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Comprehensive Field Measurement of Indoor Air and Thermal Quality in Naturally Ventilated Office Building with Double-Skin Façade

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Abstract

Double-Skin Façade (DSF), which is a kind of passive indoor environmental control technique, is effective way to control environmental loads while maintaining the transparency especially in perimeter zone and hence the adoption example of DSF keep increasing recently. The objective of this study was to perform a field survey of air quality environment with natural ventilation through DSF and thermal environment within office building with six stories during a mild climate period in Japan. Moreover, to understand the comprehensive environmental performance of the target building, questionnaire survey was conducted to subjectively evaluate the productivity and satisfaction with the environmental factors in office space. In this field measurement, there was a positive correlation between the DSF internal ventilation flow and the amount of solar radiation on the DSF normal surface; the primary driving force for ventilation in the DSF was considered to be the buoyancy force caused by solar radiation. The results of questionnaire survey with regard to productivity level indicated the need for improvement in the thermal (temperature) and spatial environment (room size and furniture placement).

Keywords: Double-skin façade, Field measurement, Natural ventilation, Office building, Questionnaire survey

1. Introduction

Although designing facilities that have passive environmental control technique, including a double-skin façade (DSF), can have energy saving effects, it is not easy to enhance environmental performance of buildings enough to attain design objectives. In general, DSF could achieve the increased transparency of walls with reduction of energy used during the occupation stage of a building (Chan et al., 2009; Fallahi et al., 2010; Sung et al., 2013). The concept of DSF is not new but there is a growing tendency by architects and engineers to use them (Shameri et al., 2001; Pasquay, 2004; Wonga et al., 2008). In view point of indoor environmental design with DSF for achieving healthy, comfortable and productive space, maintaining constant ventilation performance is critical for controlling indoor conditions so as to fulfill the requirements of thermal comfort and indoor air quality (IAQ) for residents (Gratia and Herde, 2004, 2007; Kim et al., 2011; Jiru et al., 2011). However, there have been many cases of difficulties associated with maintaining constant ventilation performance because the required amount of ventilation (outdoor air supply rate) depends on the driving force for ventilation, which relies on unsteady weather conditions around buildings especially in case of passive system. Normally, except in regions where wind direction is constant, it is not easy to design specific ventilation routes in the ventilation systems that use pressure differences as the driving force. Consequently, it is becoming increasingly important to continue environmental surveys after building is completed and to give due attention to optimizing the use conditions of passive environmental techniques.

In this research, we conducted field measurements for air and thermal environment in an office building that was integrated a DSF. The objective of this study was to perform a field survey of natural ventilation intake through DSF and air quality/ thermal environments within office spaces at an actual site during a mild climate period in Japan and to provide the information of actual condition. Moreover, to understand the impact of indoor environment on workers, we conducted questionnaire survey to subjectively evaluate the productivity and satisfaction with the office environment.

Natural ventilation provided by a DSF does not just enhance energy efficiency; it is also expected to secure a high level of indoor air quality because there may be a large intake of outdoor air through the façade to improve ventilation. In addition, the ventilation function, a DSF, when used during the mild climate period, may supply perceived airflows to the workers in the office, decreasing

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their sensible temperatures to ensure thermal comfort. We believe that such advantages are well-suited for achieving design goals to improve air quality in office buildings where OA devices are frequently used. However, in contrast with mechanical ventilation system, it is not easy to secure constant or uniform indoor airflows using natural ventilation through DSF, of which driving force depends on factors such as buoyancy forces that fluctuate with changes in wind pressure and temperature distributions. This is why it is important to understand airflow distributions produced by natural ventilation, in addition to taking due consideration during design and planning of appropriate natural ventilation systems.

We believe that the result of this field survey of actual office building with DSF could provide useful information of indoor environmental quality formed by passive technique and contribute to the improvement of design stage and in use of office building integrated DSF.

2. Outline of the Target Building for Field Measurements

The target building for field measurements was an office building with double-skin façade (DSF), which is located in Fukuoka Prefecture, Japan. Figures 1 shows pictures of the building exterior, the DSF, and a cross section of the building. This office building was completed in December 2006 and field meausurements were conducted just after the completion of construction (spring and fall in 2007).

Table 1. Outline of the building and HVAC equipments

Structure	S-type
Building Scale	6 Floors Above Ground with a 1 story tower
Building Area	599.73 m^2
Building Height	28.83 m
Standard floor ceiling height	2,700 m
Primary Construction Method	Glass-curtain Wall
Air-conditioning	Ceiling-Type Package
Est. Completion Date	Dec. 2006

Table 1 summarizes outline of the target building and the equipment. The building faces the No. 2 Fukuoka City highway. This six-story reinforced-concrete building has a DSF on the south–southwest side. The first floor contains an entrance and a parking lot and the second floor is a gallery, the third through fifth floors are occupied by offices, and the sixth floor is a meeting room. There is a

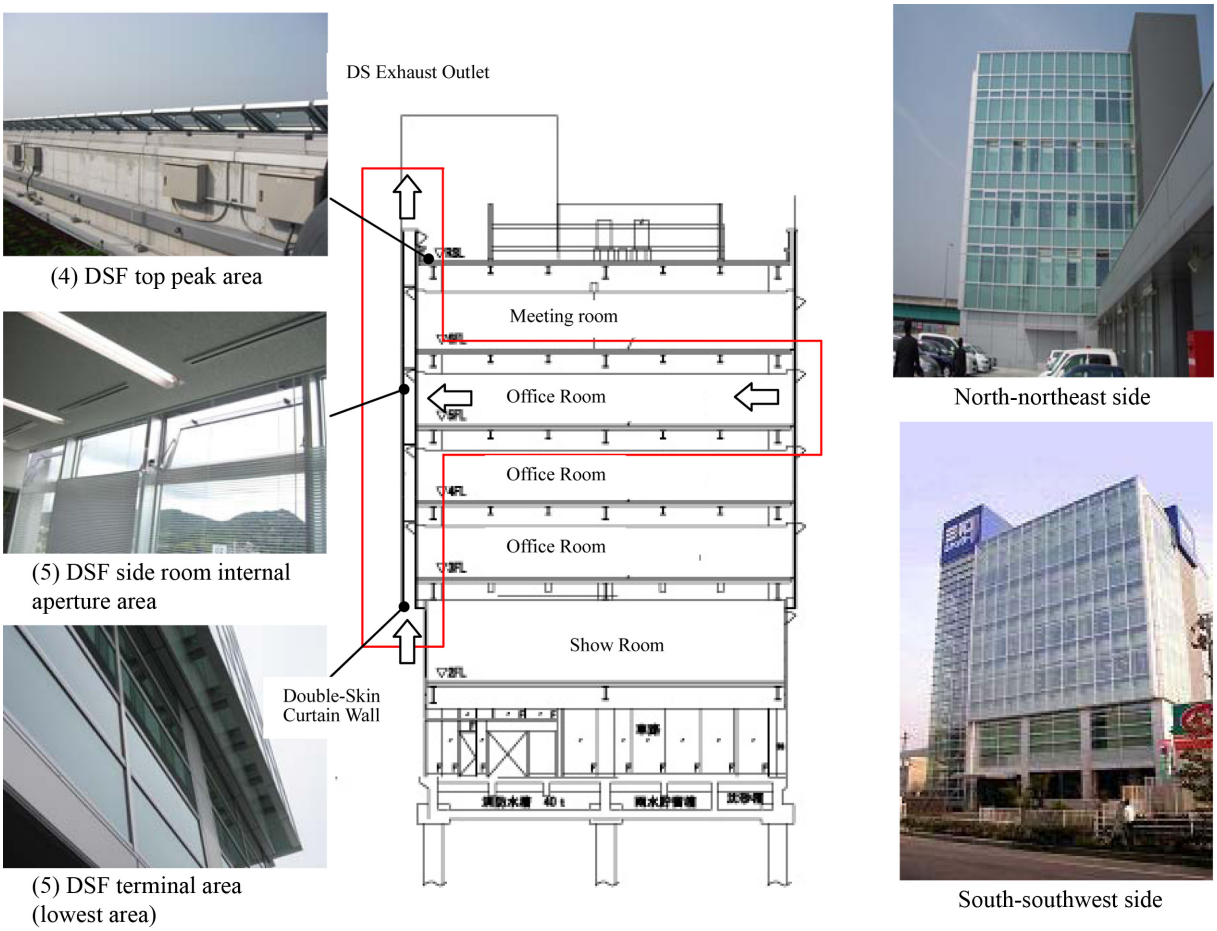
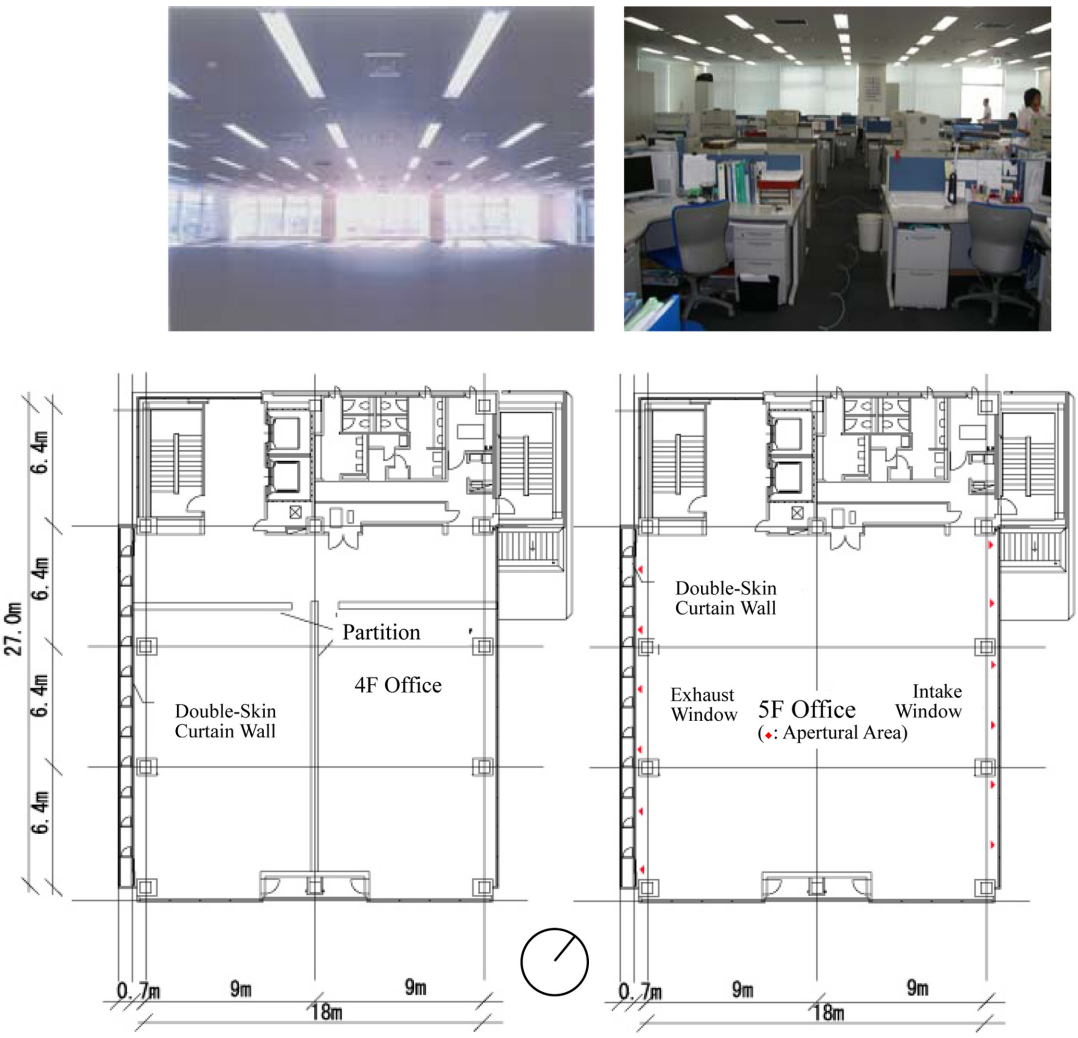


Figure 1. Overview of the target building.



