A study on dedicated outdoor air handling unit systems regarding the widespread of ZEB

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Abstract. ZEB has been promoted in the building sector to realize energy conservation and carbon neutrality. This has caused changes such as a decrease in the room sensible heat load factor and an increase in the outdoor air load ratio. In this study, the systems with a dedicated outdoor air handling unit (OAHU) are evaluated as air conditioning systems that can flexibly respond to a changing heat load, and guidelines for rational design and operation are given. A case study is conducted to evaluate the indoor environment and energy performance of a conventional air handling unit (AHU) system and an OAHU system under the assumption of a reduction in internal heat gain intensity. The study results showed that the OAHU processed latent heat and reduced the number of uncomfortable hours by 78% compared to those for the AHU system during the cooling season for cases with reduced internal heat gain. Regarding system energy consumption, the OAHU system consumed 17% more energy than the AHU-system. Thus, the OAHU system maintained a better indoor environment than the AHU system at the cost of increased energy use. Based on these results, measures for reducing the energy consumption of the OAHU system are discussed.

1 Introduction

In recent years, the conversion of buildings to net zero energy building (ZEB) has been promoted to realize a decarbonized society. In line with this trend, LED lighting and energy-saving office automation equipment are being promoted to decrease the indoor sensible heat load factor. On the other hand, the indoor latent heat load does not change because the main source of this latent heat is the building occupants. Therefore, the indoor sensible heat factor is expected to decrease. In a conventional supercooling and dehumidification system that uses a single air conditioner, which is typically used in office buildings, the supply air is used to maintain air temperature, and air humidity is controlled by the proportion of handling sensible heat for controlling air temperature, and thus the inability to handle the indoor latent heat load is expected to become more pronounced [1].

In addition, since outdoor air treatment is performed simultaneously with room load treatment by a single air conditioner, in the case of a variable air volume system, it may be difficult to introduce the required amount of outdoor air when the room load is minimal.

Therefore, there is a need to adopt an air conditioning system that separately handles latent and sensible heat and to build a system that separates the treatment of outdoor air load and room load.

Based on the above, this study focuses on systems with dedicated outdoor air handling unit (OAHU) as air conditioning systems that can flexibly respond to a decrease in the indoor sensible heat factor associated with the promotion of ZEB, and provides guidelines for their rational design and operation. Table 1 shows the main outdoor air and latent heat treatment methods. Although systems using solid or liquid desiccants or membranes are also capable of separately treating latent and sensible heat, the outdoor air conditioner considered in this study is a multi-coil system that combines a total heat treatment coil and a sensible heat treatment coil, because it has a simpler system configuration than others.

Table 1. Most commonly used outside air treatment methods

Outside air and latent heat treatment method	System details
No treatment	Direct outside air introduction
Heat recovery	Air-to-air heat exchanger
Cooling and condensation	Single coil
	Multi-coil for handling latent and sensible separately
Adsorption	Solid and liquid desiccant
Vacuum Separation	Membrane (Hollow Fiber Membrane, Separation Membrane)

This paper presents a case study of the indoor thermal environment and energy performance of a conventional air handling unit (AHU) system and an OAHU system under the assumption of a reduction in internal heat gain, and discusses measures for reducing the energy consumption of the OAHU. Note that a previous study [2] analysed the indoor environment and energy performance of an OAHU system in summer, the rainy season, and mid-season, but there have been no studies related to the different levels of internal heat gain considering ZEB oriented.

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2 Model building and study overview

A standard floor of the model building considered in this study is shown in Figure 1. It shows the location of the fan coil unit (FCU), details of which are described below. The model building is an SRC, 9-story office building in Tokyo, Japan [3]. The standard floor area is 900 m^2 and the office area is 576 m^2, with a side core on the west side. The office has windows on the north, south, and east sides. The window area ratio is 43%. Office space up to 3.6 m from the office's north, south, and east perimeters was designated as the perimeter zone, and the rest was defined as the interior zone. Table 2 shows the building envelope performance and operating conditions. Settings such as the human density and operation schedule were selected according to the standard room use conditions [4] for offices, etc. (office rooms) specified in the Technical Information on Energy Consumption Performance Evaluation (Non-residential Buildings) in the 2008 Energy Conservation Standards. For the heat gain intensity of lighting and OA equipment, assuming changes associated with ZEB conversion, three cases were set: high-level (20 W/m^2), middle-level (12 W/m^2), and low-level (6 W/m^2) [5].

