【*Technical Paper*】

STUDY ON OPERATIONAL UPGRADING IN ENERGY SELF-SUFFICIENT INNOVATION CENTER (PART 1) PERFORMANCE EVALUATION OF PERSONAL AIR CONDITIONING SYSTEM IN SUMMER AND WINTER

Mishan SHRESTHA[1], Kentaro KIMURA[1], Akihiro SHIMIZU[1], Katsuhiko SHIBATA[1]
Yu ICHIKAWA[1], Masahiro SAITO[1], Masanari UKAI[2], Sin-Ichi TANABE[2]

ABSTRACT

We are developing a ceiling-mounted air conditioning unit (hereinafter referred to as DCFCU) using DC fan with the aim of reducing the environmental impact of office buildings. The DCFCU installed at the Takasago Thermal Engineering Innovation Center (hereafter referred to as "the facility") was originally introduced as a personal air conditioning (PECS: Personal Environment Comfort System) for cooling purposes [1]. However, during peak periods in summer and winter, deterioration in the indoor working environment was observed. Therefore, DCFCU was repurposed as an ambient air conditioning to improve the working environment and reduce energy consumption. This study presents the results of improving the indoor thermal environment and reducing energy consumption in open office areas by supplying waste hot water to DCFCU discharged from a wood biomass gasification generator (hereafter referred to as biomass CHP, CHP: Combined heat and power) in winter. In summer, groundwater was utilized for cooling. These were implemented during early morning start-up and working hours.

1. INTRODUCTION

In the field of air conditioning systems, research on PECS is advancing from the perspectives of achieving ZEB (Zero Energy Buildings), improving thermal comfort, and energy saving [2-4]. IEA EBC Annex 87 is working to quantify the benefits of PECS in terms of comfort, health, energy performance, and cost, as well as to establish design criteria and operation guidelines. These efforts underscore that the integration of PECS with general ambient systems in space is an internationally significant research topic [5].

This facility has adopted and operates PECS to achieve reduced environmental impact and enhanced intellectual productivity. The PECS is localized air conditioning system developed to address individual thermal discomfort and preferences by directly cooling or heating the body without affecting the overall thermal environment. It provides low-power air supply, heating, and cooling near the user. Therefore, when the PECS is used as ambient air conditioning, it is expected to contribute more significantly to energy savings, particularly by reducing air transport power compared to conventional methods that distribute air from multiple outlets. An overview of the building, energy and heat source systems, and air conditioning systems is introduced first.

1.1 Architectural Overview

This facility is an energy self-sufficient that aims for off-grid operation by integrating solar power generation, biomass CHP, groundwater heat utilization, and large-scale batteries [6]. **Fig. 1** shows the exterior and interior views, and **Table 1** shows an overview of the facility. The facility primarily consists of office and laboratory wings. The energy-saving goal for the office wing is to achieve ZEB status, and the entire facility aims to achieve "ZEB Ready" based on actual performance [7]. During intermediate seasons such as spring and

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[1] Takasago Thermal Engineering Co., Ltd.
[2] Department of Architecture, Waseda University

autumn, natural ventilation is carried out by opening windows located at both high and low positions when outdoor climatic conditions are favorable.

Fig. 1 Exterior (upper) & interior (down) view of the facility

Table 1 Facility overview

Location	Ibaraki Prefecture, Japan
Facility Use	Office and Research facility
Number of floors	2 stories
Height	15.455m
Gross floor area	11,763.97 m²
Office wing area	4,757 m²
Completion date	January 2020

1.2 Energy and Heat Sources System for Air Conditioning

The schematic diagram in **Fig. 2** shows an overview of the energy and heat source systems adopted in the facility. Groundwater is used for cooling, whose temperature ranges from 15~17°C throughout the year. It is used for various air conditioning systems, such as the desiccant outdoor air conditioning unit (DOAS) on the first floor, the PECS, and ceiling radiant panels. Two biomass CHP units are installed, enabling the extraction of both electricity and heat. The waste heat from the biomass CHP is utilized for the air conditioning systems, hot water supply, and biomass chip drying.

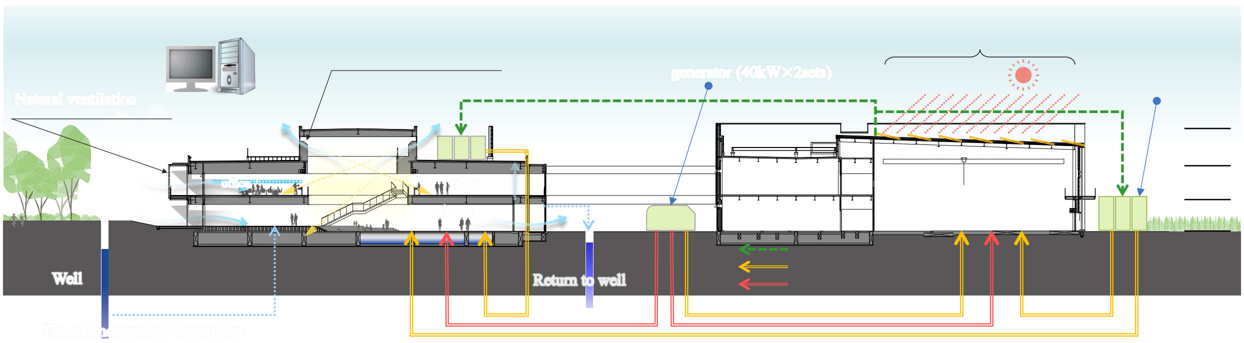


Fig. 2 Conceptual diagram of energy and heat source systems

1.3 Air Conditioning Systems

Fig. 3 shows the concept of the air conditioning system adopted for the office area. The office area on the second floor is designed based on the Activity-Based Working (ABW) concept, enabling a flexible environment. This environment consists of ambient air treated by a reheat-type outdoor air handling unit (OHU) and personal environments controlled by human centric PECS units.

