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Field Experiment on Ventilation Characteristics of a Large-Scale Wholesale Market Building

Kiyotaka DEGUCHI* Shuzo MURAKAMI** Shinsuke KATO** Takeo TAKAHASHI**

* College of Engineering,
Hosei University
Kajino-cho, Koganei-city,
Tokyo 184

** Institute of Industrial Science,
University of Tokyo
Roppongi, Minato-ku,
Tokyo 106

ABSTRACT

The ventilation characteristics of a large indoor space which is ventilated naturally are measured and analyzed by field tests. The huge room measured is a wholesale market 180m in length, 400m in breadth and 28m in height. The enclosure has many openings in the side walls totalling 2,140 m^2 and has three roof monitors for ventilation totalling 1,380 m^2 at the top of three gable roofs. The monitors are 3.2m wide where they protrude from the roof and they are 144m in length.

Although it is difficult to precisely measure the ventilation characteristics of such a huge space with field tests, we succeeded in evaluating air change rates and the wind pressure of the natural ventilation with sufficient accuracy. We were also able to estimate the ventilation efficiency in the large enclosure and evaluate the characteristics of air convection in the room.

The measured air change rate ranged from 1.5 to 7.9 ach for the outside wind velocity 2 to 5 m/s. The results of the field tests correspond rather well to those of wind tunnel tests which had been conducted before the construction of the wholesale market building.

Keywords: ***wind induced ventilation, roof monitor, large enclosure, air change rate, ventilation efficiency***

INTRODUCTION

It is rather difficult to measure ventilation characteristics of a room which is ventilated naturally, especially in the case of a large enclosure with many openings. For example, when tracer gas is used to evaluate the air change rate, it is diffucult to keep the tracer concentration uniform throughout the room and we are thus forced to estimate it with considerable error. Furthermore, when the air change rate is measured using air velocity at openings, we cannot expect that the velocity distribution and flow direction are uniform at all openings. A great number of anemometers are thus needed in order to measure accurately. In spite of these difficulties, ventilation engineers are often forced in pratical situations to measure and assess the ventilation characteristics of a large enclosure with many openings.

In this paper, we present the results of field measurement of the ventilation characteristics of a naturally ventilated large indoor space with many openings. The field measurements are compared with those of a wind tunnel test (Murakami, Kato and Takahashi, 1986) and with a numerical simulation (Murakami, Kato et al., 1986) which were conducted before the construction of this large indoor space.

OUTLINE OF MEASURED SPACE

The large indoor space of which the ventilation characteristics were investigated is a wholesale market building located at Ohta-ku, Tokyo (Fig. 1 - Fig. 4). This market consists of two parts: one is comprised of three blocks for vegetable and fruit, the other is an area for fish.

The size of the vegetable and fruit blocks is 180m by 400m in plan and 28m in height. This has many openings in the side walls totalling 2,140 m^2 (Table 1). The vegetable and fruit blocks are roofed by three large gable roofs, A, B and C respectively. The gable roof of each block is 108m by 144m (Fig. 3). The fish area, measuring 83m wide by 180m long, is roofed independently.

Roof monitors having total open area of 1380 m^2 (Fig. 5 and 6) are set on the roof in the north-south direction for ventilation, one for each of the gable roofs.

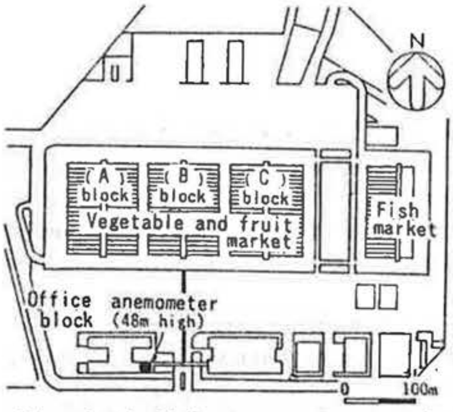


Fig. 1 Building arrangement of wholesale market (Ohta-ku, Tokyo)