The study periods were from June to September (cooling season) and from December to the following March (heating season). The operating hours of the air conditioning systems are shown in Table 3. There were employees from 8:00 a.m., and a lunch break from 12:00 p.m. to 1:00 p.m., and after 6:00 p.m., the number of employees decreased.

The comparison of the indoor environment in this report is based on the operative temperature and absolute air humidity. The comparison of energy performance is based on the energy consumption of the heat source equipment and air/water transfer equipment and the amount of heat processed by the cooling coils. The values for the indoor environment and air handling equipment were calculated from a simulation using TRNSYS (ver. 18), and the calculations for the heat source and water pumps were calculated using the LCEM tool. The meteorological data used were for Tokyo in the Automated Meteorological Data Acquisition System standard year (2001-2010). In the indoor temperature and humidity analysis, the acceptable range [6] was used as an indicator.

3 Air conditioning system overview

Figure 2 and Figure 3 show an overview of the AHU and OAHU systems considered in this study. Tables 4 and 5 show the equipment for those systems. Note that the equipment design was based on the maximum heat load for the high-level case. The locations of the FCU are shown in Figure 1. In the AHU system, the AHU handles the outdoor air load for the entire floor, including the perimeter zones, and the indoor load for the interior zone. The conditioned air from the AHU is supplied to the room through the diffusers installed in the interior zone. The FCU handles only the indoor load in the perimeter zone. In the OAHU system, the OAHU handles the outdoor air load and part of the indoor load.

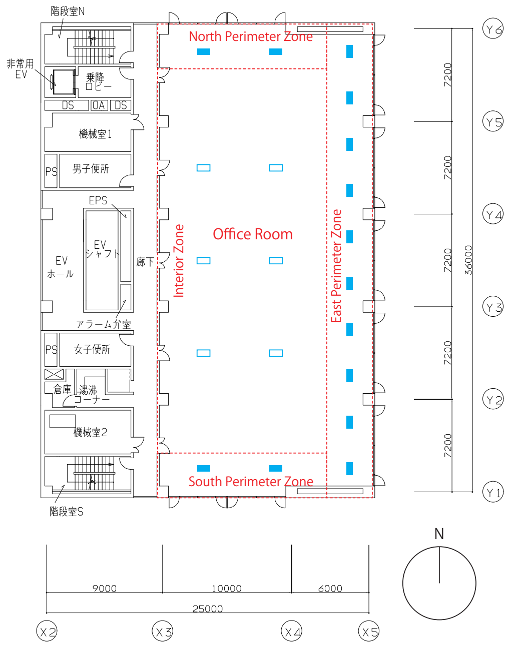


Fig. 1. Standard floor plan

Table 2. Model building envelope performance and occupancy conditions

External Wall Performance		Heat transfer rate :1.276W/m^{2}K
Window Performance		Heat transfer rate :1.1W/m^{2}K Solar Heat Gain Coefficient :62%
Set room temperature and humidity	Cooling	dry-bulb temperature :26°C humidity :50%,10.5g/kg
	Heating	dry-bulb temperature :22°C humidity :50%,8.2g/kg
Human density		0.15 人/m^2
Heat gain by lighting and office automation equipment	High	20W/m^2 / 40W/m^2
	Middle	12W/m^2 / 24W/m^2
	Low	6W/m^2 / 12W/m^2
Amount of fresh air volume		30m^3/h/people

Table 3. Air conditioning operation time

	Cooling (1176h)	Heating (1200h)
Air conditioning operation time	7-21 (Pre-cooling 7-8)	6-21 (Pre-heating 6-8)