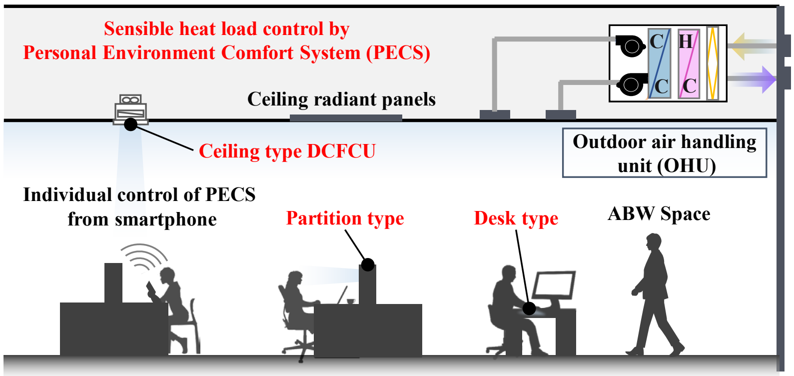


Fig. 3 Conceptual diagram of PECS uses in office area

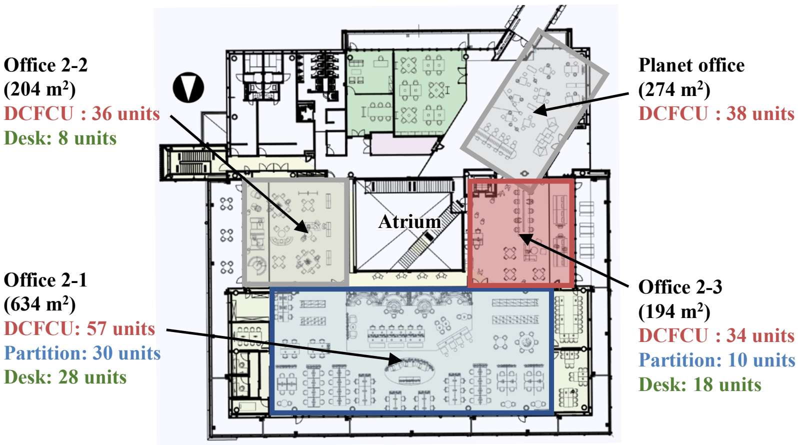


Fig. 4 2F plan view of the office area indicating PECS installation areas,
Closed area: Office area 2-1, Open area: Office area 2-2,2-3

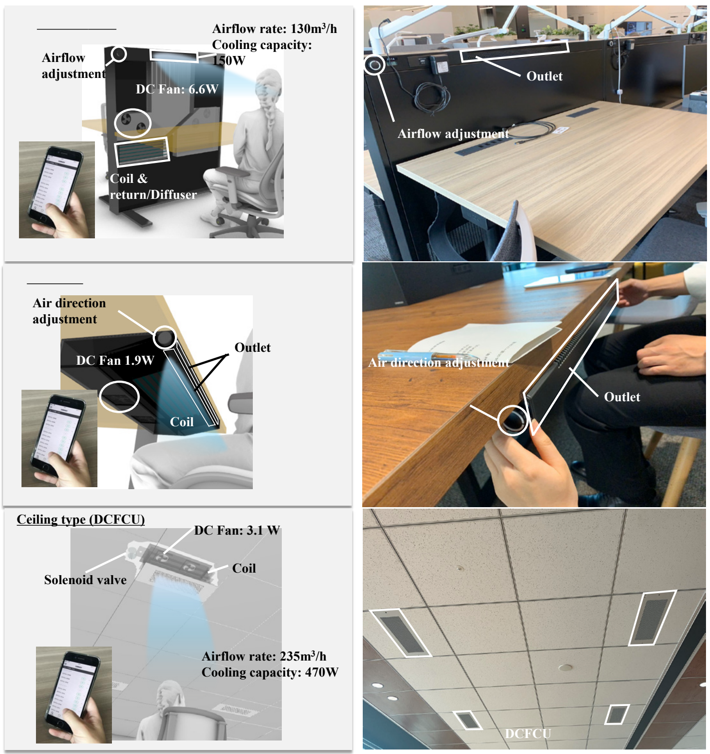


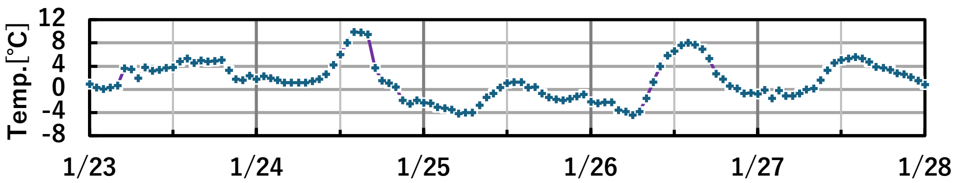
Fig. 5 Specifications of PECS: Application image (Left), Installation image in the facility (Right)

Fig. 4 shows the office area, which is mainly divided into two different areas: a closed area named Office 2-1 and an open area which consists of Office 2-2, Office 2-3, and Planet Office. The installation areas for PECS are also indicated. **Fig. 5** shows three types of PECS: partition type, desk type, and ceiling-mounted DCFCU, installed in the office area along with their specifications. These units can be turned ON/OFF using smartphones according to occupant preferences. The DCFCU uses DC fans and operates with very low power consumption.

