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nZEB with GWHP in cold region of Japan

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Abstract

The objective of this study is evaluation of the nZEB in a cold region in Japan equipped with an open-loop groundwater source heat pump (*GWHP*) system and radiant ceiling panel (*RCP*) system from both the energy conservation and the thermal environmental points of views. Firstly, the annual energy consumption was calculated based on the recorded measurements. The results indicated that this building could reach the *ZEB*-ready level in Japan. The primary energy consumption can be decreased by approximately 67% compared to that of the reference building by applying this system. Secondly, the indoor thermal comfort was evaluated based on the physical measurements and survey questionnaire. The results showed that the suspended *RCP* system could achieve comfortable indoor thermal conditions during the year. The indoor temperature was maintained within the range of 22–26 °C. Finally, energy conservation and the thermal comfort of the continuous operation methods for heating were compared to those of the intermittent operation method. Benefits of the continuous operation method were proved that a stable indoor thermal environment was maintained, and the *COP* and *SCOP* of the *GWHP* system were increased by 12%.

Keywords: nZEB, groundwater source heat pump (GWHP), radiant ceiling panel (RCP), energy consevation, thermal environment;

1. Introduction

Presently, buildings account for approximately 36% of the total energy consumption and 40% of the energy-related greenhouse gas emissions worldwide [1]. Zero energy building (ZEB) or net zero energy building (nZEB) [2] have been proposed to reduce energy consumption. In Japan, the Society of Heating, Air-Conditioning, and Sanitary Engineers (SHASE) released the definition of ZEB and the evaluation method for ZEBs in 2015. ZEBs are defined as buildings that can reduce the annual net primary energy consumption to zero through renewable energy, highly efficient systems, and controlling the building load through advanced architectural designs (Figure 1). The Ministry of Economy, Trade, and Industry (METI) then issued a national definition of ZEB with four stages to promote its widespread use: ZEB (100% decrease in primary energy consumption), nearly ZEB (75% decrease), ZEB-ready (50% decrease) and ZEB-oriented (40% or 30% decrease) [3] - [5]. On the other hand, radiant heating and cooling (RHC) systems are typically used to achieve ZEB and are accepted worldwide. Specifically, the radiant ceiling panel (RCP) system is a widely used RHC system, that can directly use renewable energy, such as geothermal heat and solar heat, to heat or cool indoor air [6]. In this study, the open-loop groundwater source heat pump (GWHP) is combined with the RCP system.

The objectives of this study are evaluation of the nZEB in a cold region in Japan equipped with an open-loop groundwater source heat pump (GWHP) system and a radiant ceiling panel (RCP) from both the energy conservation and the thermal environmental point of view. Firstly, the annual energy consumption was evaluated. The results showed that this building could reach the ZEB-ready level. The primary energy consumption can be decreased by approximately 67% compared to that of the reference building. Secondly, the indoor thermal environment and comfort were evaluated from both measurement and questionnaire. It was

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clarified that the suspended RCP system could achieve comfortable indoor thermal conditions during the year, and it contribute energy conservation due to the high performance of the heat pump chiller.

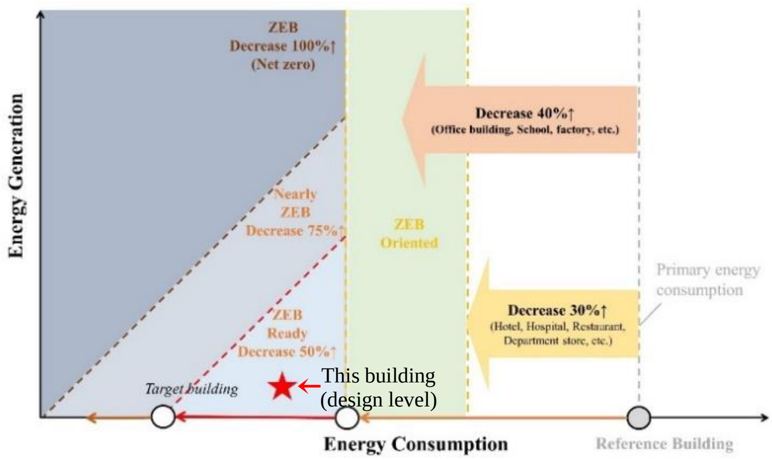


Fig. 1 Definition of the four stages of ZEBs in Japan.