(1) 4F office floor plan (2) 5F office floor plan

Figure 2. Floor plans of 4F and 5F and interior view.

core equipment space on the north–northwest side of the building that contains a staircase. All four sides of the building, including the DSF side, have exterior glass surfaces. The DSF covers from the third floor to the sixth floor as shown in Figure 1 and creates a "multilayer circulation zone" through plural floors. The DSF and the aperture (ventilation openings) used for natural ventilation, which is located on the wall opposite to the DSF, can be manually opened and closed. By continual monitoring the temperature and humidity of outside air, when natural ventilation is possible, the DSF will act to facilitate the opening and closing of oriel ventilation openings located

Table 2. Cases of Field Measurements

Date of Measurement	Floor	Type of Air-conditioning	State of Blinds
Spring: May 27	4F	Air-conditioning system and Mechanical Ventilation	Freely opened/closed by office workers
	5F	Natural Ventilation only	All Open
Spring: May 28	4F	Air-conditioning system and Mechanical Ventilation	Freely opened/closed by office workers
	5F	Natural Ventilation: (AC turned on at 13:30)	All open
Fall: October 10	4F	Air-conditioning system and Mechanical Ventilation	Freely opened/closed by office workers
	5F	Natural Ventilation only	Apertural area open only
Fall: October 11	4F	Air-conditioning system and Mechanical Ventilation	Freely opened/closed by office workers
	5F	Natural Ventilation only	Apertural area open only

at the uppermost areas using panels installed in the hallways. Inside the building, solar blinds have been installed; office workers can freely open and close these blinds as they deem fit.

3. Outline of Field Measurement

Table 2 lists the measured cases. Measurements were performed on the following dates over a mild climate period in Japan: in spring on May 27/28, 2007 and in fall on October 10/11, 2007.

Survey items and measurement instruments were carefully selected taking account into the effects that natural ventilation and natural ventilation intake have on air quality/thermal environments within office spaces. In order to clarify the natural ventilation performance by way of DSF, the measurement conditions in consideration of paired comparison, on the fourth floor (4F) assuming there is normally no natural ventilation; instead, this floor (4F) uses air-conditioning and mechanical ventilation system to keep continuous and constant ventilation rate, were set. The fifth floor (5F) uses only natural ventilation

Table 3. Methods and instruments of filed measurement

Measurement item	Instrument/Device	Measurement method
Solar Radiation	ML-020VM (EKO)	Spring measurements were carried out at two points: the area around the wall on the northeast side (wall facing the DSF side) of the building, and the area around the southwest side (DSF side). Fall measurements were taken at intervals of 30 minutes over a two-day period from 8:00 am Oct. 10th to 6:00 pm Oct. 11th. These measurements were carried out at three points: the area around the northeast side (wall facing the DSF), the area around the southwest side (DSF side), and the southeast side.
PMV	Amenity Meter AM-101 (Kyoto Electronics)	During spring and fall, measurements were conducted every 30 minutes to obtain PMV, air temperature, relative humidity, average radiative temperature, and wind speed on the insides of the fourth and fifth floors.
Thermal Imaging	Compact thermal imaging camera: CPA2200 (CHINO)	Measurements were taken at two points on the fourth floor during spring and fall.
Temperature and Humidity Distribution	Ondotori TR-52, RTR-53 (T&D)	Inside the Office: During spring and fall, temperature and RH measurements were done at intervals of 30 minutes. These devices were placed in 29 different locations in the 4F and 5F offices. In addition to these indoor points, the temperature and RH in the apertural area on the south-southwest side facing the DSF and the apertural area where the outdoor air intake enters the building on the north-northeast side were also measured Within the DS: The DSF internal vertical temperature and humidity distributions at both the terminal (lower) end of the DSF and at the apertural area at the upper end were measured.
Indoor air quality	DNPH/HPLC, TenaxTA/GCMS, Bio-Samp/PDA Medium	During spring, the concentrations of carbonyl compounds and volatile organic compounds (VOC) were measured at exterior and interior office space on floors 4 and 5 for. Samples were taken while air-conditioning and ventilation were turned off on both floors. Samplings for airborne and settling fungus were also performed simultaneously. Samplings were done for three times the following day (May 28th) in the morning, at noon, and in the afternoon, only these experiments were performed while workers were present. As for the sampling and analysis of carbonyl compounds, DNPH sep-pak was used and indoor air was sampled by using pump to perform 30-L at 500 cc/min sampling speed. Tenax TA (60/80 mesh) was ued for Volatile organic compounds (VOCs) with pomp to perform 5-L active sampling at 100 cc/min. Qualitative and quantitative analyses of VOCs were performed using a thermal desorption and GC/MS. A 90-mm diameter sterilized petri dish containing the PDA medium was used for settling fungal sampling and was opened for 60 minutes. Afterwards, fungal colony on the PDA medium was incubated at 28^{o}C constant temperature conditions and CFU (colony forming unit) was calculated by using the data of four days after the start of incubation. As for airborne fungus, we used an MBS-1000 to perform an active sampling (100 L at 100 L/min) and used a PDS for the medium, and then grew the fungus in a temperature-regulated incubator at 28^{o}C and finally CFU was determined by using the data of four days after the start of incubation.

Table 3. Methods and instruments of filed measurement (continued)

Measurement item	Instrument/Device	Measurement method
Pressure difference	Baratron pressure gauge	Measurements were conducted only during the fall. Pressure differences, which serve as ventilatory drive, between interior and exterior environments were monitored. Then a Baratron micro-differential pressure gauge was placed inside the building and wind pressure plates on the floor surface (also inside the building) and in the central part of the apertural area (air supply window) on the wall facing the DSF.
Wind Speed	Hot Wire Anemometer (KANOMAX)	Air movements at intervals of two hours in both spring and fall were measured by the devices that were spherical nondirectional sensors. Since these devices cannot measure wind direction, they were just used to measure scalar wind speed. In addition to using the same measurement points for illumination and wind speed, we set measurement points on the fifth floor at the apertural area on the south-southwest DSF side and on the apertural area (air supply window) on the north-northeast side wall facing the DSF. We also measured wind speed distributions.
Natural ventilation rate by tracer gas method	Inside Office Rooms: Photoacoustic Multi-gas monitor, Multi-point Sampler and Doser (INNOVA) Inside DSF: Mutliple room ventilation measurement device: SK-001 (Kona Sapporo)	Inside Office Room on 5F The natural ventilation rate (intake) using a constant concentration method with SF_6 as the tracer gas and a multi-gas monitor as the concentration measurement equipment were conducted. A sampling tube and a gas monitor were placed in the center of the room on the fifth floor. Dosing the tracer gas started at the start of the workday, and performed continuous measurements until 6 pm in evening. Inside the DSF Air flow rate in DSF was continuously measured by using CO_2 as a tracer gas under a constant generation method. The tracer gas was generated from the terminal end of the DSF, and then sampled at the DS exhaust outlet on the fifth floor.

basically without the usage of air-conditioning system and we performed a field survey of the indoor air and thermal environment using only natural ventilation as the basic condition; this was done by opening the normal exhaust outlet (oriel window) on the fifth floor. Lighting on the ceiling in rooms was continuously used but we turnd lights off around lunchtime (12:00 pm).

Questionnaire survey using SAP (Subjective Assessment of workplace Productivity) was conducted in conjunction with a subjective evaluation of primary physical environmental factors, such as light, sound, heat, and air (Sugiura et al., 2007). In addition, we conducted the surveys of OA equipment usage and power consumption, as well as a questionnaire survey using SAP to evaluate the employees' levels of productivity and satisfaction with the office environment. Outdoor weather conditions were also measured.

3.1. Measurement instruments and method

Table 3 shows the methods and instruments used in field measurment in the office space, the DSF internal environment, and outdoor climates during the mild climate periods (spring and fall), for each of physical environmental factors, heat and air quality, as well as outdoor climates.

In addition to the measurement items in Table 3, funda-

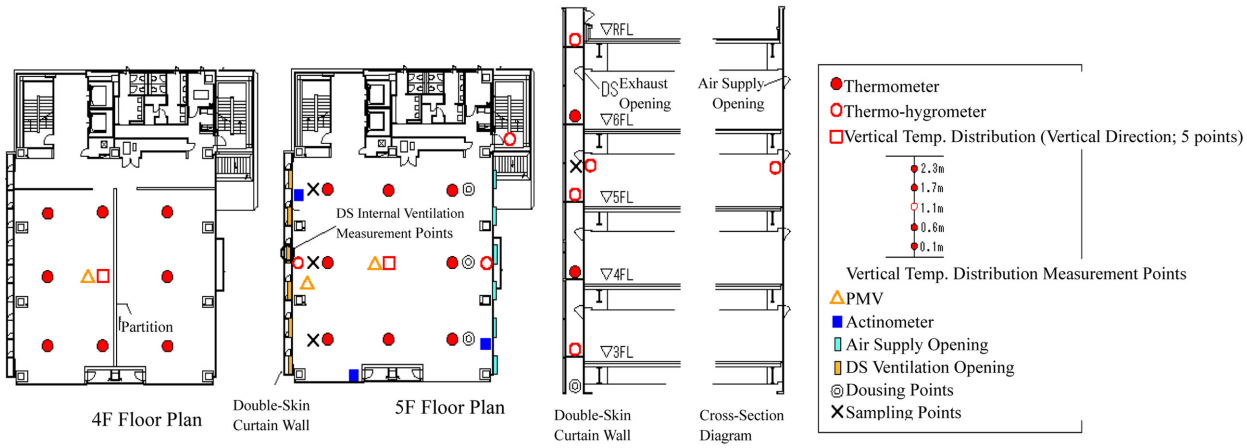


Figure 3. Measurement points for heat and ventilation flows.

mental informations, e.g., the number of people present and the OA device usage were monitored during field measurement period and power meters were used to measure power consumption on both the 4F and the 5F in order to estimate energy consumption in office space.

3.2. Measurement points

Target office space was hypothetically divided into nine modules and a total of nine measurement points for horizontal distribution were set to measure thermal environments on floors 4 and 5 of the office building.

We also measured vertical temperature distributions at five different locations in the center of the rooms at intervals of 30 minutes, and measured the PMV for the interior perimeters of floors 4 and 5 at three locations at intervals of 30 minutes. Figure 3 shows the points for thermal environment measurement and for measurements related to ventilation performance.