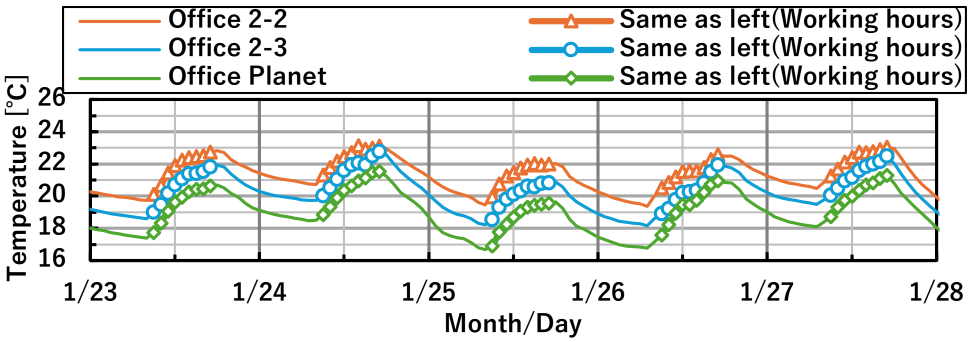
2. PERFORMANCE EVALUATION IN WINTER

The open office area is air-conditioned using OHU and PECS. During the winter, the OHU starts preheating approximately two hours before the start of work; however, there was an issue where the indoor temperature took a long time to rise, and even by the afternoon, it did not reach the required temperature of 22°C. **Fig. 6 (a)** shows the outdoor temperature and **Fig. 6 (b)** shows the indoor temperature variations in the open area during a representative week in January 2023. Although there were variations depending on indoor and outdoor temperatures, the room temperature ranged from 17~ 21°C at the start of work and gradually increased, reaching approximately 22°C by the end of the working hours.

Therefore, in order to improve thermal comfort in the open area, the piping system was upgraded so that hot water prepared by the exhaust heat of the biomass CHP could be supplied to the DCFCU. Additionally, new functions were added to enable batch scheduled operation of the DCFCUs, which were originally installed for personal air conditioning, so they could be used for ambient air conditioning as well. Specifically, a method was adopted where all DCFCUs are operated in batch before the start of working hours to preheat the open area. To evaluate the effectiveness of these operational improvements, verification study was conducted under three conditions: without preheating (Case 1), and with preheating (Case 2 and Case 3). The verification methods and results are presented below.



(a) Outdoor air temperatures



(b) Indoor air temperatures

Fig. 6 Variations of temperatures (Jan. 2023)

2.1 Methodology

Table 2 shows an overview of winter measurements. **Fig. 7** shows an overview of thermal environment measurements in the office area. During preheating operation, the hot water supply temperature to the DCFCUs (hereafter referred to as T_{HS}) was set at: 45°C (Case 2) and 35°C (Case 3). The preheating operation was carried out from 5:30~7:30, prior to the operation of the OHU, which operated from 8:00~18:00.

A questionnaire survey was conducted once a day via an online format targeting office occupants. **Table 3** shows the scales used in the questionnaire survey for the thermal sensation vote (TSV) and thermal satisfaction vote. TSV is evaluated using a seven-point scale based on the PMV, ranging from “Cold” (-3) to “Hot” (+3). Thermal satisfaction is also assessed using a seven-point scale, ranging from “Very dissatisfied” (-3) to “Very satisfied” (+3), and both are used for evaluation.

Table 2 Measurement overview in winter

Survey period	Winter (2024/1/8~1/31)
Area	Office 2-2 and 2-3 (open area)
Purpose of DCFCU use	Preheating
DCFCU operation time	Case 1: all units OFF Case 2, Case 3: 5:30~7:30
OHU operation time	Case 1: 7:00~18:00 Case 2, Case 3: 8:00~18:00
Heat source	Waste heat of biomass CHP

Table 3 Scales used for questionnaire survey

Survey period	Winter (2024/1/8~1/31)
Area	Office 2-2 and 2-3 (open area)
Purpose of DCFCU use	Preheating
DCFCU operation time	Case 1: all units OFF Case 2, Case 3: 5:30~7:30
OHU operation time	Case 1: 7:00~18:00 Case 2, Case 3: 8:00~18:00
Heat source	Waste heat of biomass CHP

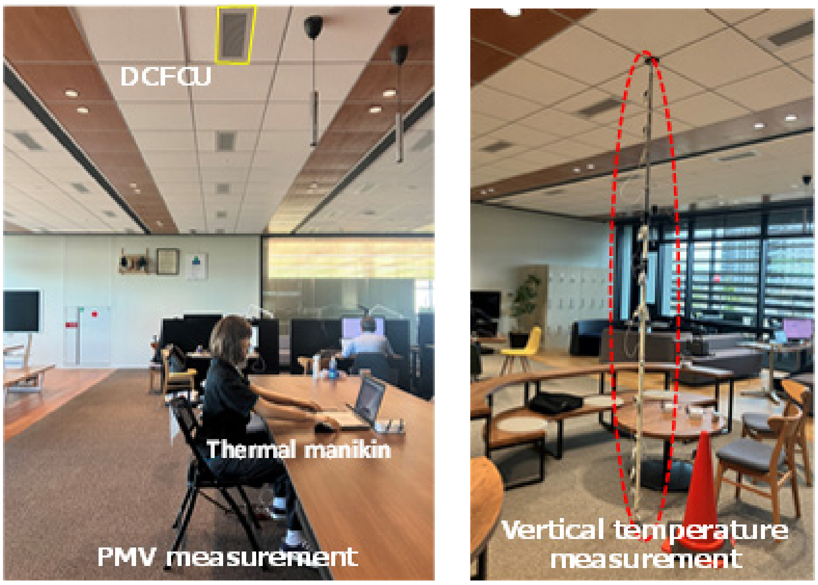
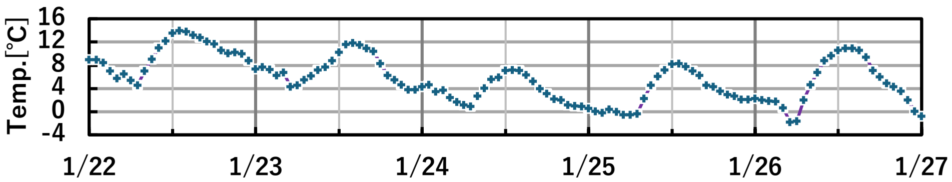