2. ZEB in cold region in Japan

2.1 Building characteristics

The present study was undertaken in a newly constructed two-storey office building, located in Sapporo (latitude: 43°03'00"N, longitude: 141°21'00"E; 32 m above sea level), Hokkaido, Japan. The floor area of this building is 1949.58 m^2. Sapporo falls under the subarctic region, characterized by a mild summer and cold winter. The cold season lasts for 3.5 months from December to March, with an average daily low temperature of -5 °C and an average daily high temperature of 0.8 °C (climate data in 2020).

In this building, the ground floor includes parking, the main entrance, equipment rooms, and meeting and reception spaces. The second floor is primarily the workplace, with two large office rooms. Almost all company employees work there during the day. As shown in Figure 2, eight strings of 112 photovoltaic polycrystalline modules are installed on the south wall. To reduce heat loss, the building envelopes are well-insulated and covered with polystyrene foam plates. Table 1 summarizes the structure and heat transmission coefficients of each element. The windows use pairs of Low-E pair glass with argon gas. The area ratio of the window to the wall is 0.09 for the south and east sides, 0.04 for the west side, and 0.02 for the north side. The heat loss coefficient of this building was estimated to be 0.9 W/(m^2·K), which was calculated based on the heat flow rate and the total floor area. The suggested value is 1.6 W/(m^2·K) in the Hokkaido region in Japan. Thus, it represents that this building has excellent insulation performance.

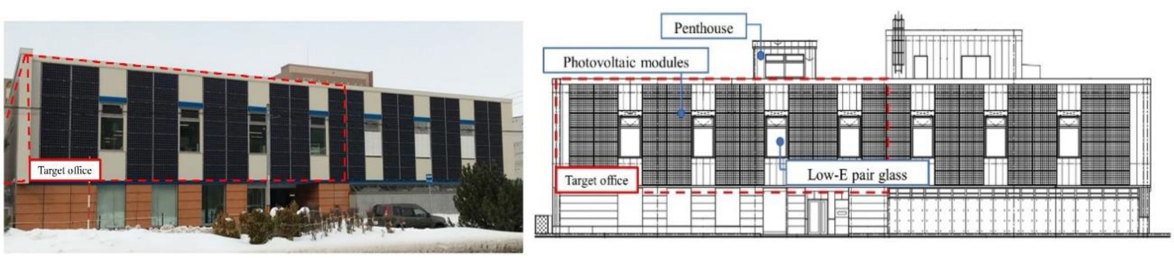


Fig. 2 South view and south elevation of the target nZEB.

2.2 HVAC systems

As illustrated in Figure 3, the radiant ceiling panel (RCP) system heats or cools two office rooms on the second floor. The outdoor-air handling units are used for the central ventilation system, which supplies fresh processed air to the workspaces through displacement ventilation. The building also uses passive stack ventilation during summer. Figure 4 shows the combined open-loop GWHP system, RCP system, and outdoor-air handling units for the second floor. The groundwater is pumped up from a water well and its temperature is almost constant at 12 °C throughout the year. The temperature of the water supplied to the RCP system is set as 18 °C in the summer and 32 °C in the winter. Free-cooling, which the groundwater directly exchanges heat between RCP and outdoor-air handling though plate type heat exchangers, is adopted during summer (Figure 4 (a)). In winter (Figure 4 (b)), a heat pump (maximum heating output capacity of 45 kW; MCRV-P450E; Mitsubishi Electric) operates and supply hot water to the RCPs, AHU and a water storage tank. The building energy management system (BEMS) controls and monitors all system components and records a total of 167 measuring points every second.

Table 1 Thermal conductivities and heat transmission coefficients of the building envelop.

Elements	Material	Thickness [mm]	Thermal conductivity λ [W/(m·K)]	Heat transmission coefficient U [W/(m²·K)]
Exterior wall	Galvalume	0.4	45	0.24
	Polystyrene foam	110	0.028	
	Concrete	170	1.6	
Roof	Concrete	80	1.6	0.36
	Polystyrene foam	100	0.028	
	Concrete	170	1.6	
	Air layer	-	-	
	Rock wool sound-absorbing board	12	0.17	
Floor	PVC floor tile	3	0.19	0.40
	Concrete	15	1.6	
	Polystyrene foam	50	0.028	
	Air layer	-	-	
	Concrete	310	1.6	
	Base (Rocks)	150	1	
Window	Low-E glass	26	-	1.40