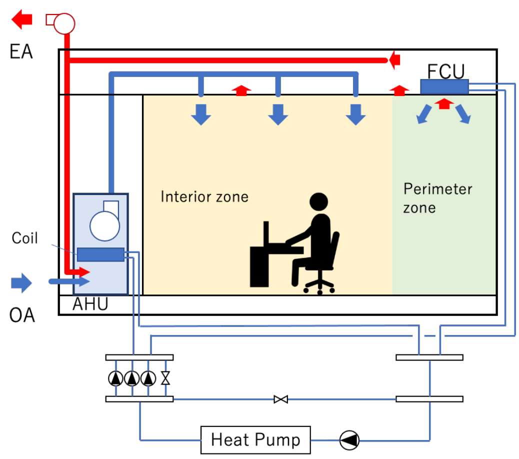


Fig. 2. System overview (AHU system)

The conditioned air from OAHU is uniformly supplied to the room through the diffusers installed in the interior zone and perimeter zones as well. The remaining indoor load is handled by the FCU installed on the entire floor.

The supply air conditions, and supply air volume control scheme of the system are shown in Table 6. For the AHU, the air volume varies according to the indoor temperature. The minimum air volume equals the amount of required outside air volume. The air supply temperature was set at 15 °C for the cooling season and 27 °C for the heating season. After the AHU air flow rate reaches the minimum value, the supply air temperature is reset and controlled to 19 °C for the cooling season and 15 °C for the heating season. In addition, the use of an induced air diffuser may be needed to avoid cold drafts from the low-air-temperature supply (e.g., 12.5 °C), but this was not modelled in this study. The humidification during heating for the AHU and OAHU systems is controlled using ON/OFF control according to the relative humidity of the room. The humidification efficiency is assumed to be constant (100%).

For the FCU control, the air flow rate is fixed, and the flow rate for the chilled water or hot water is controlled to maintain the room temperature at the set point.

Table 7 shows the equipment tables for the heat source and chilled water pumps. The heat source equipment was designed based on the heat load of the entire model building. For simplicity, the heat load of the entire model building was estimated by multiplying the number of floors of the model building with the heat load for a standard floor. The primary system, including the heat source equipment, is the same for the AHU and OAHU systems.

4 Case study of AHU and OAHU systems

In this section, the results of studies on the indoor environment and energy performance of the AHU and OAHU systems are discussed for each internal heat gain case. For the indoor environment, Figures 4, 7, and 10 show the distribution of operative temperature and absolute air humidity for each case. The enclosed range in the figures is the acceptable range. The results for the interior zone are shown here; the details for the perimeter zone are omitted because the trend was similar to that for the interior zone. Regarding energy performance, Figures 5, 8, and 11 show the periodic integrated energy consumption of the heat source equipment, chilled water pumps, and blower fan for each case, and Figures 6, 9, and 12 show the periodic integrated amount of coil-processed heat for each case. The untreated and over-treated heat rates were calculated using the difference between the set point for the room air temperature and humidity and those derived from simulation results, and the room air volume.

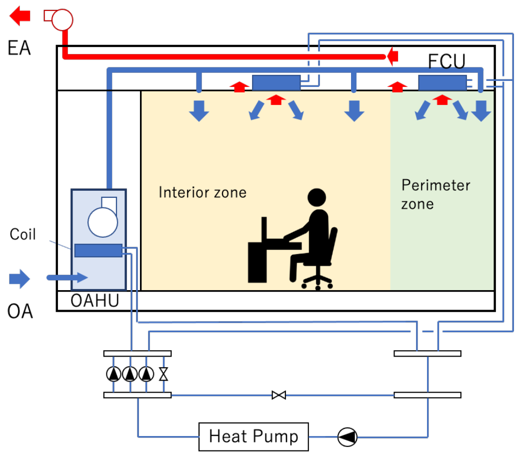


Fig. 3. System overview (OAHU system)