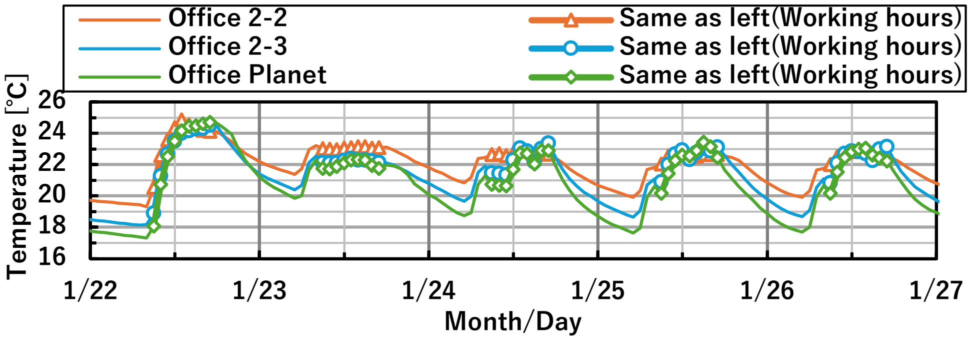
Fig. 7 Thermal environment measurement in the office area

2.2 Outdoor and Indoor Temperatures

Fig. 8 shows the variations of outdoor air temperature and indoor temperature for a representative week in January 2024 after the implementation of operational improvements (Case 3, T_{HS}: 35°C). On January 22, the first workday after a holiday, the indoor temperature was below 20°C at 9:00, the start of work. However, thereafter, it remained generally between 20~24°C, indicating the effectiveness of preheating by the DCFCU.



(a) Outdoor air temperatures

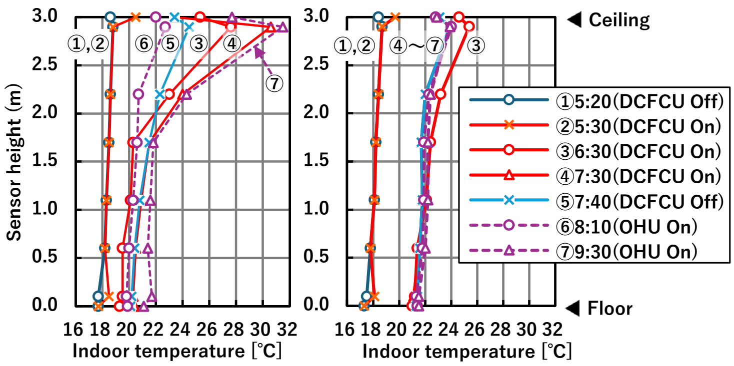


(b) Indoor air temperatures

Fig. 8 Variations of temperatures (Jan. 2024, Case 3)

2.3 Vertical Temperature Distribution

Fig. 9 shows the vertical temperature distribution before and after preheating in the Office 2-3 on a representative day. In Case 2, during preheating, the air temperature near the ceiling rises to as high as 30°C, but gradually decreases after the DCFCUs stop, with the air temperature maintaining around 20-21° C in the occupied zone. Subsequently, the OHU starts the operation, and by 9:30 (⑦ in the **Fig.9**), the air temperature near the ceiling start to increase again. This is because the DCFCU was operated again after the preheating operation was ended. On the other hand, in Case 3, the temperature rise near the ceiling during preheating operation was smaller compared to Case 2. At the end of preheating operation, the air temperature in the occupied zone was maintained at around 22°C, indicating that the air is sufficiently mixed throughout the room. **Fig. 10** shows the thermal images taken at the end of the preheating operation. As shown in **Fig. 9**, in Case 2, only the ceiling area becomes hot, and warm air did not reach the occupied zone, whereas in Case 3, the vertical temperature distribution is smaller.



(a) Case 2 (T_{HS} : 45℃) (b) Case 3 (T_{HS} : 35℃)

Fig. 9 Representative vertical temperature distribution

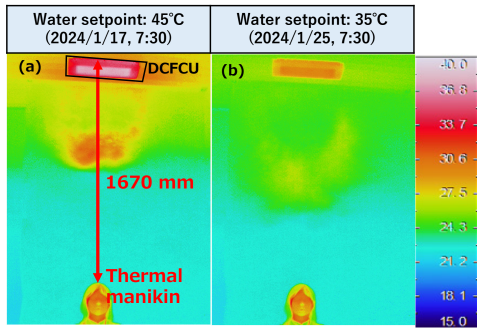


Fig. 10 Thermography image at the end of preheating

2.4 Evaluation by PMV

Fig. 11 shows a comparison of PMV during core working hours. PMV was calculated using measured values of air temperature, globe temperature, and relative humidity at a height of 600 mm from the floor. The clothing insulation was set to 0.73 clo, metabolic rate to 1.2 met, and air velocity to 0.1 m/s. In Case 1, the PMV was -1.0, indicating a cold thermal sensation. In contrast, in Case 2 and Case 3, the PMV remained within the range of approximately -0.5 to 0.5, confirming the effectiveness of the preheating operation.