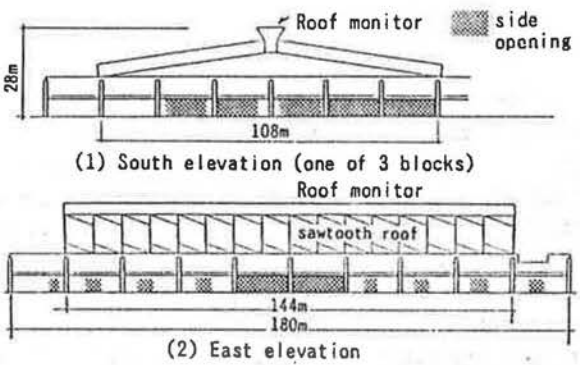


Fig. 2 Elevations of one vegetable and fruit market

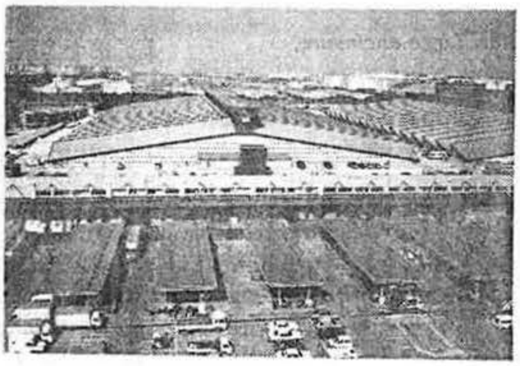


Fig. 3 Exterior of vegetable and fruit blocks

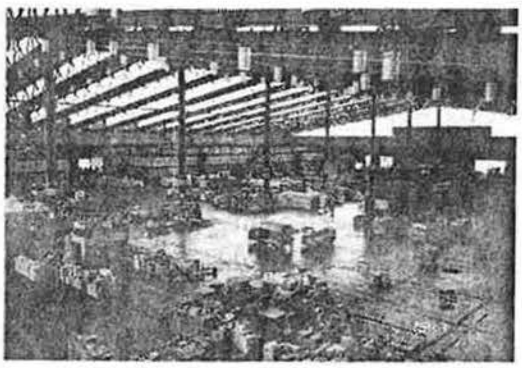


Fig. 4 Interior of vegetable and fruit blocks

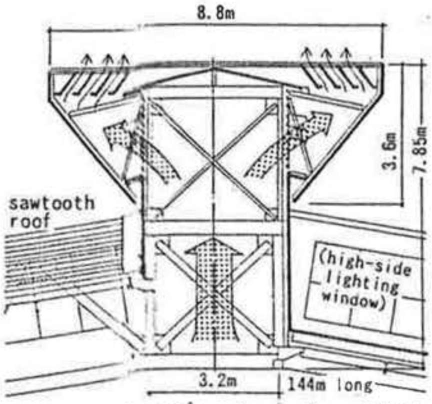


Fig. 5 Section of roof monitor for ventilation

Table 1 Openings in side walls

(1) Vegetable and fruit market (total of blocks A, B and C)

	orientation South	North	West	East	Total
Area of side opening	720 m²	840 m²	210 m²	410 m²	2 140 m²
Ratio open in summer	90 %	50%	85%	80 %	75%
Ratio open in winter	85 %	55%	90%	85 %	75%

(2) Fish market

	orientation South	North	West	East	Total
Area of side opening	320 m²	190 m²	210 m²	670 m²	1 400 m²
Ratio open in summer	70 %	100%	90%	40 %	60%
Ratio open in winter	25 %	70%	40%	55 %	50%

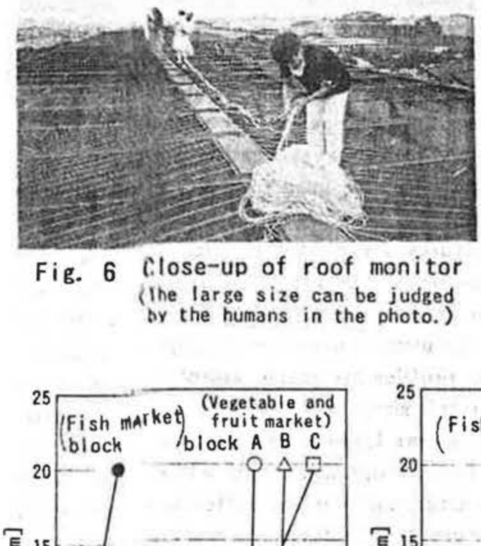


Fig. 6 Close-up of roof monitor
(The large size can be judged by the humans in the photo.)