3.3. Questionnaire survey

As for the questionnaire survey, we performed investigations for both the fifth floor office space (which uses natural ventilation) and for the fourth floor office space (which uses machanical ventilation system and air-conditioning system with no natural ventilation). For the fourth floor, we mainly allocated the questionnaires to white-collar workers in the general affairs and sales departments. The fifth floor mainly is occupied by technical and engineering related departments including the design department on the floor. We used SAP (Subjective Assessment of Workplace Productivity tool developed by Japan Sustainable Building Consortium) as questionnaire survey for evaluating self- estimated productivity, which involves a questionnaire survey seeking out core information on the research participants while inquiring about questions in 5-8 large category subjects, such as light, thermal, air, sound, spatial, and working environments. The contents of SAP are shown in Table 4. Practically, SAP is a questionnaire survey sheet that provides a subjective evaluation of the levels of employees' productivity and satisfaction with

Table 4. SAP Evaluation Items

1. Please fill in your answers regarding today's date and which floor your work on.
a. Today's Date:
b. The floor you work on:
2. Please answer the following questions about yourself.
a. Gender:
b. Age:
c. Occupation:
d. How many years have you been working at your current location?
e. Please tell us your physical condition.
f. Do you wear more or less layers of clothing than those of others?
g. Are you satisfied with your current job?
3. Please answer the questions about light environments (lighting and illumination).
a. How do you feel the current level of lighting on top of your desk?
b. Does the shadow your hands cast bother you?
c. Does the light through windows or the glares of artificial lighting bother you?
d. Do glares on your computer screen due to excessive illumination and outside light bother you?
e. Do unwanted scenes or movement out of the corner of your eyes bother you?
f. Are you satisfied with the current state of your light environment?
g. How do you think lighting and illumination in light environments affect work efficiency?
4. Please answer the questions about the thermal environments (hot and cold) found indoors.
a. How do you think the current state of general thermal environment?
b. How do you think the current state of general humidity environment??
c. Does wind blowing against you bother you?
d. Does the surrounding radiant heat bother you? (summer sunlight coming through windows, cool air through the windows in winter)
e. Does it bother you when your upper and lower bodies are exposed to different temperatures?
f. Do fluctuations in temperature bother you?
g. Are you satisfied with the current state of your thermal environment?
h. How do you feel thermal environments affect work efficiency?
5. Please answer the question about air environment (such as air pollution).
a. Does unclean or polluted air found indoors bother you?
b. Can you sense any stagnation in the indoor air? (inadequate ventilation or lack of air freshness)
c. Are you bothered when you can smell odors indoors?
d. Does dust found indoors bother you?
e. Are you satisfied with the current state of your air climate?
f. How do you feel air environment affects work efficiency?

Table 4. SAP Evaluation Items (continued)

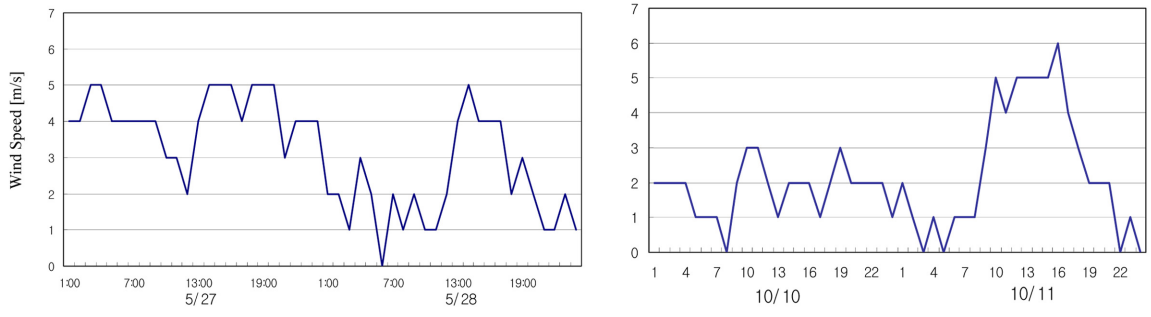
6. Please answer the questions about sound environments (noises).
a. Does indoor noise bother you?
b. If you answered "yes" or "a little bit," please tell us what kind of noises inside this office space bother you 1. Others' talking voice. 2. Noise from OA devices. 3. Noise from air-conditioning. 4. Telephone. 5. Outside noises. 6.Others.
c. Does others' talking voice when the room is quiet bother you? Does having other people hear you talk with others bother you?
d. Are you satisfied with the current state of the sound environment?
e. How do you feel sound environments affect work efficiency?
7. Please answer the questions about spatial environments (room size, furniture placement)
a. How do you feel about the size of the individual work space that has been allocated to you?
b. What do you think about the interior of this office room?
c. What do you think about the size of the area around your desk?
d. How do you like your desk?
e. How do you like your chair?
f. What do you think about the adjustability of your chair?
g. What do you think about the placement of desks and furniture?
h. What do you think about the current state of the wiring (power outlets and switches) and telephone placement?
i. What do you think about the IT environment? (computer performance, size, qty, and network environment)
j. Do you feel there are any inadequacies or insufficiencies with regard to storage space?
k. Cleaning Services: Are you satisfied with the current cleaning routine?
l. Are you satisfied with the current state of the special environment?
m. How do you feel spatial environments affect work efficiency?
8. Please answer the questions about easiness of work.
a. How do you feel the above mentioned indoor environments affect the easiness of work as well as the work itself?
b. Please tell us how many hours you feel you have lost due to such factors interfering with your work over the past month?
c. Do you feel that factors related to any of the above mentioned environments have caused you to take additional days off from work?
d. What do you think impairs or inhibits work the most?
e. 1. Light environ. 2. Thermal environ. 3. Air climate. 4. Sound environ. 5. Spatial environ. 6. Other.
f. How do you feel about the ease of concentration towards work? To what extent do you feel work efficiency will improve if factors 1-5 are improved?

their indoor environments. The application of SAP can help provide consistency for question items and wording, and it can help to collect potential data by performing intercomparisons with previous subjective evaluation case results performed by Sugiura et al. [11]. In addition, the main focus of this subjective evaluation was to compare the results for 4F (without natural ventilation) with those for 5F (with natural ventilation). The results also include significance tests for the results found.

4. Results

4.1. Outdoor weather conditions

Figure 4 shows changes in wind speed as provided by the AMEDAS climate data. During the spring, wind speeds decreased at night and increased during the day. Presumably this was due to solar radiation, which increases daytime wind coming from the sea. Daytime wind speeds during the spring were generally above 3 m/s. On the first measurement day in the fall (October 10th), the weather was cloudy and wind speeds showed an overall decrease. Daytime wind speeds in the fall averaged about 2 m/s. Given the abundance of solar radiation on the second measurement day in the fall (October 11th), daytime wind



(1) Spring (2) Fall

Figure 4. Outdoor wind speeds on the days at which measurements were taken.

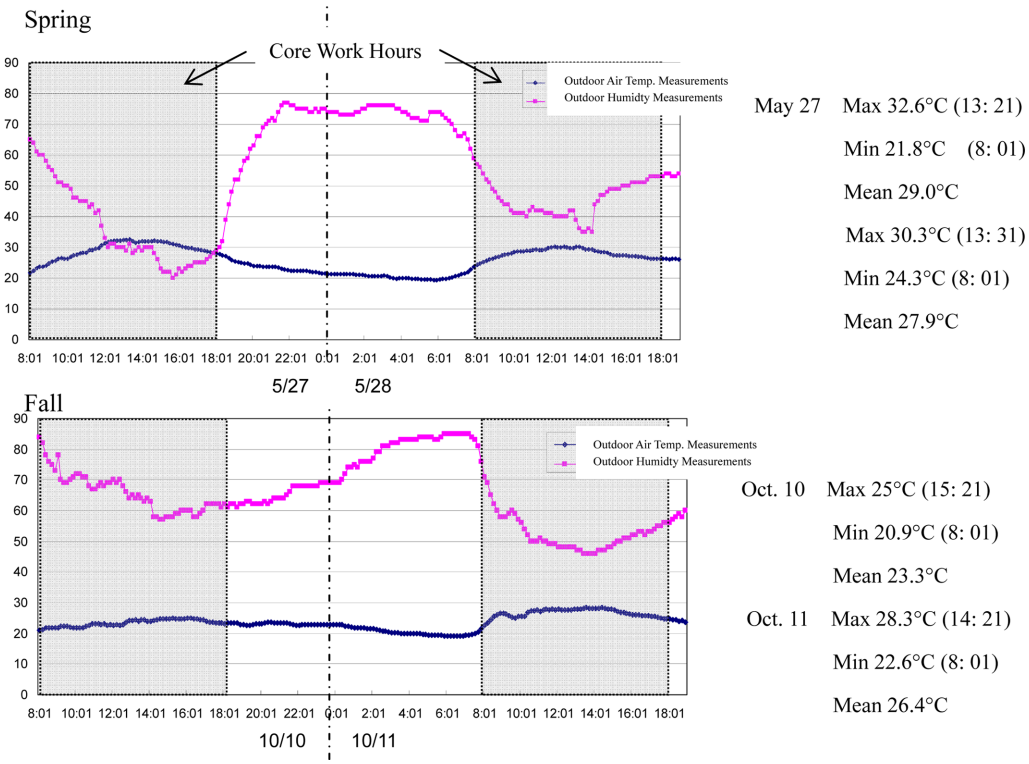


Figure 5. Outdoor temperature and humidity on the days of measurement.

speeds increased due to winds coming from the sea. Therefore, outdoor wind speeds during both spring and fall are suitable for providing adequate natural ventilation.

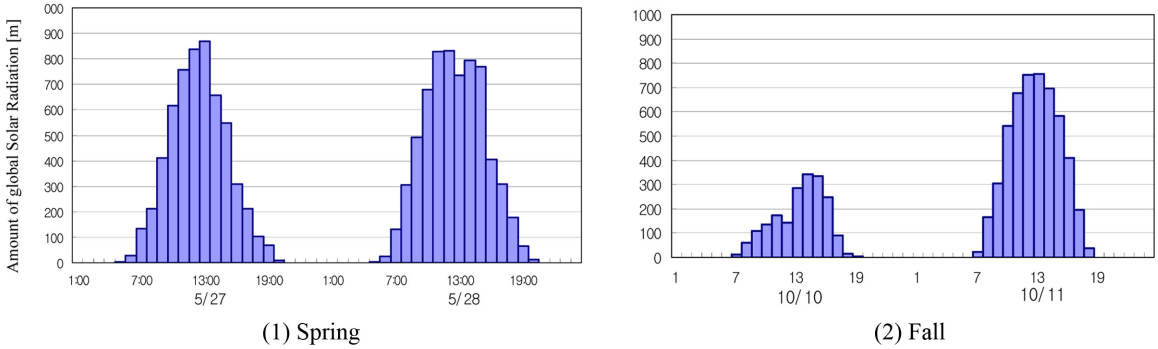
The time series of outdoor air temperature and relative humidity during field measurement are shown in Figure 5. In spring, maximum outdoor temperature was more than 30°C and average temperature during daytime was approximaltely 28°C. In fall, maximum and average temperature of outdoor was about 5°C lower than those of spring.

Figure 6 shows the hourly values of global solar radiation data collected by the Fukuoka meteorological weather station. The weather was good on the days of the spring measurements, and the amount of global solar radiation during the daytime peaked at over 800 W/m^2. On the first day of fall measurements, the weather was cloudy; however, clear skies on the following day allowed global solar radiation to peak at over 700 W/m^2.

4.2. Thermal environment

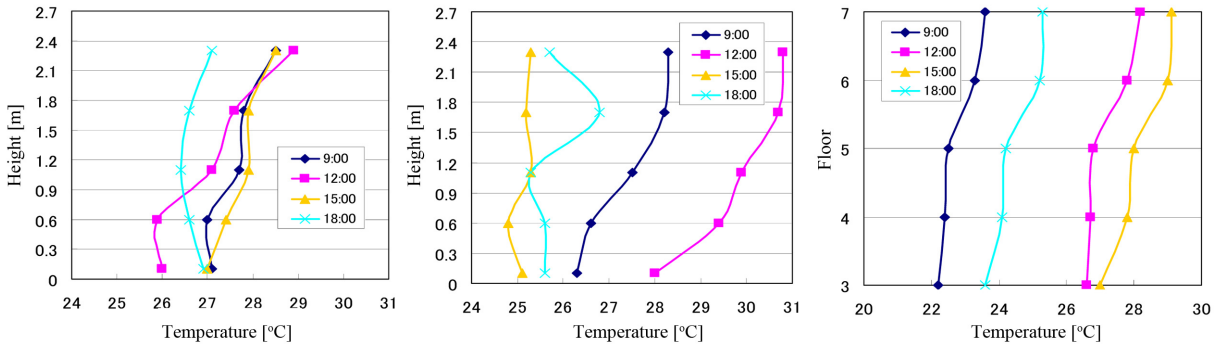
Figures 7 shows results of spring measurements for vertical temperature distributions in the midareas of floors 4 and 5, and also shows temperatures within the DSF at the height of each floor.