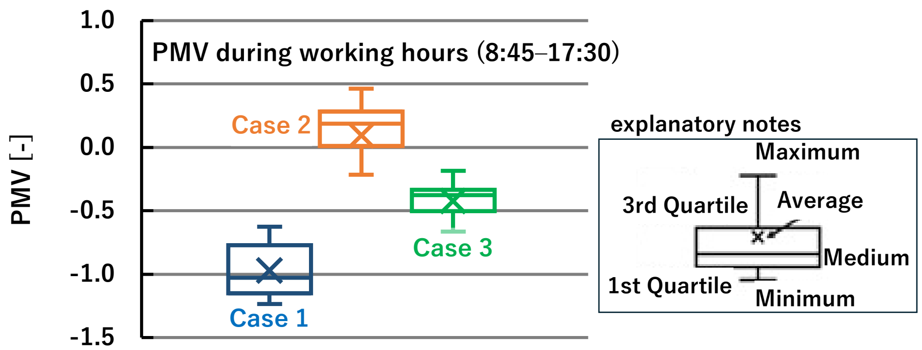


Fig. 11 Representative PMV in winter

2.5 Evaluation by Questionnaire Survey

Fig. 12 (a) shows the TSV at the start of work (8:45), and **Fig. 12 (b)** shows the thermal satisfaction vote during working hours. In Case 1, where no preheating operation was conducted, 44% of occupants voted "Cool" or "Slightly cool" at the start of work. In contrast, in Case 2 and Case 3, where preheating operation was conducted, votes of cold sensations disappeared significantly, and approximately 70% of the occupants voted feeling "Slightly warm"~"Hot".

Regarding the thermal satisfaction vote during core working hours, Case 1 showed that only 68% of occupants voted feeling "Neutral"~"Satisfied." The votes increased to 81% in Case 2, and further to 94% in Case 3. The higher thermal satisfaction in Case 3 compared to Case 2 is considered due to some occupants who voted "Hot" in TSV also indicating dissatisfied in terms of thermal satisfaction. In addition, thermal comfort was found to be higher at T_{HS} = 35°C compared to T_{HS} = 45°C. This is likely due to the smaller difference between the indoor air temperature and the supply air temperature, which led to mixing of indoor air and reduced the vertical temperature difference.

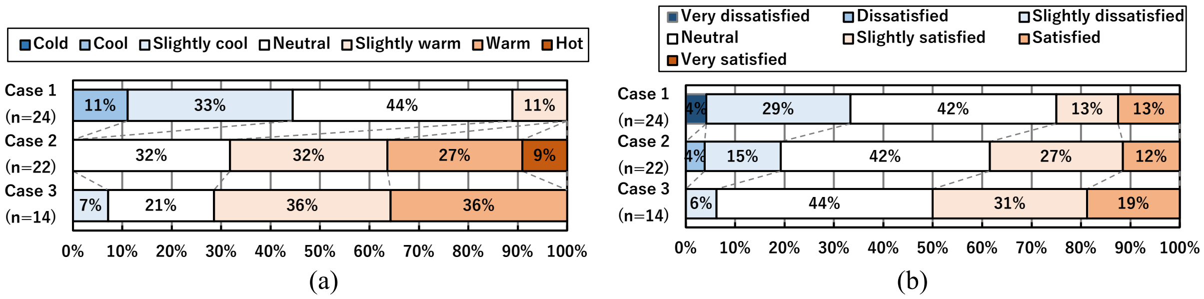


Fig. 12 Questionnaire survey results: (a) Thermal sensation votes at the start of work, (b) Thermal satisfaction during core working hours

2.6 Energy Efficiency Evaluation

To evaluate the energy-saving potential of the preheating operation, the power consumption of the OHU, hot water secondary pump, and DCFCU were analyzed. **Fig. 13** shows the comparison of the daily cumulative power consumption on a representative day (January 24, 2024) when DCFCU preheating was conducted at T_{HS}35°C with that on a similar day (January 25, 2023) in the previous year without preheating. During the preheating period, the OHU operating time was shortened by one hour, and the indoor temperature reached the specified temperature earlier during core working hours, making it possible to reduce the OHU supply airflow. As a result, daily power consumption was reduced by approximately 32% compared to the day without preheating. Furthermore, even with reduced supply airflow of the OHU, indoor CO_2 concentration remained below 700 ppm.

A comparison of power consumption over the two-month period of January and February between 2023 (without preheating) and 2024 (with preheating) confirmed an energy reduction of approximately 25%, equivalent to about 1,070 kWh.

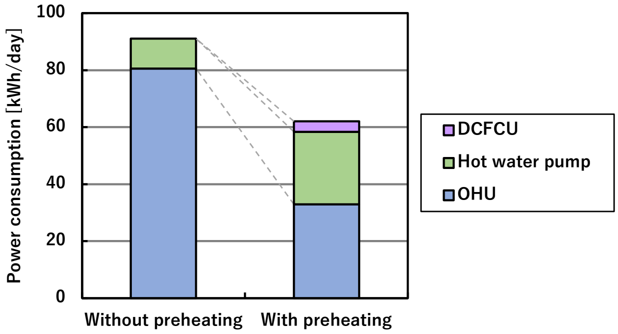


Fig. 13 Comparison of energy consumption

3. PERFORMANCE EVALUATION IN SUMMER

Using the ambient air conditioning function of the DCFCU system, which was upgraded during the winter survey, performance verification was also conducted during the summer, with the aim of improving thermal comfort and achieving energy savings. Specifically, the verification was conducted by changing the number of DCFCU operating in the open area. The verification methods and results are presented below.

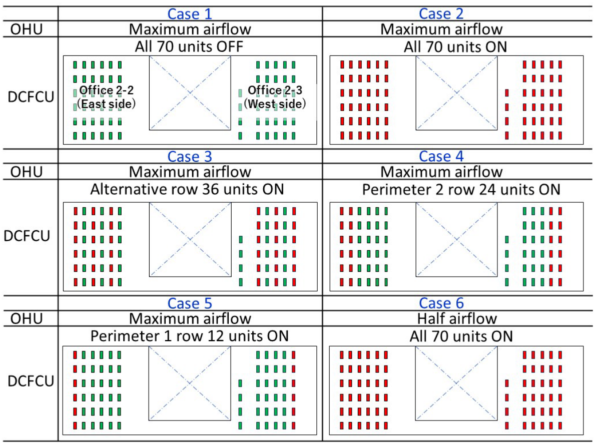
3.1 Methodology

Table 4 shows an overview of the summer measurements. The OHU operated from 6:00~18:00, including pre-cooling, while the DCFCUs operated from 8:00~17:30. The OHU operation was scheduled to start 2 hours earlier than the DCFCU operation in order to perform dehumidification during pre-cooling and prevent condensation on the surfaces of the DCFCU units during their operation. The survey was conducted once a day online, similar to the winter survey. **Table 5** shows the operation patterns of the OHU and DCFCU. In Case 1, all DCFCUs were turned off, while in Cases 2~5, the number of operating DCFCUs varied. In Cases 1~5, the supply airflow of the OHU was set to the maximum airflow (design airflow rate). In Case 6, the supply airflow of the OHU was reduced by half, with all DCFCUs in operation.