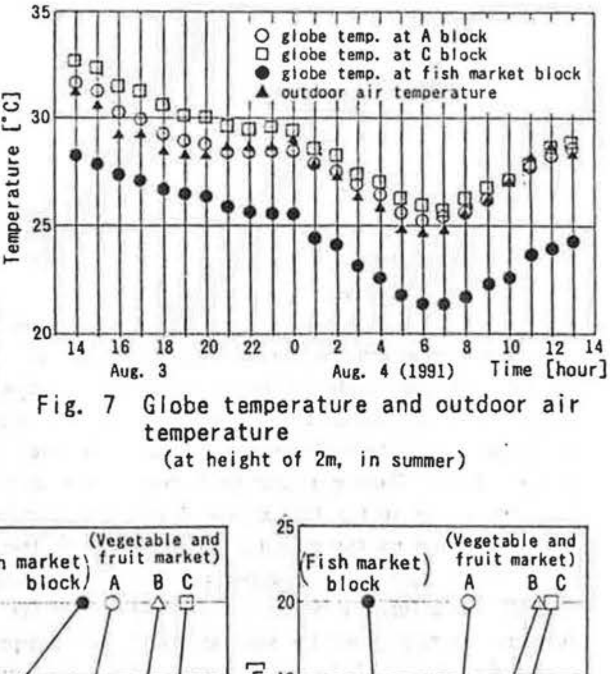


Fig. 7 Globe temperature and outdoor air temperature
(at height of 2m, in summer)

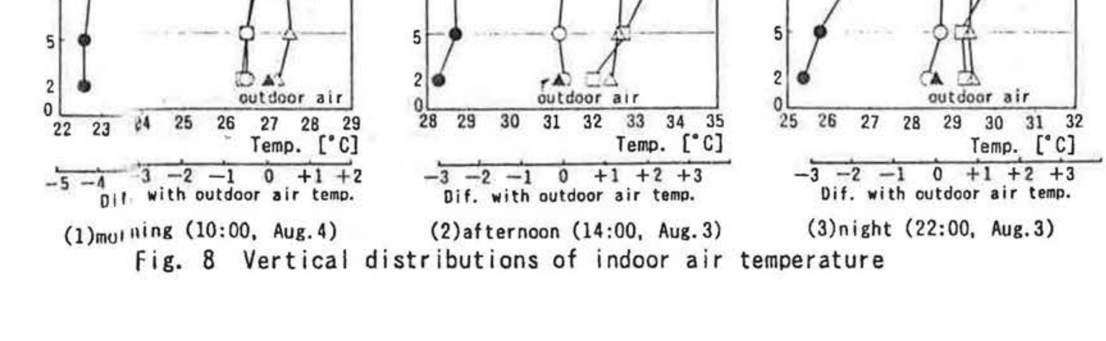


Fig. 8 Vertical distributions of indoor air temperature

METHOD OF MEASUREMENTS

In the field experiments, the indoor temperature, wind pressure, air change rate, and the characteristics of ventilation effectiveness were measured. Reference wind speed was measured by a three dimensional ultrasonic anemometer placed at a height of 48m on top of an adjoining office building block (Fig. 1). The measured wind speeds were changed to the equivalent wind speed at the height of the roof monitor, 28m high, following the vertical wind profile of power law of 1/7 exponent. Indoor and outdoor air temperatures were measured by C-C thermocouples. The vertical profile of the indoor air temperature was measured at the center of each block, and globe temperature (at 2m height) was also measured. The wall surface pressure of wind referenced to the indoor floor-level static pressure was measured by a differential pressure meter. The air change rates were measured by the tracer gas method using SF_6. The tracer gas was generated constantly and controlled by a mass flow meter. In some cases a tracer gas decay method was also used. Concentrations of SF_6 were measured at the roof monitors and at several points 2m in height in the indoor space. The wind speed of air flow through the roof monitors was also measured by thermister anemometers. These measurements were carried out both in summer (August, 1991) and in winter (March, 1992).

DISTRIBUTIONS OF INDOOR AIR TEMPERATURE

The results of air temperature measurement for summer are shown in Fig. 7 and Fig. 8. Fig. 7 shows the time history of globe temperatures and outdoor air temperatures, which were measured at a height of 2m from the floor. The globe temperatures in A and C blocks are almost the same as or a little higher than the outdoor air temperature. On the other hand, those in the fish market are 2-3 °C lower than the outdoor air temperature.