Table 4. Equipment table for AHU System

	AHU		
Details	Number of rows : 7(HF) Number of tubes : 20 Frontal area : 0.532m² Airflow rate : 4603m3/h×615.8Pa Cooling capacity : 49.3kW Chilled water flow rate : 141.3L/min (7-12°C) Heating capacity : 32.9kW Hot water flow rate : 94.3L/min (45-50°C) Outdoor air flow rate : 2640m3/h Humidification : 13.3kg/h		
Power	SA fan : 2.2kW RA fan : 1.5kW		
Number of units	1		
	FCU		
	North Perimeter	South Perimeter	East Perimeter
Power	0.045kW	0.047kW	0.031kW
Number of units	2	2	10

Table 5. Equipment table for OAHU System

	OAHU			
Details	Number of rows : 10(HF) Number of tubes : 14 Frontal area : 0.274m² Airflow rate : 2640m3/h×615.8Pa Cooling capacity : 42.7kW Chilled water flow rate : 122.4L/min(7-12°C) Heating capacity : 28.1kW Hot water flow rate : 80.7L/min(45-50°C) Humidification : 15.8kg/h			
Power	SA fan : 1.5kW RA fan : 1.5kW			
Number of units	1			
	FCU			
	Interior	North Perimeter	South Perimeter	East Perimeter
Power	0.037kW	0.061kW	0.047kW	0.031kW
Number of units	6	2	2	10

Table 6. Air supply conditions and airflow control

		Temperature and humidity	Air flow rate
Cooling	AHU	15°C, 95(Resets to 19°C when room temperature drops)	Controlled by room temperature
Cooling	OAHU	12.5°C,95%	Amount of outside air introduced
Heating	AHU	27°C, 37% (Resets to 15°C when room temperature rises)	Controlled by room temperature
Heating	OAHU	22°C, 50% (Resets to 15°C when room temperature rises)	Amount of outside air introduced

Table 7. Equipment for heat source and chilled water pumps

	Air source heat pumps module chiller	Primary pumps	Secondary pumps
Details (Per unit)	Cooling/Heating capacity : 67kW Chilled water temperature : 12°C→7°C Hot water temperature : 45°C→50°C Chilled/Hot water flow rate : 176L/min	Chilled/Hot water flow rate : 176L/min Pressure: 35.4kPa	Chilled/Hot water flow rate : 587L/min Pressure: 104.6kPa
Power (Per unit)	Cooling : 16.2kW Heating : 16.0kW	0.25kW	1.5kW
Pump Efficiency	-	0.56	0.70
Number of units	10	10	3

4.1 High-level case

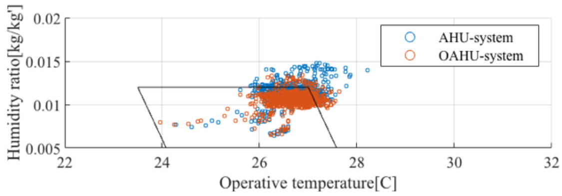
First, regarding the indoor environment, Figure 4 shows that during the cooling season, the number of hours that the indoor temperature and humidity were outside the acceptable range was 291 hours for the AHU system and 146 hours for the OAHU system. For the heating season, both systems experienced an increase in room temperature, with the AHU system and OAHU systems out of the acceptable range for 423 and 712 hours, respectively. The increase in room temperature during the heating season was due to the high level of internal heat gain, which resulted in a large cooling load.

Next, regarding energy performance, Figure 5 shows that the OAHU system consumed more energy than the AHU system during the cooling season, but the difference was only about 1%. In the heating season, the OAHU system consumed more energy than the AHU system, with a difference of about 9%. Regarding the amount of heat processed by the coils shown in Figure 6, the OAHU system processed about 4% more heat than the AHU system in the cooling season and about 9% more heat in the heating season.

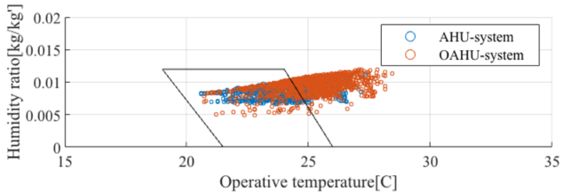
4.2 Middle-level case

Figure 7 shows that the number of hours that the indoor temperature and humidity were outside the acceptable range during the cooling season was 985 for the AHU system and 133 for the OAHU system. Compared to the number of hours outside the acceptable range for the high-level case, those for the middle-level case increased by about 3.4 times for the AHU system and decreased by 13 hours for the OAHU system. The number of hours outside the acceptable range during the heating season was 4 hours for the AHU system and 1 hour for the OAHU system.

