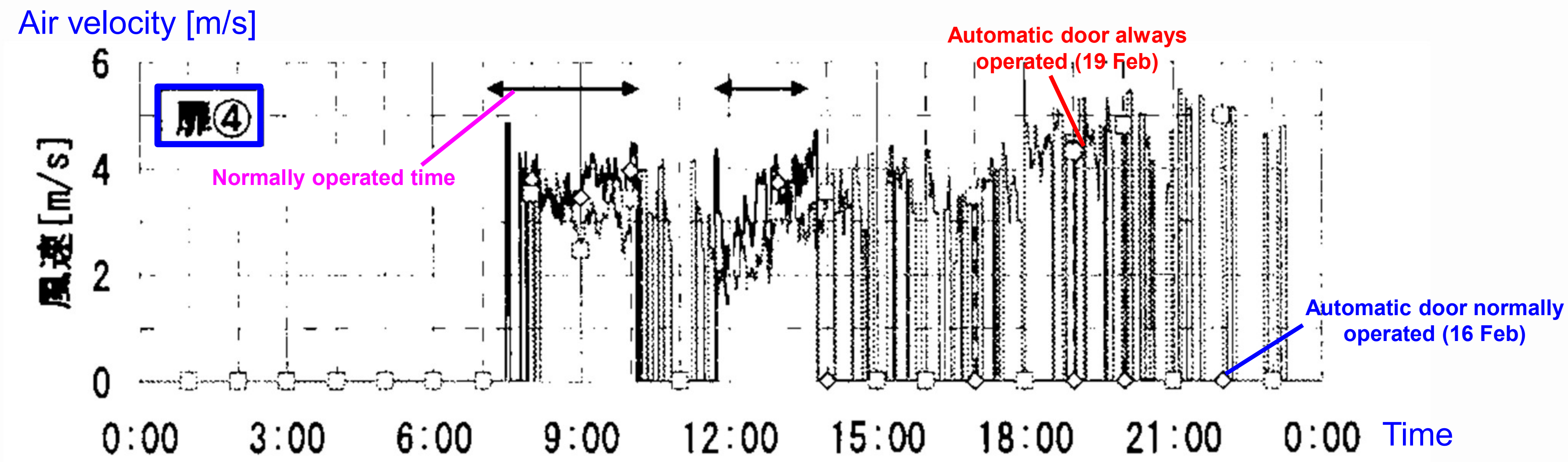
Measured Opening Ratio for Entrance Doors

- Opening ratios for entrance doors were measured using door sensors.
- By always using automatic doors, opening ratios became very large compared to the normally operated case.

Measured Pressure Difference and Air Velocity at Entrance Doors



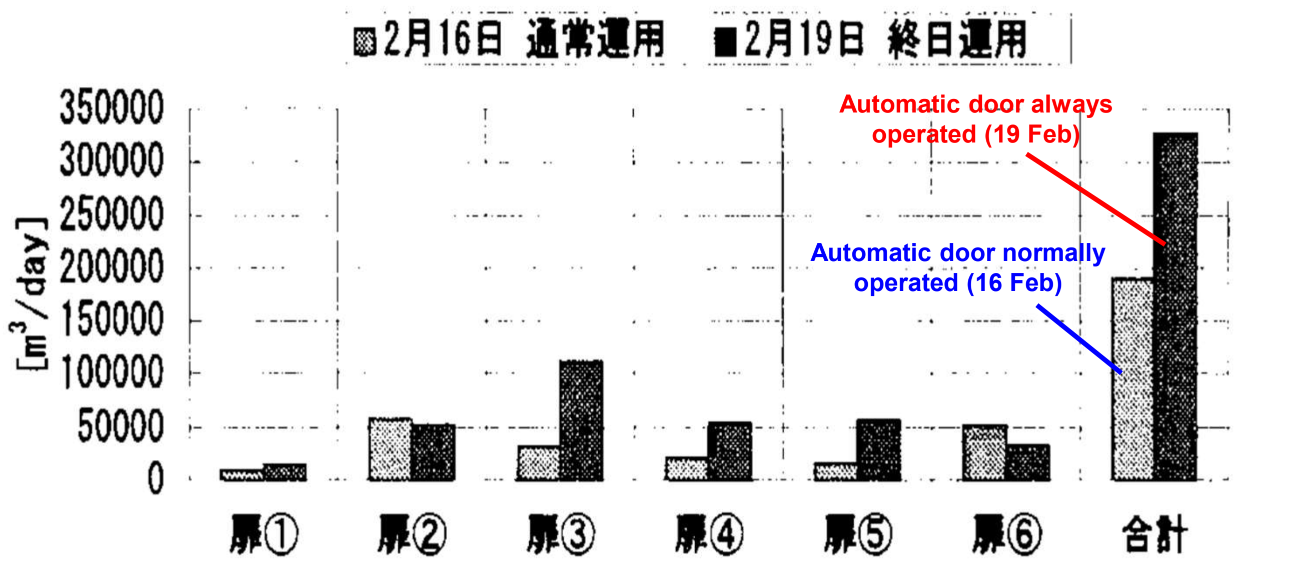
Measured Pressure Difference at Entrance Door No. 4