Air-conditioning system was in use on the fifth floor at 1:30 pm on May 28th, and hence the temperatures in the midarea of the fifth floor (Fig. 7(2)) kept constant just after turing on the air conditioner. Although temperatures between the floor and a point 1.8 m above the floor differed by about 1°C, the vertical distribution for the fifth floor midarea was almost completely uniform during afternoon. In contrast, the temperature differences in fourth floor was



(1) Spring (2) Fall

Figure 6. Amount of outdoor global solar radiation on the days of measurement.



(1) 4F Mid area (2) 5F Mid area (3) Inside of DSF

Figure 7. Time series of Vertical temperature distributions (spring 5/28).

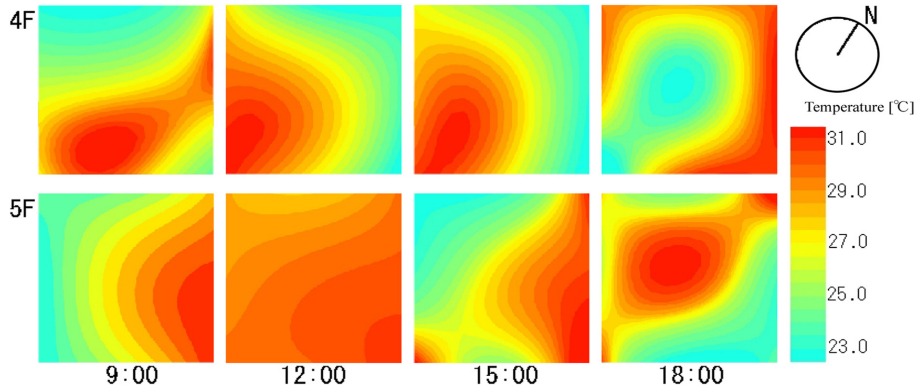
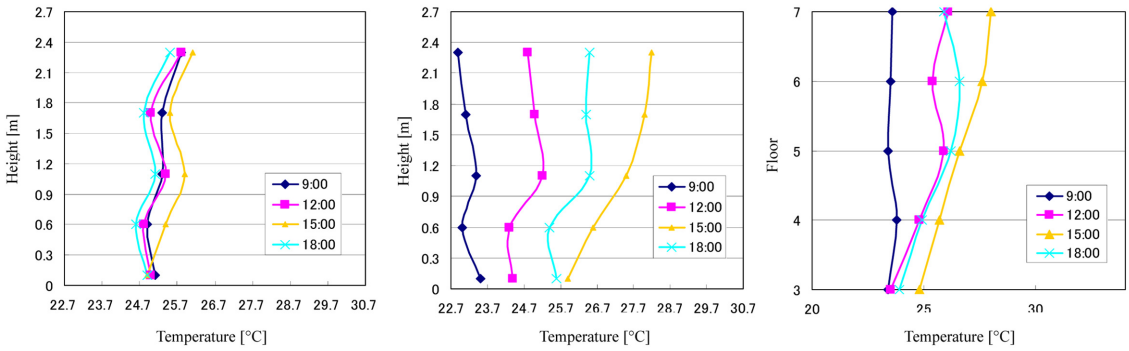


Figure 8. Temperature distributions at horizontal plane in offices on 4F and 5F (spring 5/28).

more than 2°C over heights between 0.8 m and 1.8 m during the daytime even though air-conditioning and mechanical ventilation were in use. On both floors, differences in vertical temperatures from floor (0.1 m) toward ceiling (1.7 m) stayed within the recommended comfort range of 3°C set forth by ASHRAE (American Society Heating, Refrigerating and Air-Conditioning Engineers) (ASHRAE, 2013). Temperatures on the fifth floor reached peak fluctuations of over 3°C when natural ventilation was being used. Further evaluation of measures to deal with vertical temperature fluctuations when natural ventilation is applied may be worth considering when implementing DSF systems.

Figure 8 shows results of spring measurement of temperature distributions at horizontal plane inside offices on the 4th and 5th floors (at 1.1 m from floor level). The figures show non-uniform temperature distributions that change significantly over time. These offices were heavily influenced by solar radiation because they were exposed to sunlight on three sides. As a result, indoor temperature differences of as high as 5°C occurred on the fourth floor,



(1) 4F room midarea (2) 5F room midarea (3) Inside of DSF

Figure 9. Vertical temperature distributions (fall 10/10).

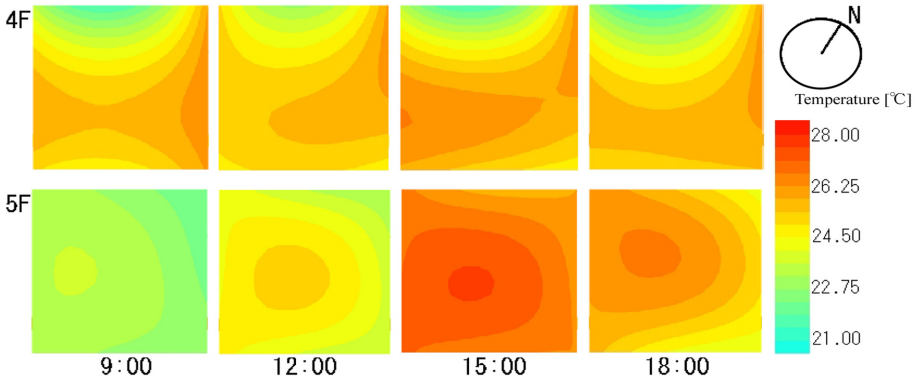


Figure 10. Temperature distributions at horizontal plane in offices on 4F and 5F (fall 10/10).

even though air-conditioning was in use. The rises in temperature at 15:00 on the east side of the fifth floor may be due to outside air inflowing through the air supply duct.

Figures 9 shows the measurement results of fall for time series of vertical temperature distributions in the midareas of floors 4 and 5, and also shows temperatures distributions inside the DSF at the height of each floor.

The weather was cloudy on the days of the fall measurements (Oct 10th/11th). The outside temperature at 8:00 am on Oct. 10th was 20.9°C with a peak of 25°C around 15:00. The vertical temperature distributions for the inside of the fifth floor and the DSF appear to depend on changes in outside temperature. The vertical temperature distribution for the inside of the office on the fifth floor on Oct. 11th continued to remain above 25°C of the temperature setting for the air-conditioning throughout the entire measurement period.

Figure 10 showstemperature distributions on the days of fall measurements; on the fourth floor where air-conditioning and mechanical ventilatin system were being used, there were almost no changes in the temperature distribution over time. In addition, the temperature in the midarea of the north side of the office was decreasing, which may have been due to air-conditioning in the core equipment space.

4.3. PMV

Figure 11 shows results of PMV measurements. In the figure, the positive (+) denotes warm side, and the cold side is indicated by negative (–). In the spring, PMV values slightly surpassed the comfortable zone ($0.5 < PMV < 0.5$). After the air-conditioning unit on the fifth floor was turned on around 13:30 and used in conjunction with natural ventilation, PMV values kept within neutral zone. However, PMV values on the fourth floor, where air-conditioning was in regular use, underwent large fluctuations. Furthermore, values on the fourth floor during the fall season also remained slightly above the comfortable zone with little variation. However, PMV values on the fifth floor showed relatively large fluctuations and tended to slightly favor the warm side of the thermal environment. Although complete details are not shown in the figure, differences in PMV values had relatively high correlation with air and mean radiative temperatures (MRT); trends also suggested a low correlation with relative humidity and airflow velocity. This may have been because of the average airflow velocity of only 0.1 m/s with a peak at 0.3 m/s on the fifth floor where natural ventilation was used and with changes in air and surrounding wall surface temperature (same as MRT).

With the exception of the core area on the northwest side of the building, all surfaces on each side consisted of glass walls. Glass walls allow more direct entry of solar radiation than concrete, so the amount of heat received from outside will also be greater. The ventilation produced by just mechanical ventilation system on the fourth floor compared to the ventilation produced by natural ventilation on the fifth floor showed that total ventilation rate in the office area on the fifth floor exceeded that on the fourth floor (as will later be described in detail). This suggests that further consideration and evaluation of the adequacy of the airflow rate produced by air-conditioning and mechanical ventilation system are needed. In addition, based on the spring measurements of the natural ventilation showed that the ventilation route, for which this natural ventilation was originally designed, had outdoor air inflow from the air supply opening (installed on the wall facing the DSF) toward the exhaust window (on the DSF side). However, the results of the morning measurements in the spring showed just the opposite. This indicates decreases in natural ventilation, which may have been one determinant factor for additional rises in indoor temperatures.

4.4. Thermal imaging measurement

Figures 12 show the representative results of thermal images that were taken over time at each measuring point. These thermal images show that heat loads locally concentrated, in both spring and fall, on ceilings (due to lighting), top surfaces of desks (due to OA equipment), and on windows at points exposed to solar radiation. The spring measurements show that overall surface temperatures in rooms on the fifth floor were high up until 13:00 (before air-

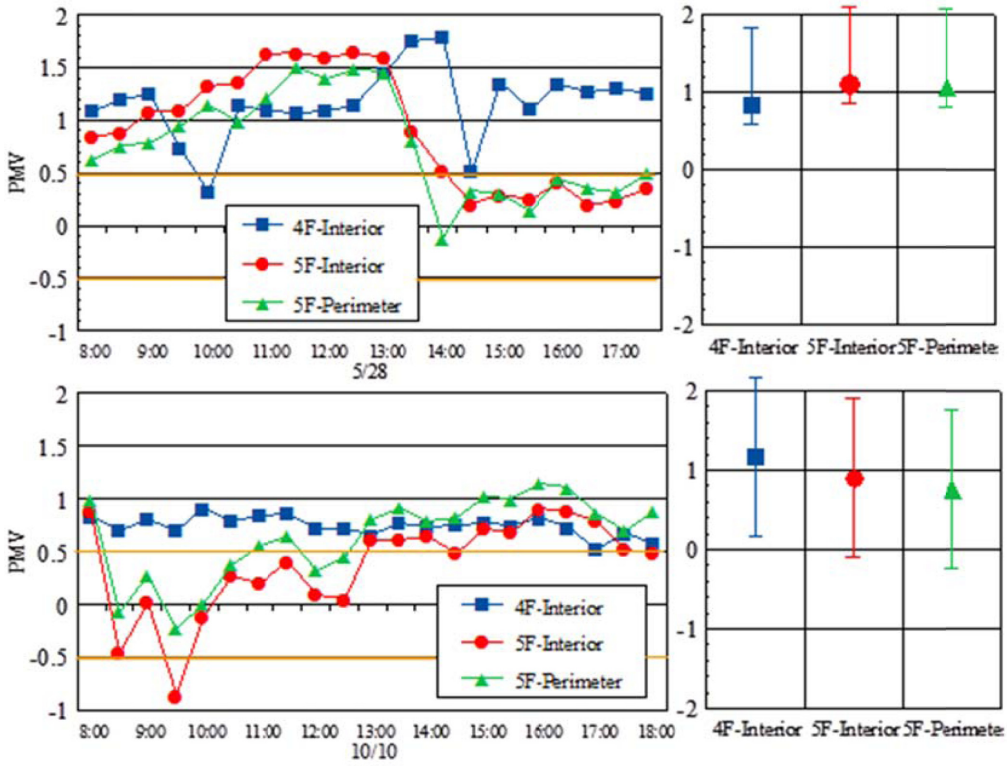
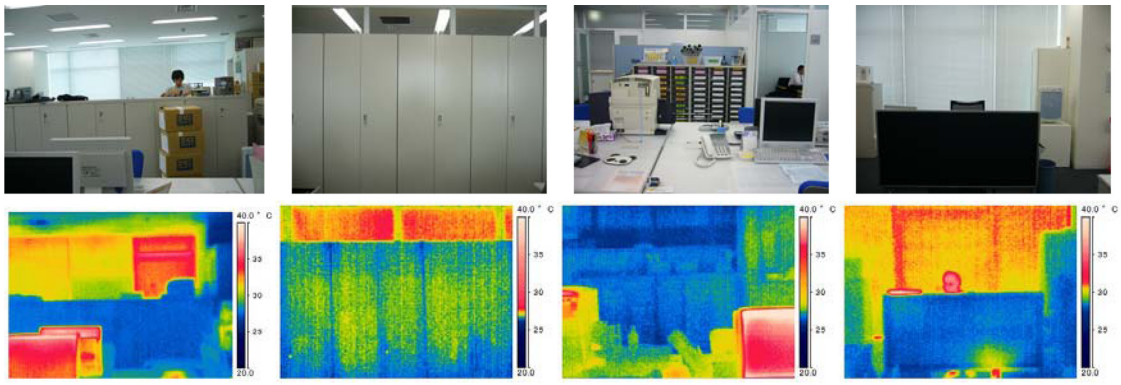
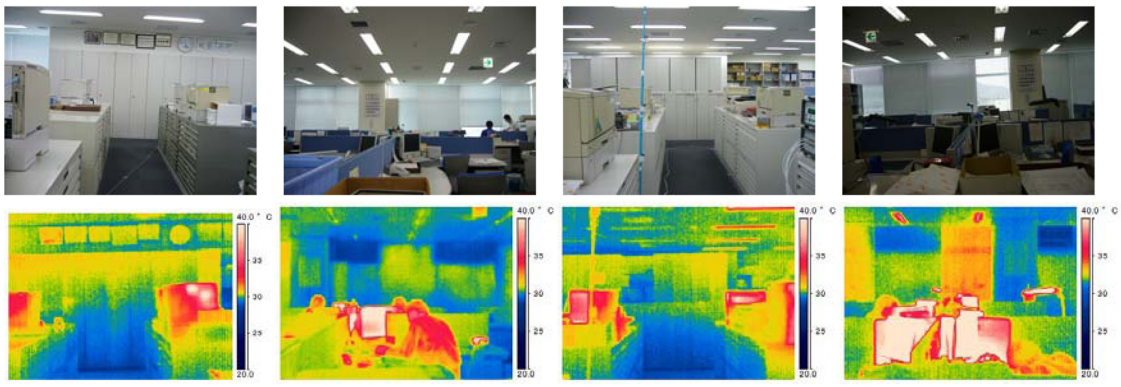