Regarding the energy consumption shown in Figure 8, the OAHU system consumed 8,620 kWh via heat source equipment, 552 kWh via pumps, and 1,301 kWh via fans more than the AHU system during the cooling season. Note that the total was about 17% more for the OAHU system over the AHU system, making the difference between the systems more pronounced than that in the high-level case. In the heating season, there was no significant difference between the two systems. Regarding the coil treatment heat rate shown in Figure 9, the latent heat treated for the cooling period was 103,000 kWh for the OAHU system and 64,372 kWh



a) Cooling



b) Heating

Fig. 4. Indoor temperature and humidity and tolerance (high-level case)

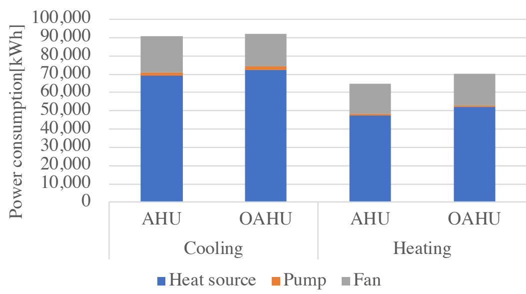
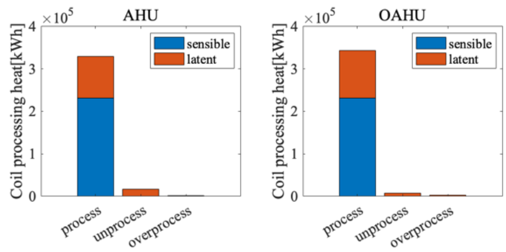
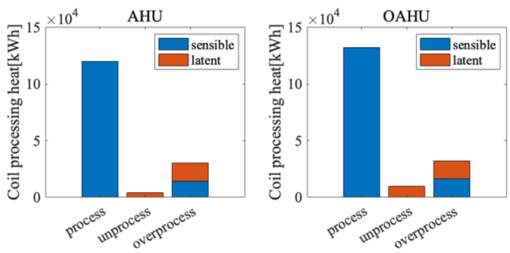


Fig. 5. Power consumption (high-level case)



a) Cooling

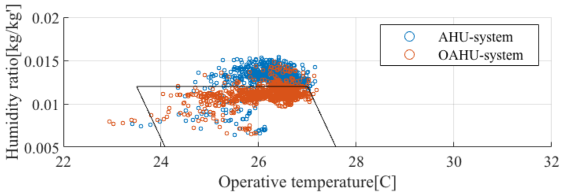


b) Heating

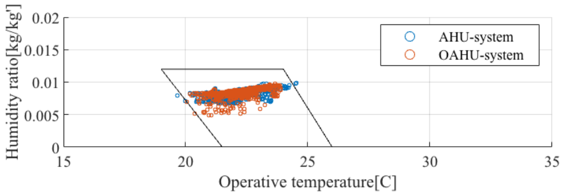
Fig. 6. Coil processing heat (high-level case)

for the AHU system, resulting (i.e., about 60% more for the OAHU system). In addition, the OAHU system had a total heat treatment rate that was about 20% higher than that of the AHU system in terms of total heat treatment rate. The AHU system allowed 37,830 kWh of untreated latent heat load. The OAHU system yielded about 35% of the untreated latent heat load of the AHU system. For the heating season, there was no significant difference between the two systems.