Table 4 Measurement overview in summer

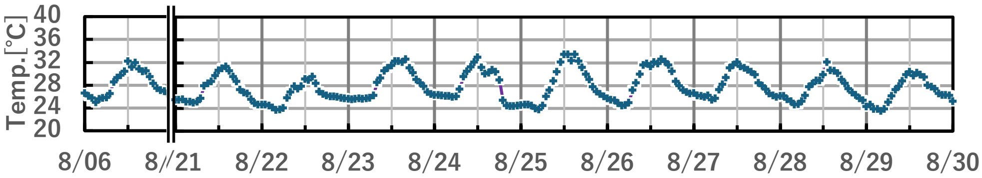
Survey period	Summer (2024/8/5~8/29)
Area	Office 2-2 and 2-3 (open area)
Purpose of DCFCU use	Zoned cooling
DCFCU operation time	8:00~17:30 (Case 2~Case 6)
OHU operation time	7:00~17:30
Heat source	DCFCU: groundwater, OHU: heat pump chiller

Table 5 Operation pattern of OHU and DCFC in summer

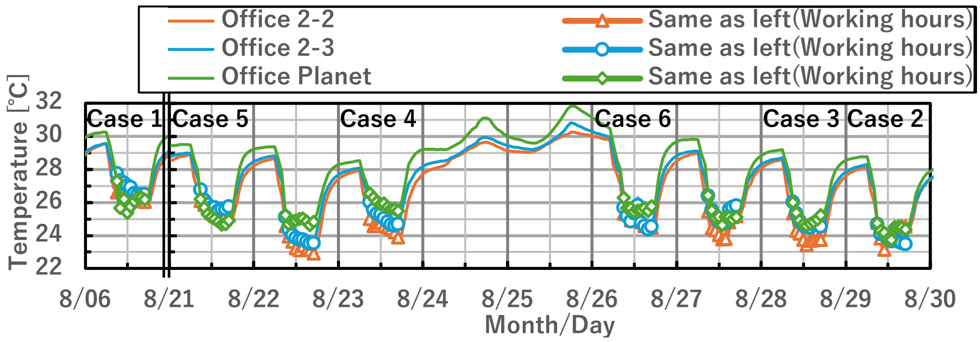


3.2 Outdoor and Indoor Temperatures

Fig. 14 (a) shows the variations in outdoor air temperatures while **Fig. 14 (b)** shows the variations in indoor air temperatures in the open area during the survey period in August 2024. In Case 1, the air temperature exceeding 26°C was frequently observed. However, in Case 2~6, the temperature remained generally below 26°C except for some periods in the morning hours at the start of work, suggesting that thermal comfort was maintained. Additionally, the indoor relative humidity during this period was generally between 50~60%, and the CO_2 concentration remained below 650 ppm in all cases.



(a) Outdoor air temperatures



(b) Indoor air temperatures

Fig. 14 Variations of temperatures (Aug. 2024)

3.3 Vertical Temperature Distribution

Fig. 15 shows a comparison of vertical temperature distributions around 14:00 PM during summer when the outdoor temperature was approximately 30~32°C, under six different operation patterns. In all cases, the vertical temperature difference in the occupied zone (height ≤ 1.7 m) was maintained below 1°C, but there are differences in the temperature range. In Case 1, where the DCFCU was not in operation, the indoor temperature approaches 26°C. In Case 2~5, the indoor temperature tended to decrease as the number of operating DCFCUs increased. In Case 6, all DCFCUs were operated with the OHU reduced supply airflow to approximately half. The indoor temperature was around 24°C, showing only about 1°C increase compared to Case 2, which operated at maximum airflow.

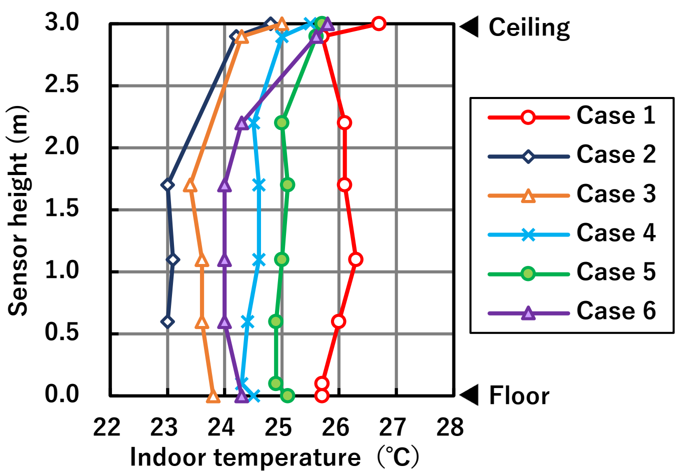


Fig. 15 Representative vertical temperature distribution

3.4 Evaluation by PMV

Fig. 16 shows a comparison of PMV during the core working hours. For the PMV calculation, the clothing insulation was set to 0.5 clo, while all other parameters were kept the same as in the winter survey. The PMV values showed a trend similar to the indoor temperature variations observed in **Fig. 15**, under the varying number of DCFCUs operations. The average PMV values for Case 1 and Cases 4~6 fell within the comfort range (PMV ≤ ±0.5).