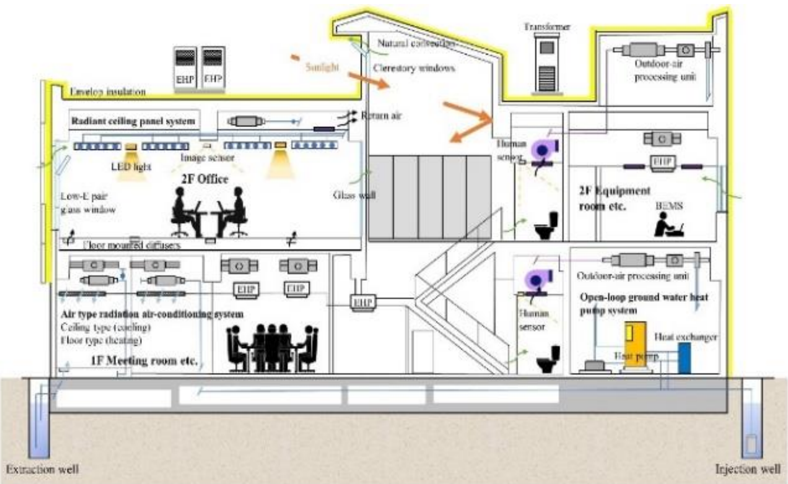
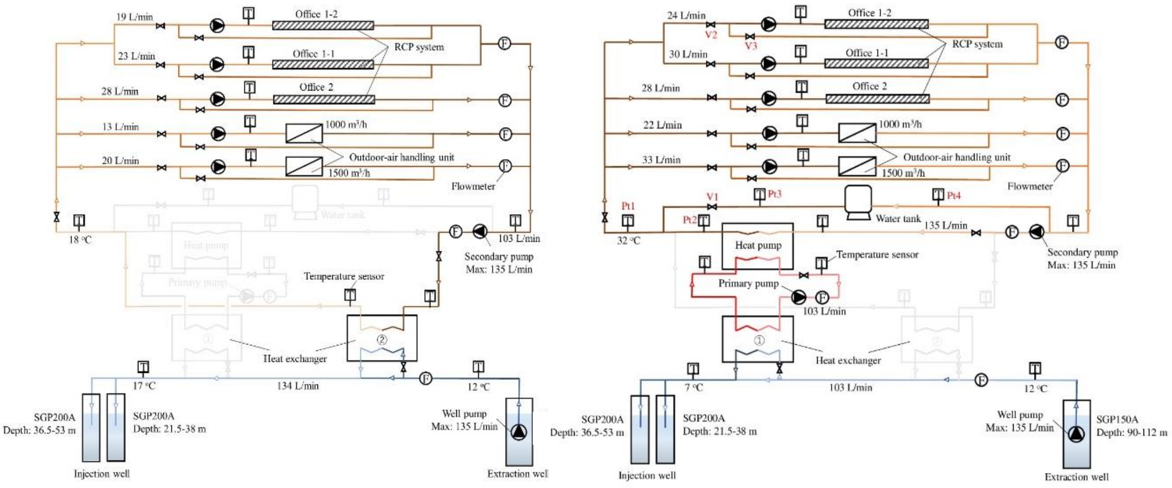


Fig. 3 HVAC systems in the target nZEB.



(a) Summer (b) Winter

Fig. 4 Schematic diagram of an open-loop GWHP system and RCP system for heating and free cooling.

2.3 Indoor space and radiant Ceiling Panels (RCP) for heating and free cooling

The target office has a large open-space office, denoted as Office 1 (457.39 m^2), where all staff sit together without partitions. In this office, the east wall is the internal wall, connected with another office and the stairwell. The west, south, and north walls are well-insulated exterior walls. The south windows (2.2 m × 1.3 m) use roller blinds that cover all window areas to prevent sunlight exposure during mid-day. In contrast, the west and north windows (1.4 m × 0.5 m) are exposed without shading. The thermal time constant of the target building, which represents the building's ability to retain heat, was calculated as 89.7 h based on the thermal mass and heat loss. As shown in Figure 5, radiant ceiling panels are suspended 1.4 m beneath the ceiling and 2.7 m above the floor, covering over 50% of the ceiling area. Each ceiling panel consists of five concave aluminum segments, with a serpentine water pipe fixed on the upper surface. The system is divided into two parts (RCP Group 1 and Group 2), which are independently controlled using different water supply circuits, as shown in Figure 6.