Estimated Air Velocity at Entrance Door No. 4

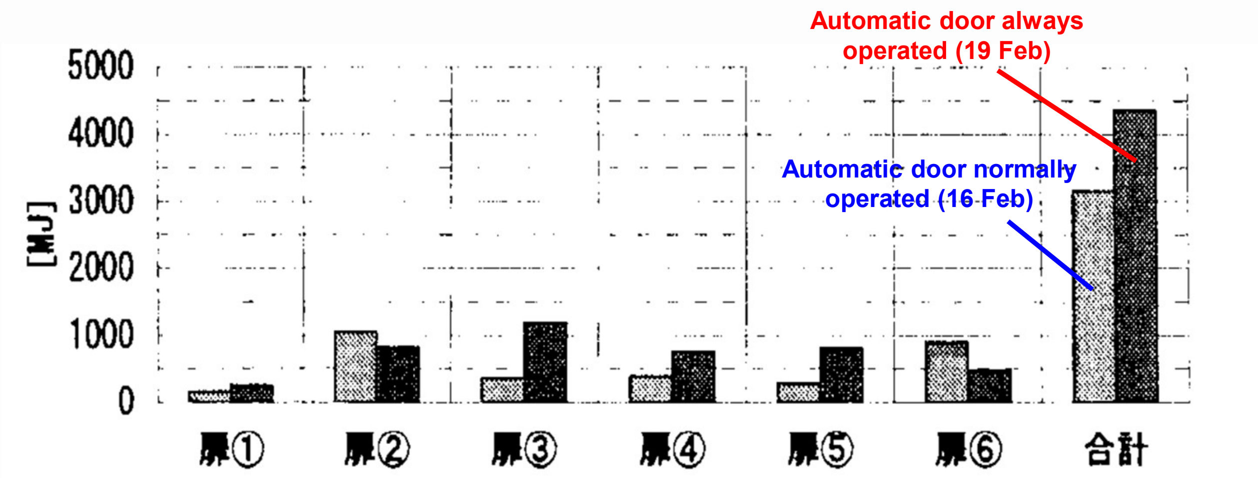
- Measured pressure difference at entrance doors can be converted to air velocity at the entrance doors using Bernoulli Equation.

Accumulated Daily Outdoor Air Volume & Heating Load through Entrance Doors



Accumulated daily outdoor air volume through entrance doors

- Accumulated outdoor air volume through entrance doors became large when automatic doors were used for a long time.



Accumulated daily heating load through entrance doors

- Accumulated heating loads became also large when automatic doors were used for a long time.
- Revolving doors are effective to reduce heating loads in the winter.

6. Conclusions

Conclusions

- A measurement method of airtightness that uses buoyancy caused by stack effect in a high-rise building was introduced.
- Based on the measurements, airtightness of different types of exterior walls were analyzed and categorized.
- We calculated the amount of air leakage at the exterior walls of 3 model buildings (low-rise, middle-rise and high-rise buildings). Results were summarized as Guideline for Calculating Cooling/Heating Loads of SHASE.
- Another method to measure the airtightness of exterior walls using individual air-conditioning systems for each floor was also introduced and measurement results were discussed.
- Considering the large impacts of stack effect, measurement results for outdoor air volumes entering through entrance doors and resulting heating loads in a high-rise building in the winter were also discussed.
- Air volume infiltrated through entrance doors in high-rise buildings is very large especially in winter and it's important to make the lower part of the building airtight to reduce heating loads caused by air entering through entrance doors.

References (1)

1. HAYAKAWA, S. and S. TOGARI. 1990. “Simple Test Method for Evaluating Exterior Wall Airtightness of Tall Office Buildings” Air Change Rate and Airtightness in Buildings (STP: 1067), American Society of Testing and Materials (ASTM), 231-245.
2. HAYAKAWA, S. and S. TOGARI. 1988. “Study on the Stack Effect of Tall Office Buildings (Part 1) Pressure Distribution in Tall Buildings Caused by the Stack Effect and Solutions of Troublesome Problems” Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 387, pp.42-52 (In Japanese).
3. HAYAKAWA, S. and S. TOGARI. 1989. “Study on the Stack Effect of Tall Office Buildings (Part 2) Airtightness of Main Doors and Exterior Walls” Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 402, pp.9-18 (In Japanese).
4. HAYAKAWA, S. and S. TOGARI. 1990. “Study on the Stack Effect of Tall Office Buildings (Part 3) The Evaluation of Infiltration Air Rates Caused by Stack Effect and Wind for Tall Buildings” Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 407, pp.47-56 (In Japanese).

References (2)

5. MIURA, K., M. HIRAOKA, and Y. TAKEMASA. 2003. “A Study of Air-Conditioning System utilizing Natural Ventilation by Wind Pressure in a High-rise Building (Part 2) Measurement of Airtightness of Exterior Walls before Completing Construction” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2003, pp.1097-1098 (In Japanese).
6. TAKEMASA, Y., M. KATOH, Y. TAKAHASHI, and Y. USHIKI. 2011. “Field Measurement of Stack Effect in a High-rise Building with Revolving Doors (Part 1) Outline of the Measurement and Thermal Environment at the Entrance” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2011, pp.735-736 (In Japanese).
7. KATOH, M. and Y. TAKEMASA, Y. TAKAHASHI, and Y. USHIKI. 2011 “Field Measurement of Stack Effect in a High-rise Building with Revolving Doors (Part 2) Usage and Pressure Difference of Doors and Estimation of Air Infiltration Rate and Heat Loss” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2011, pp.737-738 (In Japanese).

Thank you for your attention!