Figure 11. Predicted mean vote (PMV) measurements obtained in both spring and fall.



(1) 4F, east side (spring)



(2) 5F, west side (spring)

Figure 12. Thermal images of 12:00 (Noon) at each floor.

conditioning was turned on). The fifth floor also provided a relatively poor radiative environment compared with the fourth floor.

4.5. Heat balance for offices (fall)

Here, heat balance for each floor is discussed based on fall measurement results. Tables 5 and 6 show results for internal heat loads on the fourth and fifth floors, respectively. Here, the internal heat loads mean the sensible heat load generated by lighting and OA devices, and we recorded the number of units found in the room for each device and the rated power consumption for each. The internal loads for the fourth and fifth floors were approximately 27 and 26.6 kW, respectively, being almost the same for both floors. This was primarily due to OA devices. We also measured temperature, humidity, and air flow rates from ventilation diffusers and air-conditioning system on the fourth floor (without natural ventilation). These were used in calculations of the heat balance for rooms on the fourth floor. The measurements in fall for air flow rates on the fourth floor by tracer gas method are shown in Table 7. The results in Table 7 were used to calculate the heat balance for the entire fourth floor, as shown in Figure 13. Here, the operating duration for OA devices were assumed to be 65%. Given the cloudy weather on October 10th, the thermal loads (internal loads + perimeter loads) incurred during the day were almost completely due to OA devices, and air-conditioning system was operated to make adjustments in accordance with these loads. The perimeter load was relatively small compared the heat load from OA devices, and the ventilation load from machanical ventilation was almost negligible even though it was measured during the mild climate period. Skies cleared the following day (Oct. 11th), and the ratio of the perimeter load became relatively high in the daytime thermal load. This thermal load was about the same as the load being generated from OA devices around 15:00. In addition, depending on the time of day, the residual error of heat balance for both days (Oct. 10th/11th) reached about 30% of the entire thermal load. Since the main

Table 5. Internal Load on 4F (thermal load of lighting equipment + OA devices)

Lighting Equipment	Calorific Value (per unit) [W]	Qty	Calorific Value (Total) [W]
Flourescent Lighting			
Room1	32	48	1536
Reception 1	32	4	128
Room2	32	35	1120
Reception 2	32	4	128
		Total	2912
OA Devices	Calorific Value (per unit) [W]	Qty	Calorific Value (Total) [W]
PC			
Room1	197	24	4728
Room2	197	14	2758
Copy Machine			
Room1	1500	4	6000
Room2	1500	2	3000
Printer			
Room1	370	5	1850
Room2	370	11	4070
Shredders			
Room1	300	1	300
Room2	1350	1	1350
		Total	24056

Table 6. Internal Load on 5F (thermal load of lighting equipment + OA devices)

Lighting Equipment	Calorific Value (per unit) [W]	Qty	Calorific Value (Total) [W]
Flourescent Lighting	32	108	3456
		Total	3456
OA Devices	Calorific Value (per unit) [W]	Qty	Calorific Value (Total) [W]
PC	197	44	8668
Copier	1500	6	9000
Printer	370	13	4810
Shredder	210	2	420
		Total	22898

Table 7. Air flowrates of diffusers for air-conditioning and ventilation on the 4F (Oct. 10th/11th)

4F		4F Interior (East)		4F Perimeter (East)		4F Perimeter (SE)		4F Ventila-tion R		4F Air-cond. R		4F Interior (West)		4F Perimeter (West)		4F Perimeter (NW)	
		1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time	1st Time	2nd Time
Oct. 10	9:00	136	136	334	377	182	183	170	185	1227	1233	159	156	440	456	134	136
	11:00	155	159	346	332	184	181	179	175	1107	1108	143	145	204	213	144	146
	13:00	139	141	324	332	173	174	170	156	1093	1124	154	154	197	192	130	133
	15:00	129	130	330	356	175	185	184	171	961	946	142	152	192	193	132	134
	17:00	156	156	327	344	182	178	151	169	1094	1102	141	146	216	206	151	141
Oct. 11	9:00	145	145	341	339	187	186	93	94	1111	980	138	129	201	204	137	147
	11:00	155	150	335	350	180	181	176	176	1096	1102	139	138	202	207	136	128
	13:00	150	144	381	342	185	187	163	177	1084	1066	142	145	198	200	129	139
	15:00	147	115	346	336	179	183	170	176	1197	1206	143	139	202	205	132	133
	17:00	160	158	335	361	179	189	155	167	1048	1101	141	143	178	178	118	123

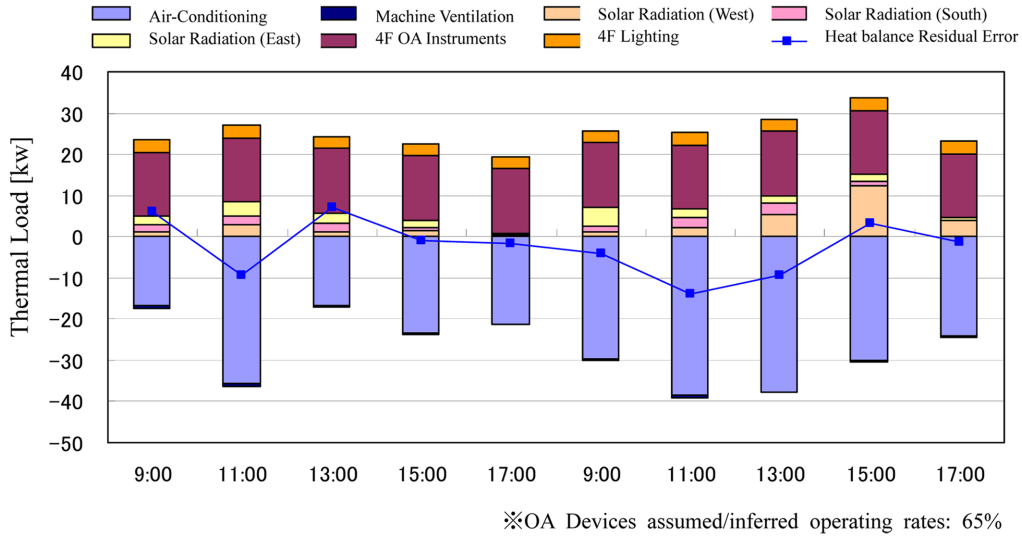


Figure 13. Overall 4F heat balance (October 10-11).

reasons for this may be attributed to (1) errors in airflow rate measurements, (2) inappropriately assumed operating rates for OA devices, and/or (3) disregard for heat loss due to transflux and air leakage, we believe that these issues need further consideration.

4.6. Indoor air quality

During spring measurements, indoor concentration of carbonyl compounds and volatile organic compounds (VOCs), fungal concentration were measured. Air samplings were done on both floors with air-conditioning and ventilation both turned off and was also taken from the roof space and the roof space on the north–northeast side of the building. These samples were also subjected to analyses for airborne and settled fungus.

Figure 14 shows the results for concentrations of settled and airborne fungus at each measuring point. The concentration of settled fungus was used to determine the number of colonies on the PDA (Potato dextrose ager) medium per unit area, i.e., units of cfu/100 cm^2. The concentration of airborne fungus was expressed by the unit of cfu/100 L because indoor air was sampled total 100 L air and collided with the PDA medium. With the exception of measurement points 1 and 2, which sampled outside air, fungal concentrations were confirmed to be low inside of the building.

Based on qualitative assessment of colony size, color, and organization, the existence of the following types of fungi: *Cladosporium*, *Alternaria*, *Fusarium, Trichoderma*, *Penicilium*, *Aspergillus*, and *Eurotium* were revealed.

Figure 15 shows concentrations of chemical compounds at each measurement point. In cases where we used the total volatile organic compound (TVOC) value to assess these compounds, such as those for point 5, we can see that the chemical compound concentration level was below 100 μg/m^3, which satisfies the indoor air quality guidelines set forth by the Ministry of Health, Labor and Welfare in Japan. The aromatic hydrocarbons found at all measure-

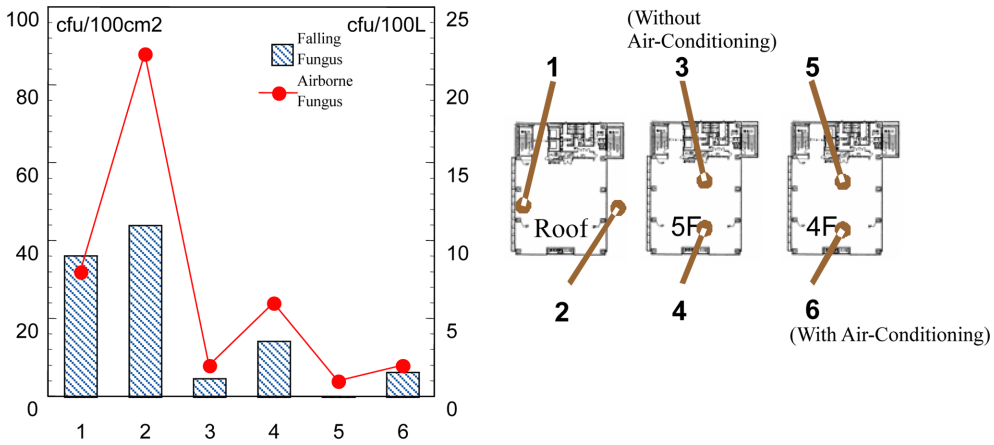


Figure 14. Fungi concentration measurement results and sampling points.

ment points were detected in fixed quantities and can be traced to the outdoor air where VOCs also exist in fixed quantities. Since the outside air containing VOCs flows into the building, VOCs will be detected indoors.