Since the roof is well insulated, the surface temperature of the ceiling is almost the same as the air temperature, and the globe temperature is also the same as the air temperature. The small difference betweeen indoor and outdoor air temperature may be caused by the high air change rate. In the fish market, the wet floor and plentiful ice used to cool fish result in an indoor air temperature lower than that of outdoors.

The vertical distributions of indoor air temperatures are shown in Fig. 8 (1)-(3). The temperature difference in the vertical direction increases in the afternoon (Fig. 8 (2)). The maximum temperature difference measured between heights of 2m and 20m was 3 °C in the fish market block. This is rather small compared with those usually observed in large enclosures. In block C and in the fish market block, the vertical profiles are rather complicated since the heat generated by the external cooling units of the retail shops is discharged directly into the large indoor space. The upper portion consequently shows higher temperatures, in particular during the afternoon when the cooling units are in full operation. In winter, the indoor temperature was almost the same as the outdoor temperarture and vertical differences were small.

A difference of 1 °C between indoor and outdoor temperatures corresponds to a wind pressure of 0.06 mmAq acting on the side openings, if a neutral zone is assumed to be located in the middle level (15m). This is estimated to be the equivalent of an air change rate of 3 ach (900 m^3/s), on the assumption that the opening area is 1500 m^2, and the coefficient of discharge at the opening is 0.6.

SURFACE WIND PRESSURE

The distributions of surface wind pressure are shown in Fig. 9. The reference point for static pressure is the center of the indoor floor of block A. Coefficients of wind pressure are normalized by the dynamic pressure at the height of the roof monitor. In the case of wind direction WNW, at points No. 2 and 3, the coefficients of wind pressure are 0.17 and 0.34 respectively. These positive values of pressure coefficient suggest that air flows into the space

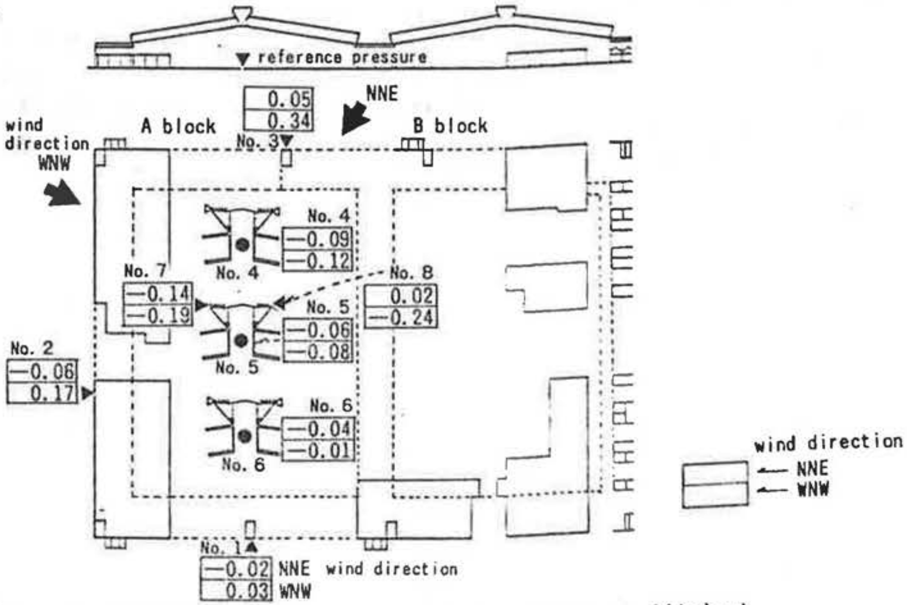


Fig. 9 Distribution of surface wind pressure coefficient
(refered to static pressure at floor of block A and normalized by the wind speed at roof monitor level)

effectively through the openings near these points. In the wind direction NNE, the values at points No. 2 and 3 are -0.06 and 0.05, so the side openings are not so effective to taking in air. The values of roof monitor points No. 4, 5 and 6 show negative values against the reference pressure on the floor, and the averages of No. 4, 5 and 6 are -0.07 in WNW and -0.06 in NNE wind direction. If it is assumed that this wind pressure at the monitor corresponds to the dynamic pressure at the monitor opening, the wind speed passing the monitor space compared to the outdoor air flow velocity may be estimated as 0.24, because $\sqrt{0.06} \fallingdotseq 0.24$. This velocity ratio of 0.24 roughly agrees with that measured by the wind speed in the monitor, as will be discussed later.