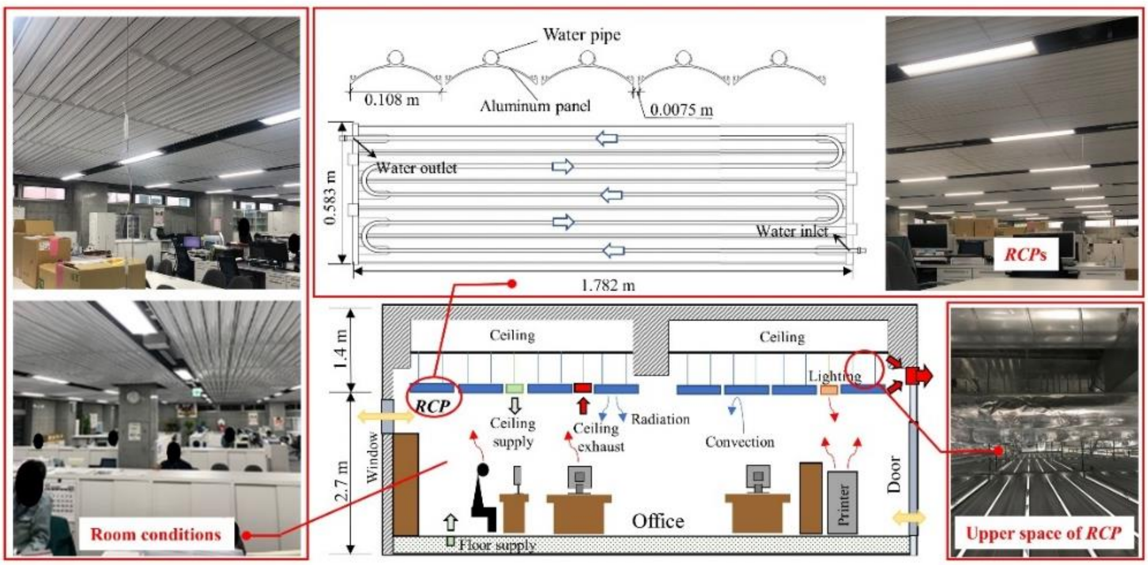


Fig. 5 Room inside views and Radiant ceiling panels (RCP) for heating and free cooling.

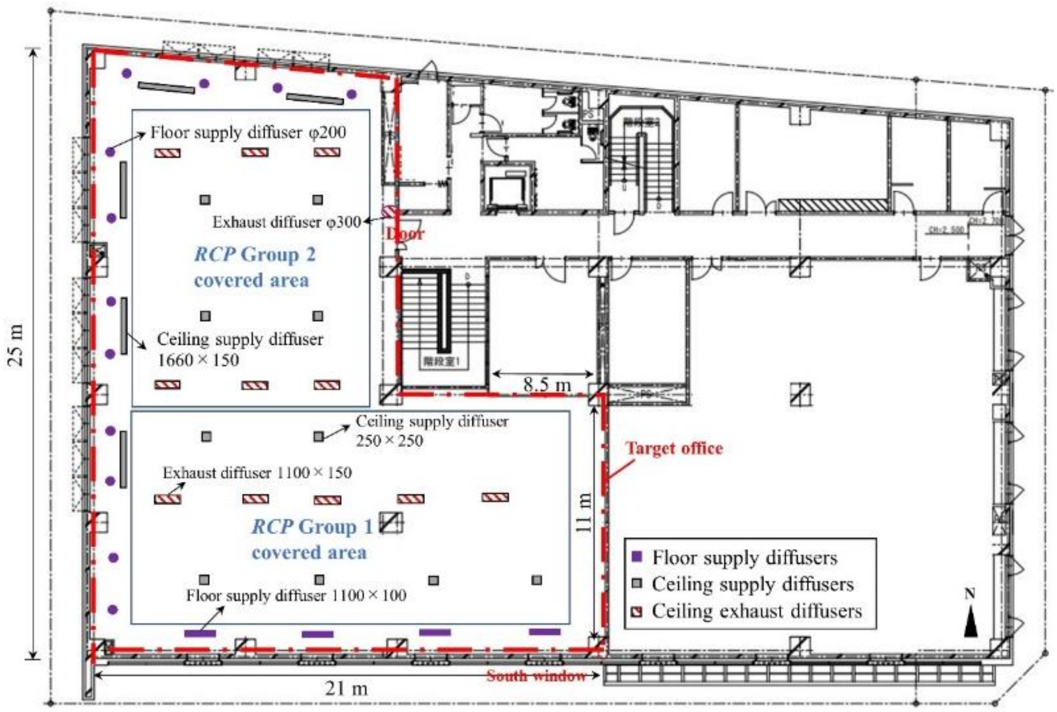


Fig. 6 The Plane of the second floor and two RCP groups.