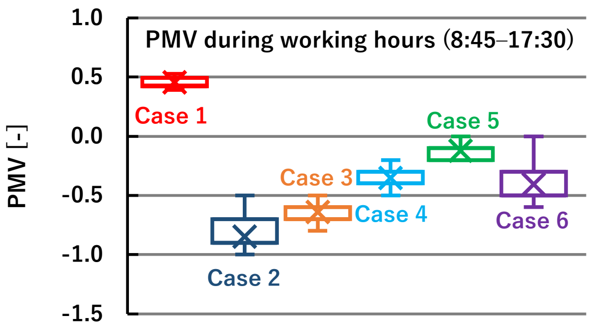


Fig. 16 Representative PMV in summer

3.5 Evaluation by Questionnaire Survey

Fig. 17 (a) shows the TSV results for each case during the summer. In Case 1, where no DCFCU was in operation, more occupants voted "Hot", whereas in Cases 2 and Case 3, where a greater number of DCFCUs were in operation, high number of occupants voted "Cold". On the other hand, in Cases 4 and Case 5, where a small number of DCFCUs were in operation, and in Case 6, where the OHU supply airflow was halved, a relatively high number of occupants voted "Neutral".

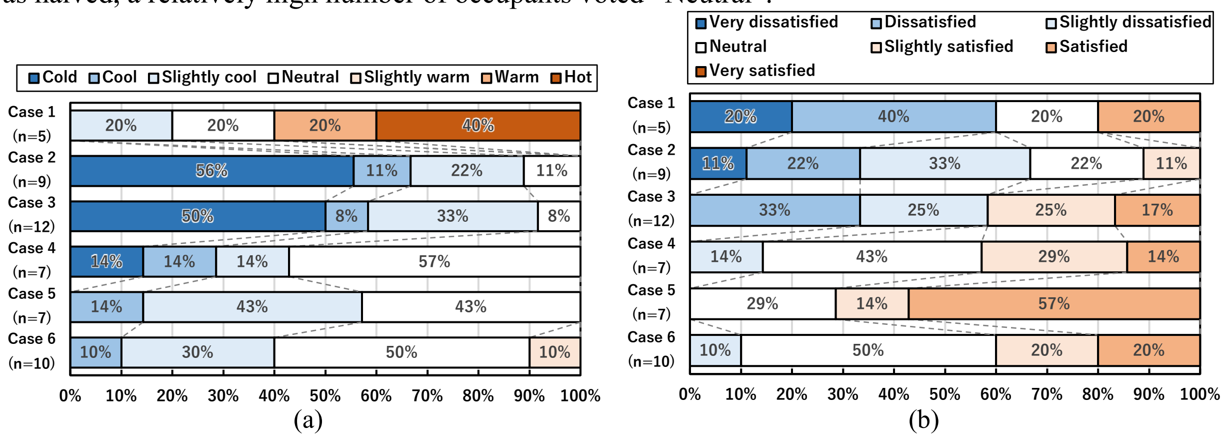


Fig. 17 Questionnaire survey results in summer: (a) Thermal sensation vote, (b) Thermal satisfaction vote

Fig. 17 (b) shows the results of the thermal satisfaction vote. Similar to the TSV results, Cases 1~3, the percentage of occupants who voted "Neutral"~"Satisfied" was below 50%, indicating low thermal satisfaction. On the other hand, in Cases 4~6, where "Neutral" votes were more frequent, over 80% of occupants voted "Neutral" to "Satisfied," indicating high thermal satisfaction. Thermal satisfaction varies significantly depending on individual preference, but the results suggest that adjusting the operation of DCFCU and OHU can improve average TSV and thermal satisfaction of occupants.

Based on the results of PMV, TSV, and thermal satisfaction vote as shown in Fig. 16 and 17, Case 5 showed the best results. In this study, Case 6 showed slightly cooler evaluations, but reducing the number of DCFCUs could further enhance comfort. It was suggested that by controlling both the OHU airflow and the number of DCFCUs, the PMV could be brought even closer to zero.

Fig. 18 shows the relationship between indoor air temperature, questionnaire survey results, and PMV for each case in summer. The average values of TSV and thermal satisfaction votes were quantified using the scales shown in **Table 3** and average for each case. Compared to PMV, TSV showed a steeper slope, indicating higher sensitivity to indoor air temperature. Furthermore, both PMV and TSV were neutral around the indoor air temperature of 25.5°C, suggesting that the thermal comfort indicated by TSV is reliable. Since thermal satisfaction also peaked at around 25.5°C, this temperature appears to represent the optimal comfort condition under the present HVAC system.

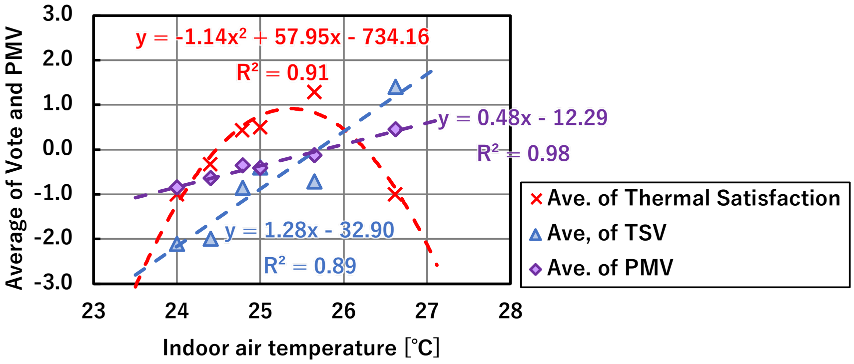


Fig. 18 Relationship between the indoor air temperature, questionnaire survey results, and PMV

3.6 Energy Efficiency Evaluation

Fig. 19 shows a comparison of the average power consumption per hour for each case. Compared to Case 1, where the DCFCUs were not in operation, Case 2~5 showed increased power consumption due to the operation of the chilled water secondary pump and DCFCUs. But the increase of power was relatively small in the context of total energy consumption. On the other hand, in Case 6, the power consumption of the OHU was significantly reduced, resulting in 18~36% reduction compared to the other cases. Based on a comprehensive evaluation of these results, Case 6, in which all DCFCUs were operated while the OHU supply airflow was halved, showed the best performance in terms of both thermal comfort and energy efficiency within the scope of this study.