4.7. Indoor air flow direction and velocity

Figure 16 shows indoor air flow directions and velocities measured on May 28th (spring). The figure also shows air motions sampled at intervals of two hours using a hot-wire anemometer and a compact smoke generator.

The peak wind speed on the fourth floor (which used machine ventilation and air-conditioning without natural ventilation) was under 0.3 m/s over the entire measurement period. We also observed formation of flow fields where no draft could be felt. The peak wind speed on the fifth floor (with natural ventilation) was also under 0.3 m/s. This was because of inflow air speed restraints caused by use of blinds. Outside these blinds (in other words, around the apertural area) there were areas where the wind speed was as high as 0.8 m/s.

Results from the smoke test show the wind direction for air inflow/outflow coming from the apertural area on the fifth floor (with natural ventilation) showed that in the morning, outside air flowed in from the DSF side and flowed out through the natural ventilation opening on the wall facing the DSF, and In the afternoon/evening, outside air flowed in from this same natural ventilation opening and flowed out toward the DSF side.

Figure 17 shows wind speeds and directions measured on Oct. 11 (fall). Air flowpatterns were also measured using a hot-wire anemometer and a compact smoke generator. Some of these measurements were done with the blinds removed from the DSF apertural area. Although a few measurement points had wind speeds of over 1.0 m/s around the apertural area after we removed the blinds, the wind distributions on average showed wind speeds of under 0.3 m/s. The measurements by the smoke tester demonstrated that the flow fields were formed where in earlier times of the day such as morning, air flowed in from the DSF side and out through the natural ventilation opening on the wall facing the DSF, and there were signs of complex changes in air inflow/outflow due to the location of the apertural area. These indoor flow fields were heavily influenced by changes in outdoor wind speed and direc-

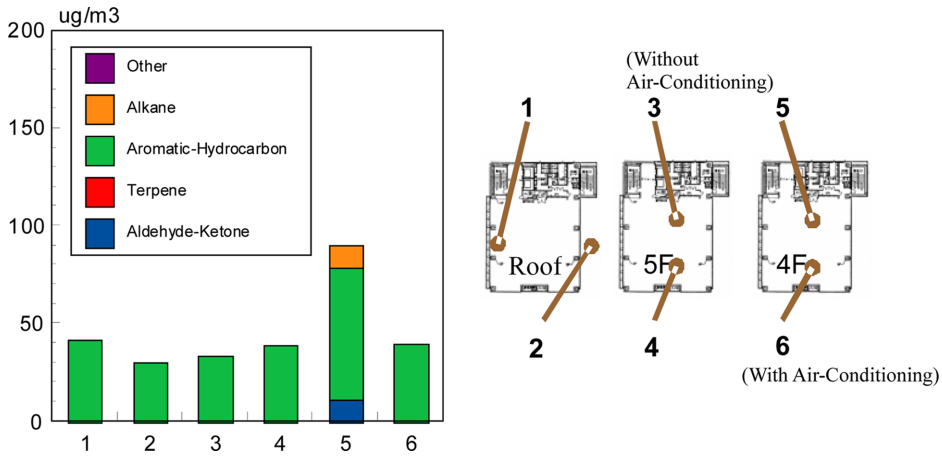
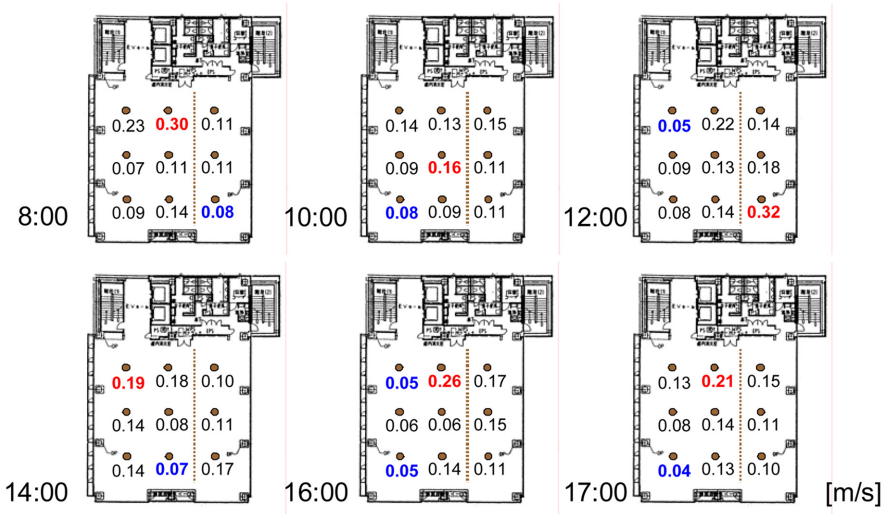
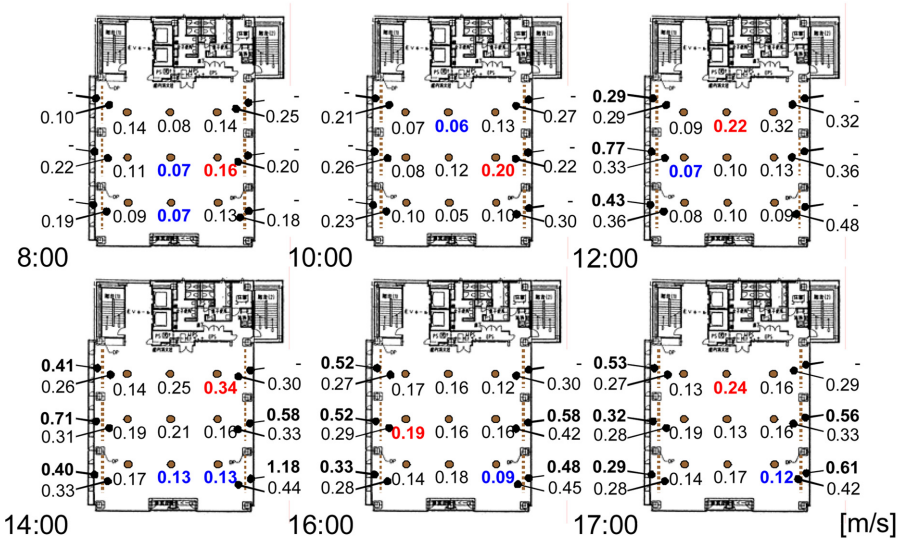


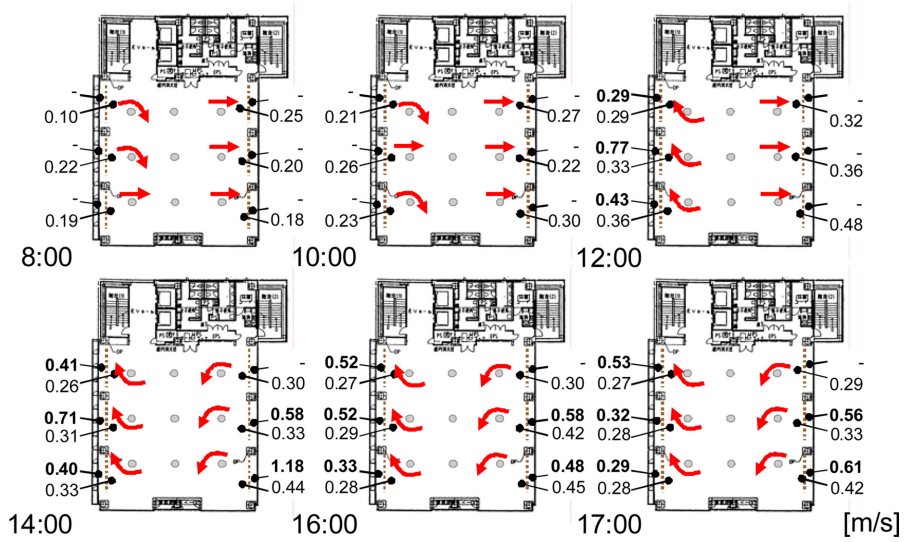
Figure 15. Indoor chemical substance concentrations (VOCs) and sampling points.



(1) 4F scalar wind velocity distributions (with air-conditioning)

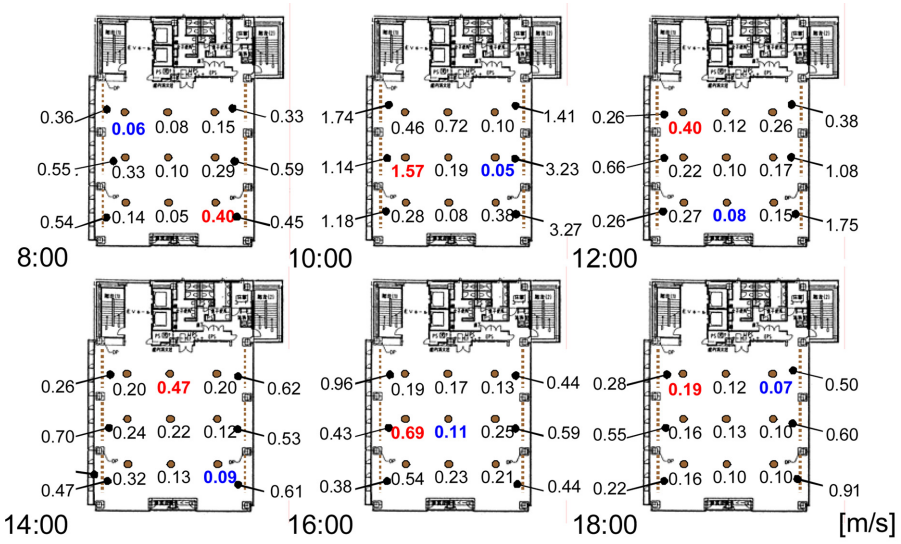


(2) 5F scalar wind velocity distributions (Natural vemntilation without air-conditioning)

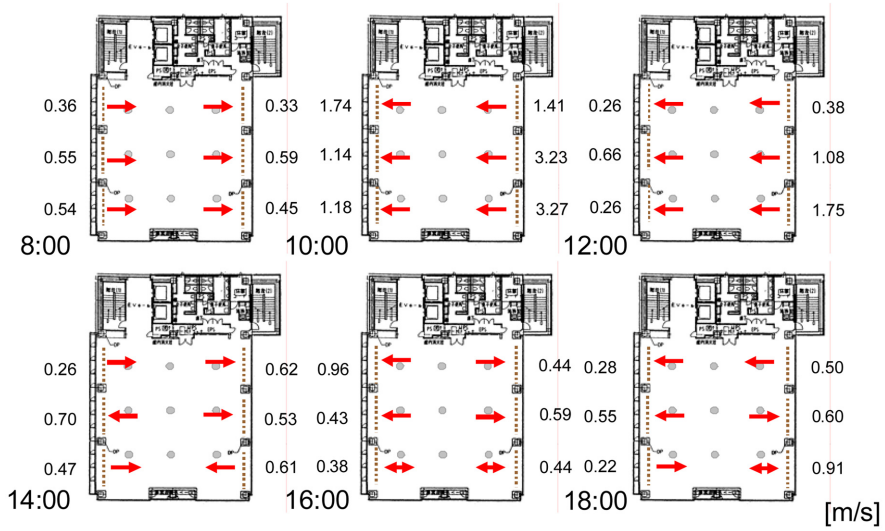


(3) Wind directions of air inflow/outflow on the 5F (visualization measurements)

Figure 16. Scalar wind speeds and wind directions (visualization measurements) at each indoor measurement point (spring).



(1) 5F scalar wind velocity distributions (Natural vemntilation without air-conditioning)



(2) Wind direction of air inflow/outflow on the 5F (visualization measurements).

Figure 17. Scalar wind speeds and wind directions (visualization measurement) at each indoor measurement point (fall).