In the middle-level case, the air flow rate for the AHU during the cooling season was a minimum air (equal to outside air intake) for 653 (60%) hours, at which time the behaviour of the AHU is similar to that of the OAHU. Therefore, the comparison study is no more meaningful in the case of low-level heat gain since it is expected that the AHU and OAHU systems will show the similar operation.



a) Cooling



b) Heating

Fig. 7. Indoor temperature and humidity and tolerance (middle-level case)

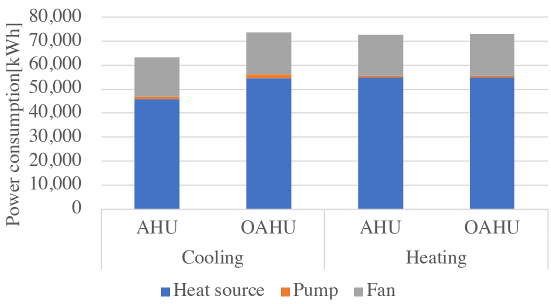
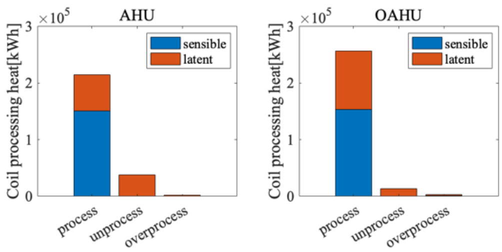
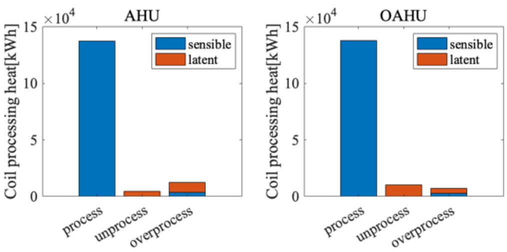


Fig. 8. Power consumption (middle-level case)



a) Cooling



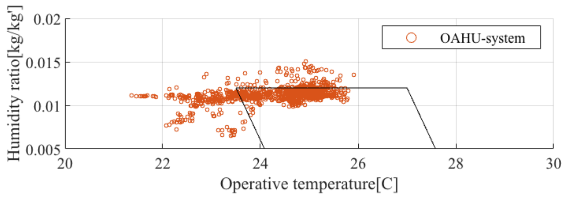
b) Heating

Fig. 9. Coil processing heat (middle-level case)

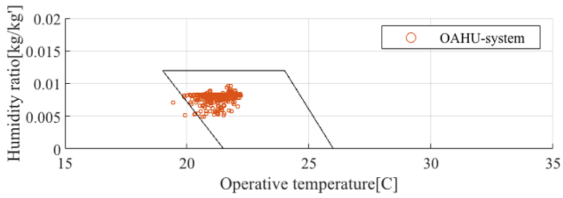
4.3 Low-level case

Regarding the indoor environment of the OAHU system shown in Figure 10, the number of hours that the indoor temperature and humidity were outside the acceptable range during the cooling season was 380 (about 35% of the time), an increase of 247 hours compared to that for the middle-level case. 256 of the hours outside the acceptable range were due to a decrease in room temperature. For the heating season, almost the whole period was within the acceptable range.

Regarding the energy consumption shown in Figure 11, in the cooling and heating seasons it was about 66,000 kWh and 90,000 kWh, respectively. Regarding the amount of heat treated by the cooling/heating coil shown in Figure 12, the amount of latent heat treated during the cooling season was 101,619 kWh, which is almost the same as that in the middle-level case. However, the amount of over-treatment sensible heat was about 10% higher than that in the middle-level case.



a) Cooling



b) Heating

Fig. 10. Indoor temperature and humidity and tolerance (low-level case)

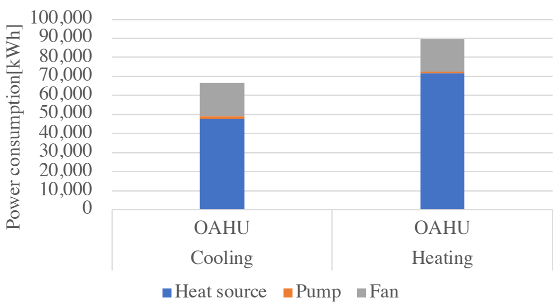


Fig. 11. Power consumption (low-level case)