3. Annual energy consumption

Figure 7 shows changes of the monthly average indoor air temperature and electric energy consumption of each part, including air conditioning, ventilation, lighting, hot water, elevator, and power generated by solar *PV* during 2019. From the breakdown pie chart of the annual energy consumption, it is understood that the energy consumption of the air-conditioning system accounted for 48% of the total annual energy consumed as 61,306 kWh/y, and more than 60% of that from December to March.

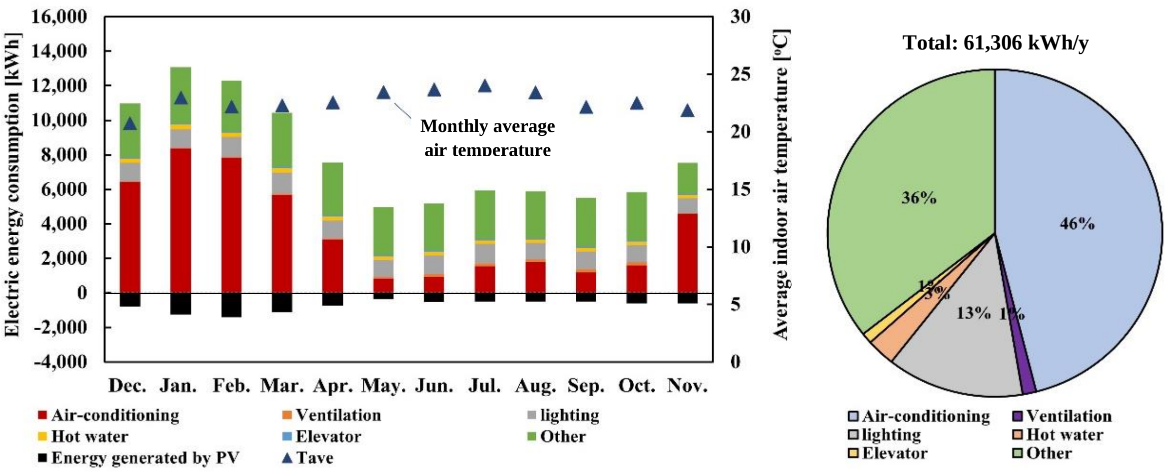


Fig. 7 Monthly electric energy consumptions and breakdown of the annual energy consumption (2019).

Figure 8 is comparisons of primary energy consumptions between for the reference building, design stage and actual measured ones in 2019 and 2020. When primary energy was calculated, conversion coefficients from electric energy to primary energy in energy-saving standards was used as 9,970 kJ/kWh during the day and 9,280 kJ/kWh in the night.

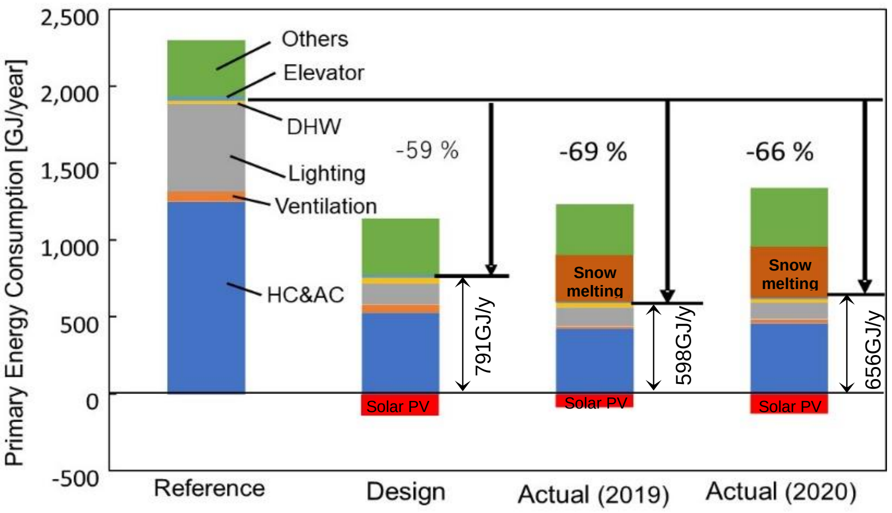


Fig. 8 Reduction of the annual energy consumption compared to those of the reference and design phase.