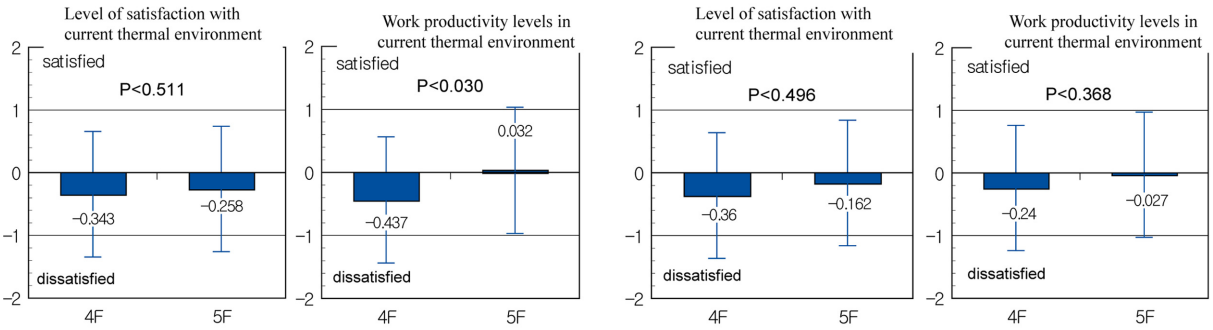
tion, instead of steady flow fields in which outside air flowed in from the natural ventilation opening and flowed out toward the DSF side.

4.8. Questionnaire survey measurement

The main focus of the questionnaire was to conduct paired comparison of workers performance on 4F (which did not used natural ventilation) with those on 5F (which did use natural ventilation). The fourth floor comprised of mainly white-collar workers (Administration and Sales Dept.), while the fifth floor was mainly occupied by engineering-related departments (Design). There was a large difference in the seating capacity between the two floors, which can be inferred from the type of work being performed.

Figure 18 shows the self-estimated levels of productivity for workers and satisfaction with regard to the current thermal environments, especially in temperatures, as answered by the questionnaire surveys. The majority of workers were dissatisfied with their current thermal environment in both the spring and fall, and no significant differences was observed between the fourth and fifth floors. That is, there were no significant differences between those on the floor with natural ventilation and those on the floor without it. Temperature differences were found between the fourth and fifth floors, and although temperatures on the fifth floor (with natural ventilation) were relatively high, we found no indication that these differences affected the subjective evaluation.

As for worker's productivity levels, there were little significant differences between floors. We are aware that changes in thermal environments can lower worker pro-



(1) Thermal environment evaluation results (spring) (2) Thermal environment evaluation results (fall)

Figure 18. Self-evaluation results for satisfaction and work productivity in the current thermal environment.

ductivity, but no significant differences was observed between either floor during the fall, despite the majority of worker expressing an overall slight dissatisfaction with their current thermal environments. Furthermore, detailed research and investigation is necessary to evaluate the causes of dissatisfaction with regard to the spring thermal environments on the fourth floor (without natural ventilation).

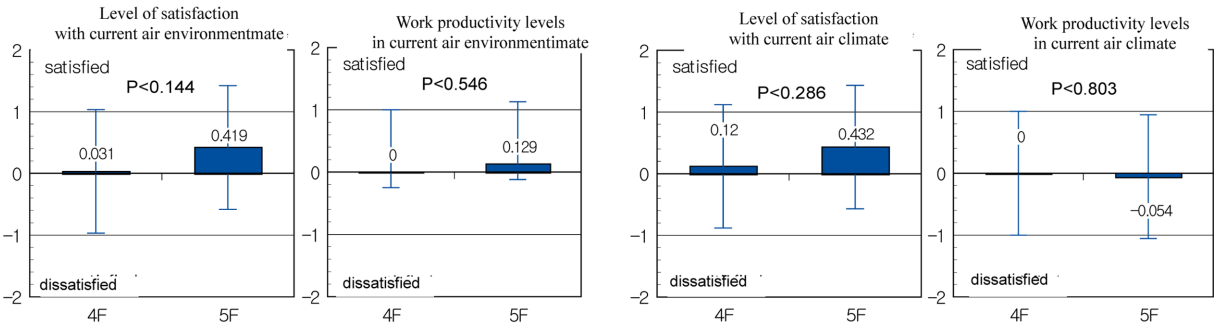
Figure 19 shows levels of worker productivity and satisfaction with the regard to current air environment, as answered by the questionnaire surveys. The majority of workers on the fourth floor held a neutral stance in both spring and fall, while workers on the fifth floor were overall slightly satisfied with their air environment. Although there were no significant differences found between the spring and fall results, participants on the fifth floor were somewhat satisfied with their current air environment (with natural ventilation), suggesting that there was a constant effect from natural ventilation.

The results regarding workpace productivity were neutral in both fall and spring for both floors, and there were no subjective indications of air environment influencing worker productivity.

Figure 20 shows levels of worker productivity and satisfaction with regard to the current spatial environment (room size and furniture placement). Workers on the fourth floor appeared to be somewhat dissatisfied in both the spring and fall assessments, while workers on the fifth floor appeared to lean toward being satisfied. Since the fifth floor occupied by a single department, there was no partition from floor to ceiling in the midarea, which separated the floor into two spaces. There was such a partition on the fourth floor, and this may have been a significant factor in how workers perceived the space.

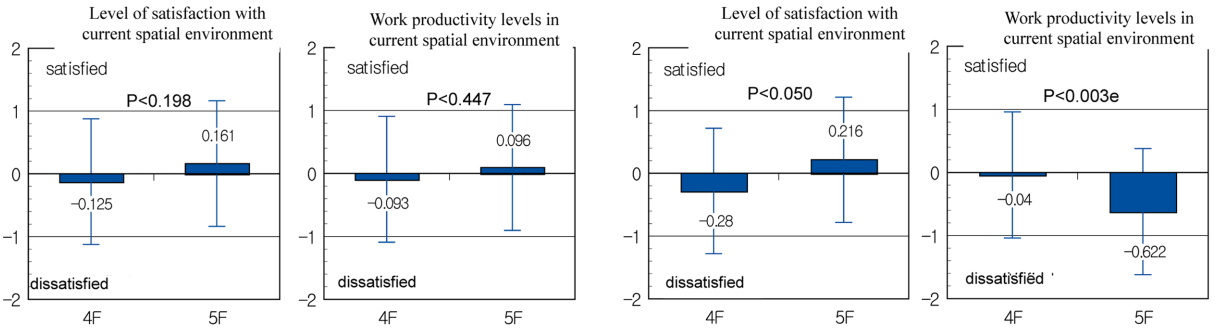
In the spring, there were no significant differences in workpace productivity levels, though workers on the fourth floor showed a slight dissatisfaction with their spatial environment while the fifth floor participants appeared to be slightly satisfied. However, large changes in spatial environment awareness occurred on the fifth floor during the fall assessment, with a shift toward a decrease in overall work productivity. If we compared these results with those for spatial environments in previous buildings, although there are relative amounts of satisfaction with new work environments, compared with old, observations show that there is still room for improvement in performing work more productively.

Construction of this building was completed in December of 2006, and these questionnaires were completed in May and October of 2007. Consequently, “honeymoon effect” seemed to be observed in the spring results as the room setup had been completed and workers had just begun working in their new office environment; we infer this is why these workers were somewhat satisfied with



(1) Air environment evaluation results (spring) (2) Air environment evaluation results (fall)

Figure 19. Levels of satisfaction and work productivity in the current air environment.



(1) Spatial environment evaluation results (spring) (2) Spatial environment evaluation results (fall)

Figure 20. Self-evaluation results regarding levels of satisfaction and work productivity in the current spatial environment.

their work environments. But in the fall, a shift toward an overall neutral is observed.

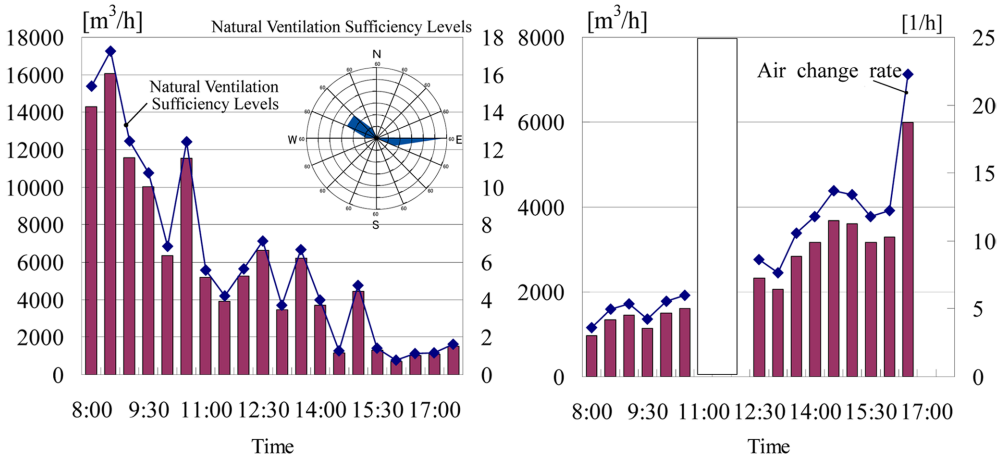
A comprehensive assessment of these surveys showed that, with regard to environmental satisfaction levels, there is still room for improvement in the thermal environment. With regard to productivity levels, the results indicate the need for improvement in the spatial environment (room size and furniture placement), particularly on the fourth floor. In addition, the (1) overall environment satisfaction levels and the (2) intellectual productivity levels obtained from the self-assessment for the fifth floor (with natural ventilation) were both relatively high.

4.9. Natural ventilation rate

Figure 21 shows the spring measurements for natural ventilation rate on the fifth floor. During the morning, natural ventilation intake (rate) were high, but the values gradually decreased over time. However, it is demonstrated that the values for the direction and speed of wind coming into the office from each ventilation opening were large in the morning, where the ventilated air was flowing from the DSF side to the air supply opening on the facing side (this ventilation route was completely opposite to the design intent). For this reason, the ventilation measurements obtained by the tracer gas constant concentration method seemd to be included a constant degree of uncertainty.

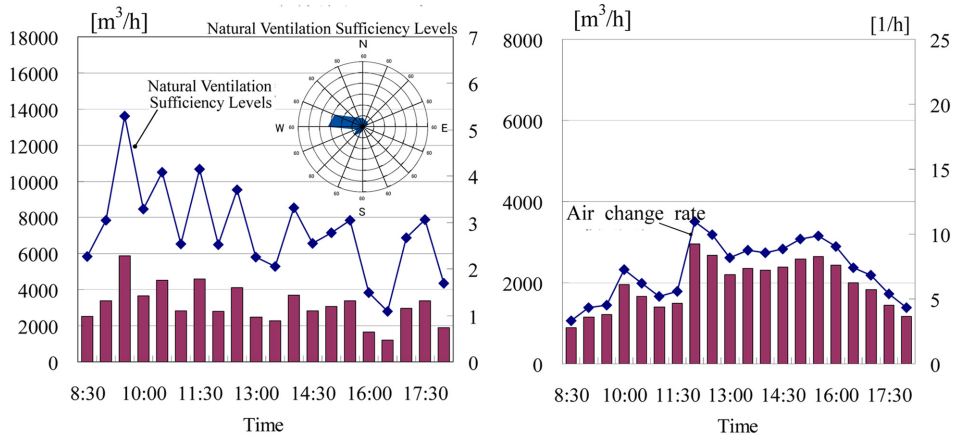
Figure 21(2) shows calculated results for the ventilation rate inside the DSF. Although a sufficient amount of data were not available between 11:00 am and 12:30 pm, the figure does show increases in outdoor wind speed coming from the sea as the afternoon progresses, indicating increasing ventilation flow inside the DSF.