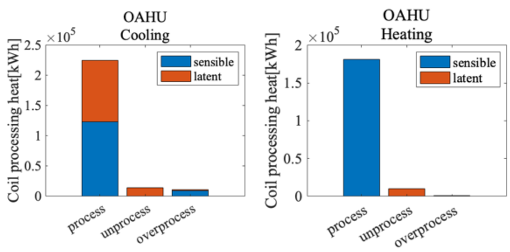


Fig. 12. Coil processing heat (low-level case)

5 Measures for improving the operation and design of OAHU systems

As mentioned, there was no significant difference in the indoor environment and energy performance between the two systems in the high-level case even though the room temperatures increased during the heating season.

In the middle-level case, for the AHU system, air humidity and the number of hours outside the acceptable range were higher than those for the high-level case. This was due to a decrease in the sensible heat factor as the internal heat gain was reduced, resulting in an unprocessed latent heat load for the AHU system. In contrast, the OAHU system sufficiently processed the latent heat load even with the lower sensible heat factor, resulting in an improved indoor environment. However, the OAHU system consumed more energy than the AHU system because the heat source equipment was forced to provide a higher heat rate than that provided by the AHU system to process a sufficient amount of latent heat.

In the low-level case, the OAHU system showed the same high latent heat treatment ability as that in the middle-level case. However, the low-temperature air supply of the OAHU resulted in over-processing of sensible heat, causing the room temperature to drop for a period of time.

The above results indicate that the OAHU system can maintain a better indoor environment than that for the conventional system during the cooling season under an environment with a reduced internal heat gain at the cost of higher energy consumption. Therefore, it is necessary to consider ways to improve the energy performance of OAHU systems while maintaining comfort. Table 8 shows the possible improvement measures for the OAHU system based on the comparison results. These include stopping the FCU blower and adopting radiant cooling and heating panels to reduce air transfer power consumption, using medium-temperature chilled water and cascading chilled water to reduce water transfer power consumption, and devising air-supply temperature control methods to reduce the amount of heat that the coil must process.

5.1 Stopping FCU during blower operation

Since FCUs are operated at a constant air volume, fan operation continues even no heat load is required. Therefore, energy consumption can be reduced by stopping fan operation when there is no required heat load. Although stopping the FCU would lead to a drop in the indoor circulating air, the effect is considered to be more limited in the OAHU case than in the AHU case because the OAHU diffusers are located throughout the entire indoor area. Figure 13 shows the energy consumption when this strategy is applied. The reduction of the FCU's fan power reduces the energy consumption by about 0.2%, 2%, and 7% in the high-, middle-, and low-level cases compared to the case without this measure, respectively. Therefore, although the power reduction is small, shutting down the FCU during the operation without heat load is considered to be a simple and effective measure that does not require additional equipment.

5.2 Use of radiant panels

The use of radiant panels as indoor load handling equipment in OAHU systems is expected to reduce air transfer power. The reduction of the air transfer power for FCUs and the increase of water transfer power required to operate the radiant panels should be considered. Figure 14 shows the power consumption when this measure is applied. The fan power consumption with radiation panels applied was obtained by subtracting the fan power consumption of the FCU from that for the case with FCUs. The pump power consumption for radiant panels was estimated under the assumption that the pump efficiency is 70%, which is the same value for the secondary pump, and adding it to the pump's power consumption. According to Figure 14, the power consumption was reduced by approximately 7%, 10%, and 11% in the high-, middle-, and low-level cases, respectively. Therefore, the adoption of radiant

Table 8. Improvement measures for low internal heat gain decreases

	indicator		Improvement measures
Thermal comfort	Operation temperature & Absolute humidity		–
Energy performance	Power consumption of transport equipment	Pump	Design: Cascade use
		Fan	Operation: Blower operation of indoor FCU stopped Design: Radiant air conditioning
	Heat source power consumption		Design: Medium temperature chilled water use
	Coil processing heat		Operation: Supply air temperature variable control