VENTILATION EFFICIENCY

An example of the concentration distributions of SF_6 used as tracer gas is shown in Fig. 10. The values shown in the figure are normalized by a reference concentration as follows:

$$C^* = C/Cs = C/(q/Qs) = C/(q/v \cdot A) \tag{1}$$

C^* :	normalized concentration	[-]
C :	measured concentration	[m³/m³]
Cs :	reference concentration	[m³/m³]
q :	tracer gas volume generated	[m³/s]
Qs :	reference air volume	[m³/s]
v :	wind speed at monitor height	[m/s]
A :	opening area of monitor at neck	[m²]

(A=460 m² for each of the three vegetable and fruit market blocks,
A=370 m² for the fish market block)

The normalized concentration shows the relative concentration referenced to the concentration $(q/A \cdot v)$, where $A \cdot v$ (m³/s) is the flow rate ventilated at the speed of v (m/s) passing through the neck area A (m^2) of the roof monitor.

Fig. 10 shows the distribution of the normalized concentration measured in the vegetable and fruit market building in wind direction S (wind speed: 2.4 m/s at roof monitor height). Tracer gas SF_6 was released continuously at the center of A block. Gas samplings at the measuring points were taken three times at 30 min. intervals, beginning one hour after the start of tracer gas gneration; the averaged values of the three samplings are shown in the figure. In the windward half of the space at a height of 2m, normalized concentrations were less than 1.0. On the other hand, the values at leeward points and at the roof monitors were over 1.0. The tracer gas was thus not fully diffused at the level of a human, it diffused leeward and also upward towards the roof monitor. The concentrations at the side openings were thus low. The values in B block were rather low and it thus may be concluded that the air change between A and B blocks is negligible. These characteristics of the diffusion field indicate that most of the tracer gas generated in A block is exhausted through the roof monitor of the same block.

These estimations of indoor flow pattern are also confirmed by flow visualizations using smoke. Fig 11 shows a flow visualization in which the smoke was generated at the center of the floor. Smoke moved horizontally because of indoor convection and was diffused rather slowly in this case. A flow visualization of the upper portion of the space is shown in Fig.12. Smoke generated near the ceiling moved upward immediately and was discharged efficiently through the roof monitor. This area is well ventilated. These characteristics of air movement agree with the estimations based on the measured concentration of tracer gas.

AIR CHANGE RATE

The air exchange rate was calculated by equation (2). When calculating the air change rate, the indoor space is assumed to be separated into blocks A, B, and C, *i.e.* air exchange between blocks is considered to be small. This assumption seems reasonable because the concentration in B block is very low compared with the value in A block when the tracer gas was generated within block A, as is shown in Fig 10. The effect of the air exchange between A and other blocks on the value of the observed air change rate can be investigated by a simple model described in note 1. Based on this model, the error in the observed air change rate, which is