Just as for spring measurements, the solar radiation screening blinds around the air supply openings and the exhaust openings were removed during fall measurements for natural ventilation. Figure 22 shows the natural ventilation rate measured on the inside of the fifth floor office. As a result, the ventilation within the office area was found to be low during the daytime for fall compared with spring. Changes in ventilation corresponded to increases and decreases in solar radiation, which occurred through the day. There was a positive correlation between the amount of solar radiation and ventilation flow inside the DSF during both the spring and fall measurement periods.



(1) Natural ventilation rate in Office space (2) DS internal ventilation measurements

Figure 21. Natural ventilation rate in spring (May 28).



(1) Natural ventilation rate in Office space (Oct. 10th) (2) DSF internal ventilation (Oct. 11th)

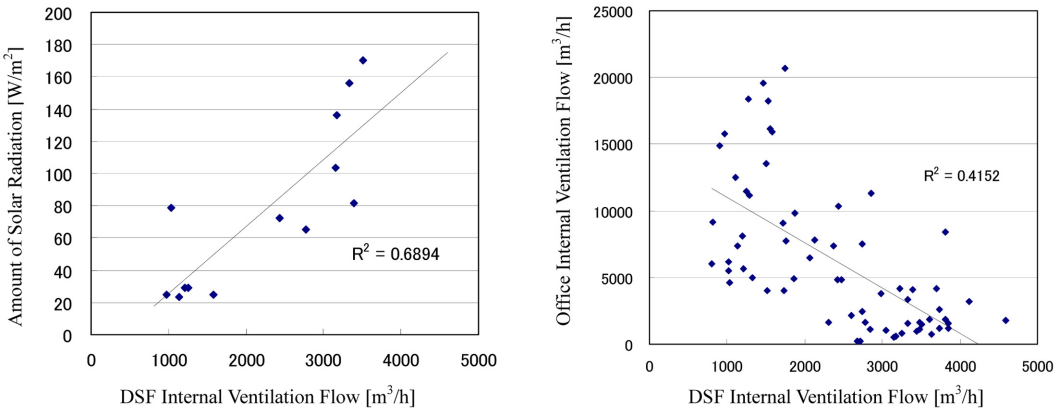
Figure 22. Natural ventilation rate in fall (Oct. 10th, 11th).

4.10. Characteristics of the natural ventilation in DSF

Figure 23 shows the correlation between the DSF internal air flow rate (ventilation rate) and the amount of solar radiation (normal surface amount of solar radiation for the DSF) for the vertical surface on the west side during the spring. This figure also shows the natural ventilation sufficiency levels (the ratio of natural ventilation flow as required for the design). A positive correlation exists between the measured DSF internal air flow rate and the amount of solar radiation on the DSF normal surface. Note that the primary driving force for ventilation in the DSF is considered to be the buoyancy force derived from solar radiation. This kind of chimney effect is brought about by differences in indoor and outdoor temperatures and can occur in buildings having low differences in temperature, such as residential houses. This suggests that natural ventilation might be an adequate ventilation system for use in residential houses.

Figure 23(2) shows the attenuation of indoor ventilation as the ventilation (surface wind speed) in the DSF increased. As the wind speed inside the DSF increased, the inducing (attraction) effect got smaller, and indoor ventilation flows also decreased. Figure 24 shows the correlation between fall measurements for DSF internal ventilation flow and the amount of solar radiation (amount of solar radiation for DSF normal surface) for the vertical surface on the west side; the trends here are the same as in Figure 23 for spring measurements.

The DSF was originally intended to be used on daytimes. Solar radiation would heat the air inside the cavity, causing upward airflows as a result of differences between indoor and outdoor air densities. Those upward flows would improve the effectiveness of drawing out the indoor air, thereby increasing the indoor ventilation flow. Here, the DSF can be considered to be a kind of buffer that makes environmental adjustments; it can control the amount of natural ventilation flow that enters a building, thereby avoiding excess inflows and rectifying the outdoor airflow entering the building. Use of a DSF may provide a technique for forming relatively serene indoor flow



(1) Correlation between DSF normal surface solar radiation and DSF internal ventilation flow

(2) Correlation between office internal ventilation flow and DSF internal ventilation flow

Figure 23. Correlative relationships based on spring measurements.

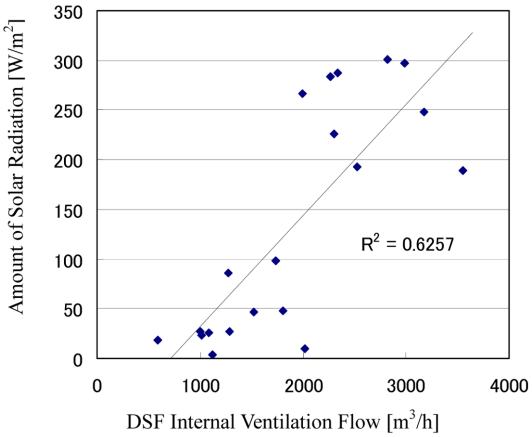


Figure 24. Correlation between DSF normal surface solar radiation and DSF internal ventilation flow (fall).

fields. We believe that additional assessments will be needed to check the pressure balance inside the ventilation route and to consider measures for improvement (shapes and degree of opening for DSF vertical apertural areas and ventilation openings) that will facilitate indoor natural ventilation flow.

4.11. Wind pressure (inflow/outflow directions)

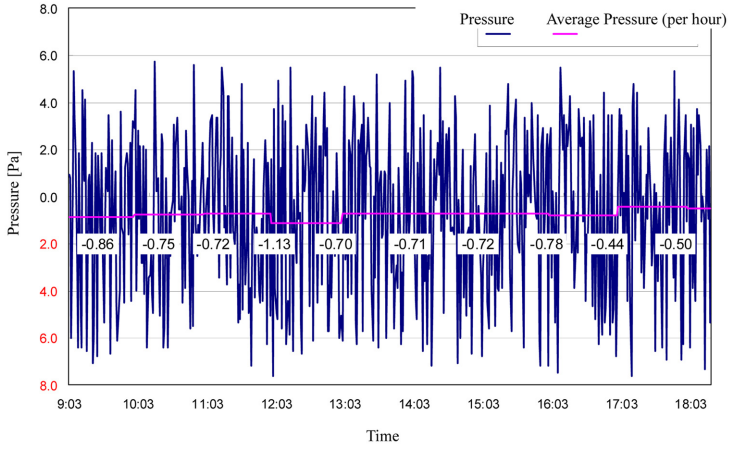
Figure 25 shows measured differences in indoor and outdoor pressure, as measured with wind pressure plates placed at different locations (natural ventilation opening area and indoor floor surface areas) and using a precise differential pressure gauge. Pressure differences showed large fluctuations over time, consistent with unsteady natural ventilation. Hourly average indoor pressures were negative, indicating a constant (average) intake of outdoor air.

5. Discussions and Conclusions

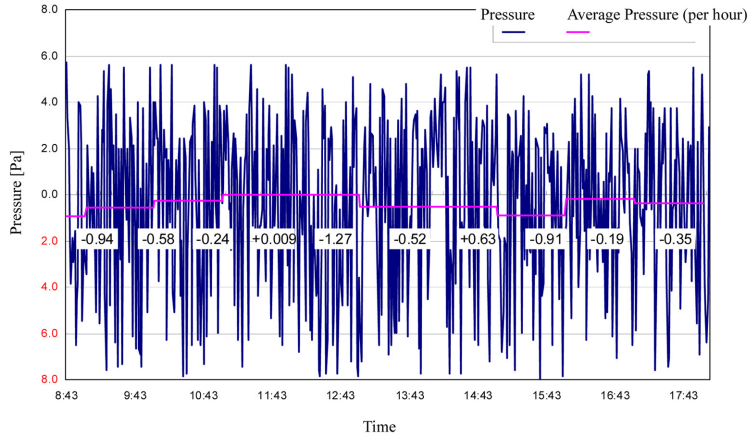
The finding of this field measurements are summalized as follows:

(1) Thermal environments

Thermal indoor environments were heavily influenced by heat load at the perimeter zone, and there was a noteworthy temperature distribution along the horizontal plane inside office spaces. With natural ventilation by way of DSF, indoor air temperatures were strongly affected by



(1) Measurements taken in fall (Oct. 10th)



(2) Measurements taken in fall (Oct. 11th)

Figure 25. Pressure Differences.

outside air temperatures, and comparison of this with that of air-conditioning system with mechanical ventilation (4F), revealed considerable changes in indoor temperatures as well as in vertical temperature distributions. Such large temperature differences did not appear in indoor thermal environment for the fourth floor (with mechanical ventilation and air-conditioning constantly in use). The significant differences of PMV were not observed between fourth floor and fifth floor. Since PMV values for the fourth floor stayed slightly above the comfortable zone, the primary reasons for the formation of this thermal environment was the solar radiation through glass surfaces (these glass surfaces brought in light from three sides of the building). Relatively, ventilation systems have little influence on the formation of thermal environments in this field measurement.

Placing blinds to screen solar radiation inside the DSF may be a theoretically reasonable measure for improving indoor thermal environment.

(2) Air quality environment

From measurement results of VOCs and fungal concentrations, indoor air quality satisfied the guidelines levels by the Ministry of Health, Labor and Welfare in Japan and the guidelines by the Arichitectural Institute of Japan (AIJ) in the academic standards. The actual ventilation route for inflows and outflows of outside air were found to be opposite to that intended in the design stage and there were also large daily fluctuations. The daily average natural ventilation rate was at the same level as required for building code based on the density of workers.

(3) Indoor airflow

The spring results showed that indoor airflows on the fifth floor with natural ventilation and on the fourth floor with air-conditioning and mechanical ventilation system were the same; even the peak values matched at 0.3 m/s. The blinds installed on the inside of the room at the ventilation opening were considered to be functioning as a rectifier. In contrast, the fall results showed that with these blinds removed, the indoor airflows for the fifth floor peaked at over 1.0 m/s. This suggests that a flow regulator or some other kind of equipment that could produce a constant airflow is necessary when applying natural ventilation to office spaces. In both spring and fall, the indoor ventilation route during the morning took in air from the ventilation opening, and then it would pass through the building and exit through the DSF side. This route is opposite to that intended in the original design. We believe further evaluation is needed for the shape, location, and ventilation route of ventilation openings that have a high dependence on wind direction.

(4) Questionnaire survey

Since the spring survey was conducted shortly after the building construction had completed, "honeymoon effect" seemd to be observed in the survey results, which is considered to have contributed to overall positive satisfaction levels. In contrast, in the fall results, overall satisfaction levels shifted toward neutral. A comprehensive assessment of these questionnaire results showed that, with regard to environmental satisfaction levels, there was still room for improvement in the thermal environment. As for self-evaluated productivity levels, the results indicated the need for improvement in the spatial environment, e.g., room size and furniture placement, particularly in regard to the space on the fourth floor. The overall environment satisfaction levels and the productivity levels obtained from the self-assessment for the space on the fifth floor (with natural ventilation) were both relatively high.

(5) Natural ventilation

In both the spring and fall results, there was a positive correlation between the DSF internal air flow rate and the amount of solar radiation on the DSF normal surface; the primary driving force for ventilation inside the DSF was considered to be the buoyancy force caused by solar radiation. Although the air flow rate inside the DSF increased, the inducing effect from indoor to DSF decreased and the ventilation rate in office spaces also decreased. The DSF was designed to use the upward airflows inside the cavity, thereby providing increased ventilation in indoors. In addition, the DSF should be considered to be a kind of buffer that makes environmental adjustments, thereby controlling the amount of natural ventilation to either enhance or reduce outdoor air inflowing into the building. Use of a DSF should also provide a technique for forming relatively stagnant indoor flow fields.

We believe that an additional assessment will be needed to check the pressure balance inside the ventilation route. In addition, further consideration should be given to measures for improvements of shapes and degree of opening for DSF vertical apertural areas and ventilation openings), that facilitate indoor natural ventilation.

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