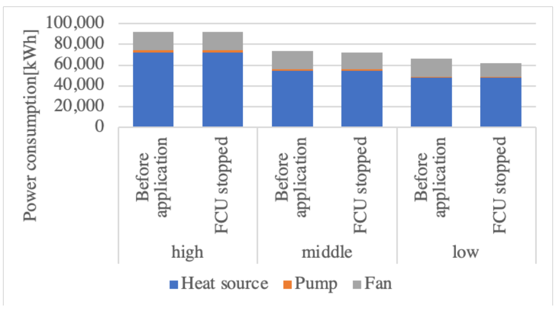


Fig. 13. Power consumption when FCU blower operation is stopped

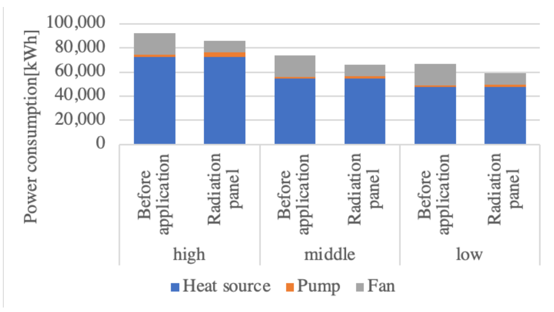


Fig. 14. Power consumption with use of radiant panels

panels, which is expected to reduce heat transfer power, is considered to be an effective measure in an environment with a low internal heat gain.

5.3 Other measures

Energy consumption can be further reduced by modifying the supply air temperature setting and control scheme for the OAHU to address the over-processing of sensible heat load in the low-level case. Although setting a higher supply air temperature is expected to be effective, it is undesirable to use a fixed value throughout the cooling period because it causes a latent heat load treatment shortage. Therefore, it is recommended that further study is needed on the supply air temperature variable control for the OAHU.

It is considered that the medium-temperature chilled water can be applied to the FCU, and that cascading chilled water can be used for the FCU after providing OAHU. Here, medium-temperature chilled water refers to chilled water that is 9 °C or higher. Since the FCU is responsible only for sensible heat treatment in the OAHU system, chilled water temperature can be increased to a level that does not cause a reduction in the capacity of sensible heat treatment. Cascading allows the FCU to supply a higher chilled water temperature and it aims to reduces water transfer power consumption by increasing the difference between the chilled water temperature and the return temperature.

The amount of heat processed by the secondary-side equipment of the OAHU system during the cooling season is shown in Figure 15. The case with lower internal heat gain case shows a decrease in the amount of heat processed by the FCU, which is about 39%, 18%, and 7% of the total heat processed in the high-, middle-, and low-level cases, respectively. Thus, the amount of heat treated by the FCU in an environment with a lower internal heat gain is relatively smaller, and the expected energy savings are considered to be smaller. Therefore, the application of medium-temperature chilled water and cascading for OAHU systems may not result in significant energy saving, and it is suggested that when adopting these measures, it should not be limited to FCUs, but should be considered for wider implementation, for example in systems incorporating thermal storage.

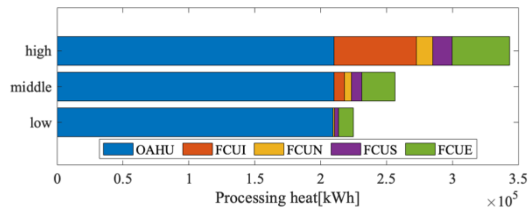


Fig. 15. OAHU system processing heat during cooling season

6 Conclusion

The case study results for AHU and OAHU systems showed that the OAHU system consumed more energy than the AHU system while maintaining a comfortable indoor environment with the designed humidity.

In the study of measures to reduce the power consumption of the OAHU system conducted based on the case study, stopping FCU during blower operation and use of radiant panels are considered to be effective measures because they resulted in reduced power consumption of fans. Regarding the use of medium-temperature chilled water and the cascading chilled water, it was shown that the OAHU system may not be able to reduce power consumption much because the amount of heat treated by the FCU is extremely small.

Future studies will examine appropriate methods for relevant control schemes for the supply air temperature of the OAHU.

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