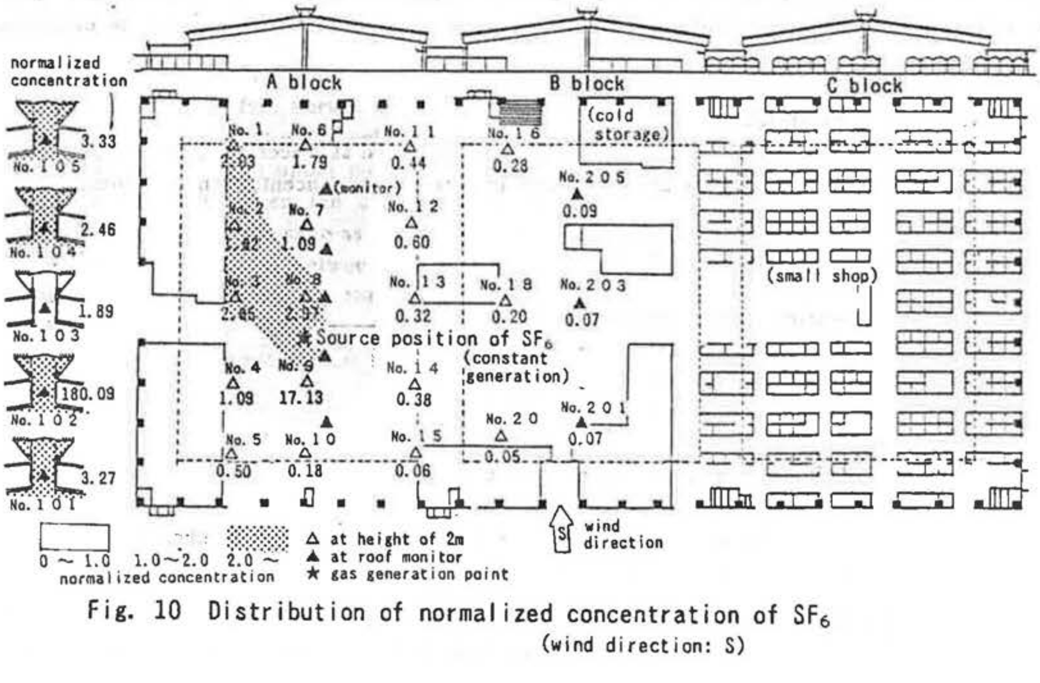
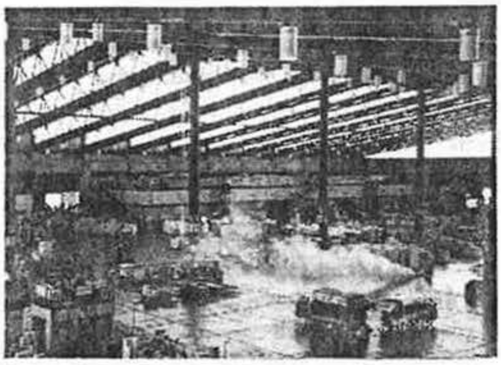
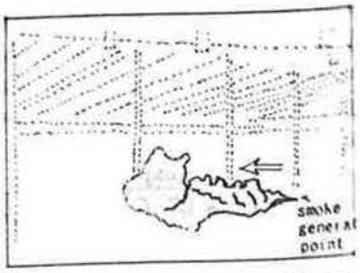
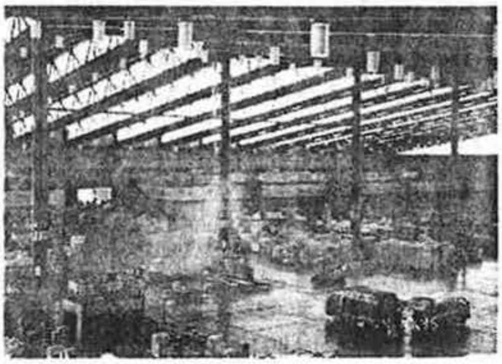


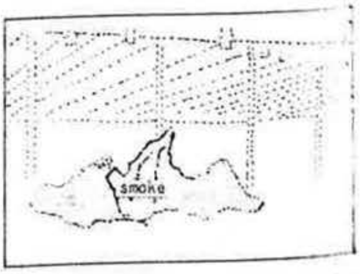
Fig. 10 Distribution of normalized concentration of SF_6
(wind direction: S)





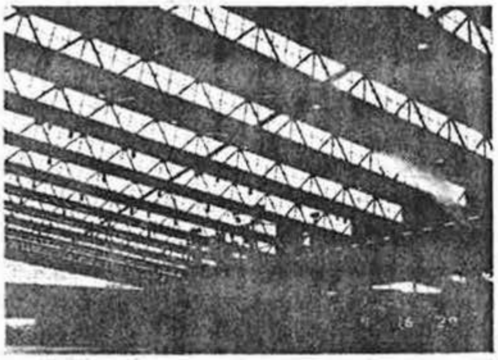
(1) Smoke flows horizontally for a few seconds after generation.

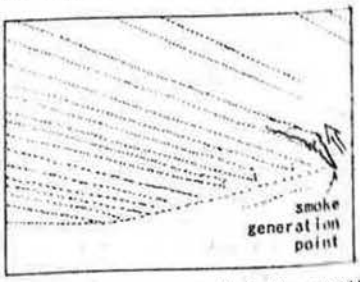




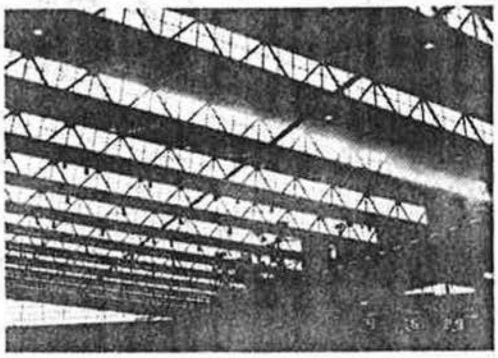
(2) Smoke diffuses rather slowly.