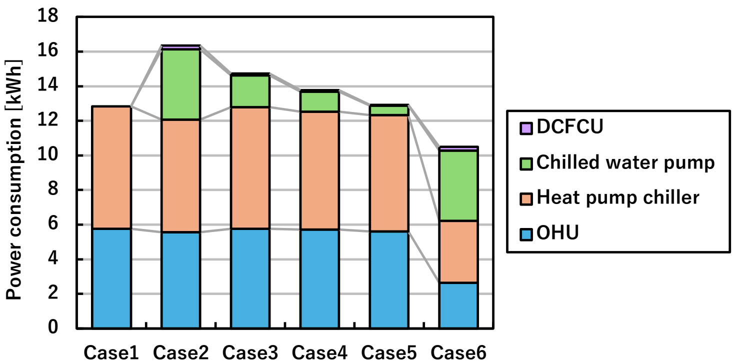


Fig. 19 Comparison of energy consumption in summer

4. CONCLUSIONS

This study introduces the facility overview, energy systems, and air conditioning systems of the Takasago Thermal Engineering Innovation Center, an energy-self-sufficient research facility. It examines the ambient performance evaluation of DCFCU units, which were installed in the open office area as personal air conditioning. These units were operated and implemented for preheating in winter and zone cooling in summer, with the aim of improving indoor environmental conditions and enhancing energy efficiency. The major findings of this study are summarized as follows:

1. In winter, preheating operations using waste heat from the biomass CHP were conducted with two temperature settings, T_{HS}: 35°C and 45°C. The results showed that a T_{HS} setting of 35°C provided

higher occupant satisfaction in terms of thermal comfort. This is likely because the supply temperature of DCFCU being closer to the temperature in the occupied zone contributed to more uniform indoor temperatures and improved indoor thermal conditions. By preheating operation, 93% of occupants voted to the warm side at the start of work, and the overall thermal satisfaction vote reached 94%. From the point view of energy, preheating allowed for a reduction in the air transport power of the OHU, resulting in a 32% reduction in daily power consumption, and a 25% reduction over the two-month winter operation period.

2. In summer, performance evaluation was conducted in the open office area by operating DCFCUs as ambient air conditioning. A total of 6 cases were investigated and compared by changing the number of operating DCFCUs and the OHU supply airflow. In terms of thermal comfort, Case 5, where only one row of DCFCUs on the perimeter side was operated with full OHU airflow, provided the highest comfort level, followed by Case 6, where all DCFCUs were operated with half OHU airflow. On the other hand, in terms of power consumption, Case 6 achieved 18% reduction compared to the conventional operation in Case 1. Therefore, Case 6 showed the best overall results in terms of both thermal comfort and energy efficiency.

Based on the results of this study, the DCFCU system can be used for both PECS and ambient air conditioning purposes. Furthermore, by improving the operation method, it is possible to reduce power consumption and the improvement of thermal comfort. To achieve optimal operation, it is important to consider not only adjustments to the operation of DCFCU and OHU based on thermal load fluctuations, but also a multifaceted approach that includes whether the energy source for the heat supply is renewable or fossil based. At this facility, efforts to improve equipment operation and indoor environmental conditions will continue, with the aim of reducing global environmental impact and enhancing intellectual productivity.

REFERENCES

[1] Kimura et al, Planning and Evaluation of the Energy Self-Sufficient Innovation Center (Part 11), Proc. SHASE, pp. 201–204, 2021 (Japanese).
[2] Olesen and Kazanci, Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS), AIVC Workshop, May 2023, Tokyo.
[3] Khovalyg et al, Personalized Environmental Control Systems (PECS): Systematic Review of Benefits for Thermal Comfort, Air Quality, Health, and Human Performance, Building and Environment (2025), doi: https://doi.org/10.1016/j.buildenv.2025.113541.
[4] UC Berkeley Center for the Built Environment (CBE), Using Personal Comfort Devices to Save Energy and Improve Comfort
[5] IEA EBC - Annex 87 - Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems, https://annex87.iea-ebc.org/.
[6] Mutoh et al., Planning and Evaluation of the Energy Self-Sufficient Innovation Center (Part 1), Proc. SHASE, pp. 185–188, 2019 (Japanese).
[7] SHASE, Definition and Evaluation Method of Net Zero Energy Building, pp. 5, 2015 (Japanese)

要　約

我々は、オフィスビルの環境負荷低減を目的として、直流ファンを用いた天井型ファンコイルユニット（以降 DCFCU と称す）の開発に取り組んでいる。高砂熱学イノベーションセンター（以下、本施設）に導入した DCFCU は、当初冷房専用のパーソナル空調機 (以下、PECS：Personal Environment Comfort System)として導入[1]したが、夏期と冬期のピーク時には執務環境の悪化が散見されたため、DCFCU をアンビエント空調機として活用し、執務環境の改善と消費エネルギー削減の両立を目指した。

本報では、吹抜け廻りのオープンエリアを対象とし、冬期には木質バイオマスガス化発電機（以下、バイオマス CHP、CHP : Combined heat and power）の排温水、夏期には地下水を DCFCU へ送水し、早朝の立上り運転や就業時間帯の運転に利用することで室内環境の改善と消費エネルギーの低減を実現した結果を報告する。