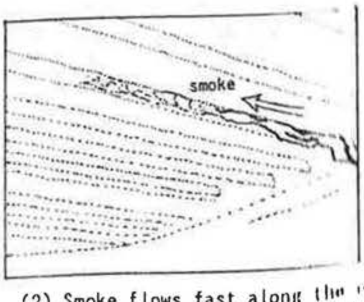
Fig. 11 Flow visualization when smoke is generated on the floor
(outside wind speed of 3.6 m/s, wind direction of N)





(1) Smoke generated at the upper deck flows upward immediately.





(2) Smoke flows fast along the ceiling and is sucked into the roof monitor; area is well ventilated.

Fig. 12 Visualization of air movement at upper space
(outside wind speed of 3.9 m/s, wind direction of ESE)

overestimated becuse of the air flow between the blocks, may be evaluated to be no more than about 10%. The concentration values C and C_1 in equation (2) use data measured at the roof monitor positions because the result in Fig. 10 suggests that the roof monitor may be considered the sole exhaust port open to the indoor air flow.

$$Q = \frac{q\ \{1-\exp(-(Q/V)\cdot t)\}}{C-C_0-(C_1-C_0)\cdot \exp(-(Q/V)\cdot t)} \qquad (2)$$

Q: air exchange rate [m^3/h]
q: generation rate of tracer gas [m^3/h]
V: air volume of the space [m^3]
(V=323 000 m^3 for each of the three vegetable and fruit market blocks,
V=170 000 m^3 for the fish market block)
t: duration of gas concentration measurements between C and C_1 [h]
C: SF_6 concentration at end of measuring duration (time t) [m^3/m^3]
C_1: concentration at start of measuring duration [m^3/m^3]
C_0: background concentration [m^3/m^3]

The ratio of the area actually open at the time of measurement to the total area of the side openings is roughly 75% in the vegetable and fruit market and 50%-60% in the fish market, as is shown in Table 1.

Table 2 shows values for the air change rates obtained in blocks A and C (vegetable and fruit market) and the fish market in summer and in winter. The data was converted to values equivalent to the case of monitor-height wind speed of 4m/s on the assumption that ventilation is only caused by wind force and is proportional to wind speed. This assumption is derived from previous wind tunnel tests (Murakami, Kato and Takahashi et al. 1986), where ventilation given by wind force became sufficiently predominant over ventilation given by buoyancy when the wind speed exceeded 2m/s.

Table 2 Results of air change rate*

	summer	winter
A block (Vegetable and fruit market)	1.4 ach ESE	3.8 ach S 6.7 ach N
C block	2.1 ach ESE	4.8 ach W
Fish market block	6.5 ach ESE	15.1 ach W

* Measured by constant gas generation method. Values are expressed by ach for monitor-level wind speed of 4m/s.

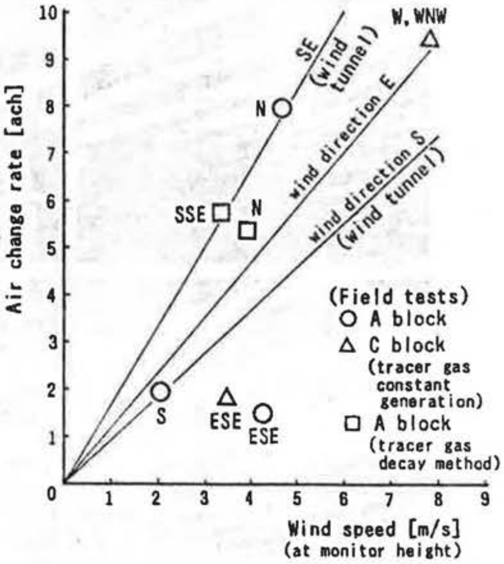


Fig. 13 Relationship between measured air change rate and wind tunnel tests
(At vegetable and fruit market; straight lines indicate the results of wind tunnel tests.)

(1) *Results in summer*

The air change rates obtained in summer were 1.4 ach (wind direction ESE) at A block and 2.1 ach (wind direction ESE) at C block for a wind speed of 4 m/s. These values seem a little smaller than the expected air change rates based on wind tunnel tests and numerical simulations. On the other hand, in the fish market block which is located at the east end of the building complex, an air change rate of 6.5 ach was obtained in the wind direction ESE. It is supposed that much of the outside wind from direction ESE flowed in through the east side openings.

(2) *Results in winter*

The air change rates in winter in the vegetable and fruit blocks were 3.8 ach (at A block, in wind direction S) and 6.7 ach (wind direction N), and 4.8 ach (C block, wind direction W), for a wind speed of 4 m/s. These values are larger than those measured in summer. Wind direction S or N is expected to be effective for air intake through the large side openings. This tendency is particularly remarkable in wind direction N because there are no tall buildings north of the market. The maximum value of 15.1 ach was recorded in the fish market block in winter. One reason for this large value is that the fish market is independent of the vegetable and fruit market and the side opening area is large compared to the relatively small indoor air volume.

(3) *Results from the tracer gas decay method*

The air change rate measured by the SF_6 tracer gas decay method was 7.0 ach (at wind speed of 4m/s) in wind direction SSE measured at A block.

(4) *Wind speed of air flow at the neck of roof monitor*

The speed of air flow at the neck of the roof monitor of A block ranges between 0.6 m/s and 2.0 m/s in wind direction WNW - W, in which direction the outside wind is at right angles to the line of the roof monitor. The ratio of the air flow velocity at the monitor to the outside wind speed is about 0.2. This agrees with the estimated wind speed ratio (24%) based on the wind pressure difference mentioned above. When the outside wind speed is 4m/s, the air change rate given by this wind speed ratio in the monitor is 4.1 ach for the vegetable and fruit market, which corresponds well to that measured by the tracer gas method.

(5) *Relation between wind speed and air change rate*

Fig. 13 shows the relation between wind speed and air change rate. The lines in the figure indicate the estimations given by the wind tunnel tests (Murakami, Kato, and Takahashi, 1986). According to the tests, the air change rates are estimated to be 3.7 ach (wind direction S) - 6.7 ach (wind direction SE) for a wind speed of 4m/s. Although the field test and wind tunnel test conditions were not exactly the same, the values of the full scale measurements agree rather well with those estimated by the wind tunnel tests, except for those in wind direction ESE measured in A and C blocks during summer.

CONCLUSIONS

In a large-scale space naturally ventilated indoor space with many openings, the methodology for measuring the air change rate by means of a tracer gas was tested and its reliability was investigated.

Based on this method, the air change rates at wind speed of 4m/s at roof monitor level were 1.4 - 2.1 ach in summer and 3.8-7.6 ach in winter for the vegetable and fruit market blocks. In the fish market block, they are 6.5 ach (in summer) and 15.1 ach (in winter). Measured air change rates correspond rather well to the estimated values given by the wind tunnel tests.

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Note 1

The effect of air exchange between the blocks is estimated as follows.

Assumptions used in the estimation model:

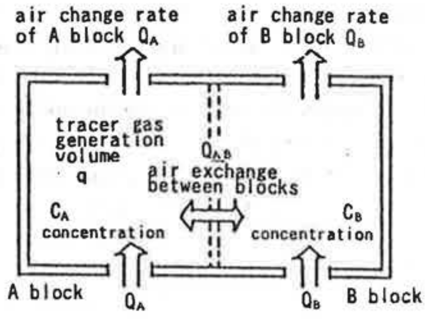
1) 2 rooms: A and B block
2) steady state
3) outdoor gas concentration is neglected
4) equations of gas balance

$$Q_A \cdot C_A + Q_{AB} \cdot (C_A - C_B) = q \quad \text{at A block (1)}$$

$$Q_B \cdot C_B = Q_{AB} \cdot (C_A - C_B) \quad \text{at B block (2)}$$

From equations (1) and (2)

$$q/C_A = Q_A\{1 + 1/(Q_A/Q_{AB} + Q_A/Q_B)\} \quad (3)$$



The left side of eqn. (3) is the measured air change rate. The air exchange between blocks gives rise to the second term of { } in the right side, and this gives rise to the overestimation of the value of Q_A. Assuming that the value Q_{AB} of the air exchange between blocks is 10% of Q_A, the ratio of overestimation to Q_A is calculated to be 1.09 (when $Q_A/Q_B=1$), 1.08 ($Q_A/Q_B=2$) and 1.095 ($Q_A/Q_B=0.5$).

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