4. Evaluation of the Groundwater source heat pump system (GWHP)

Table 2 summarizes the operation status and performance of the groundwater heat source heat pump system (GWHP) in the second year of operation. The stand-alone COP of the water-cooled chiller used as a heat pump was 4.11, the SCOP including the primary well water pump and circulation pump was 3.62, the SCOP including the secondary circulation pump and radiant panel circulation pump was 3.28, and the SCOP of the entire heat source system including the external controller was 3.12. The SCOP of the entire heat source system including the external controller was 3.12. The SCOP of the entire heat source system was 26% lower than the COP of the heat pumps alone. This value is in the general category because the energy consumption of the well pump is large in the groundwater heat source utilization system, but the target should be 20% or less when aiming for ZEB.

Table 2 Operation status and performance of the groundwater heat source heat pump system (December 2019 – March 2020).

For heating season from December 2019 to March 2020	
Total heating amount of heat pump chiller (1)	42, 772 kWh
Power consumption of heat pump chiller[kWh] (2)	10419 kWh
Power consumption of pumps [kWh] (3) (well/heat source/room/RCP)	993/555/348/1468 kWh
COP of heat pump chiller [-] (1)/(2)	4.11
SCOP of the heat pump/RCP system [-] (1)/{(2)+(3)}	3.62/3.28/3.12
Supply temp. to the RCP	35 °C
Return temp from RCP	29 °C

The detail operating conditions of GWHP is shown in Figure 9. It can be seen that the temperature at a representative point in the room is stable at around 24°C ± 2°C per year, regardless of whether the room is free cooled in the summer, heated in the middle of the year, or heated in the winter. This room temperature stability is characteristic of an exterior-insulated building with high thermal insulation and huge heat capacity of the concrete construction. However, if the room temperature can be controlled at 22°C for heating in winter and 26°C for cooling in summer, energy savings of approximately 10% over the current level can be expected, based on the temperature difference between the inside and outside.

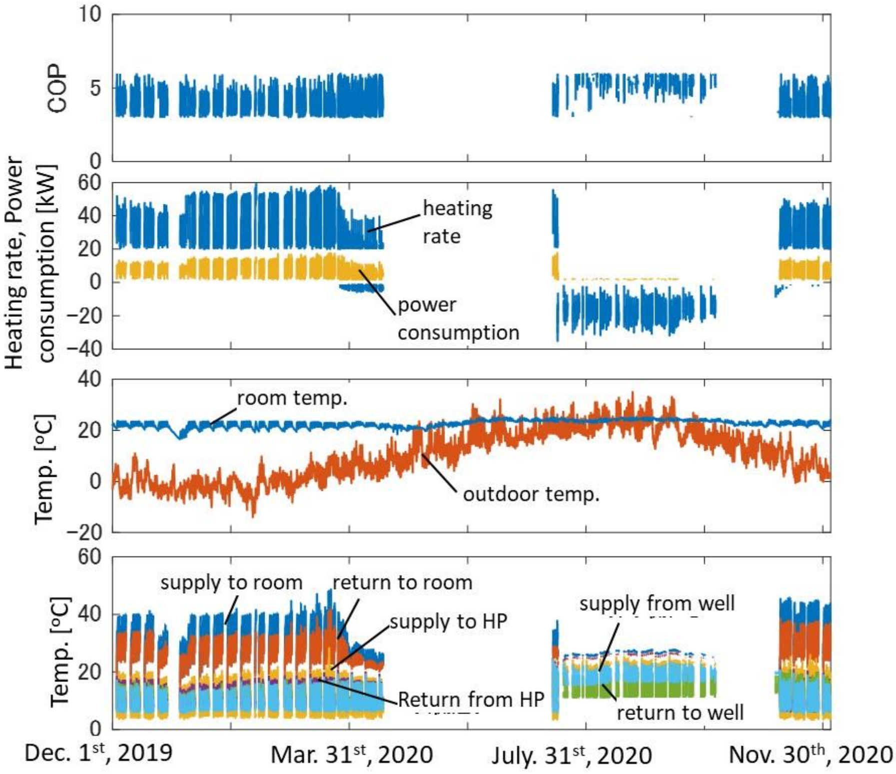


Fig. 9 Operating conditions of Groundwater source heat pump system and room temperature variations (December 1, 2019 - November 30, 2020).

5. Evaluation of vertical room temperature profile

The vertical temperature distribution in the room (6 measuring points; just below the ceiling, 0.1 m below the ceiling, FL +1.8 m, +1.0 m, +0.1 m, and just above the floor) was measured. The daily and period-averaged vertical temperatures at 10 a.m. and noon on weekdays from February 1 to February 12, 2020, including the coldest day, are shown in Figure 10. It is understood that the temperature difference between the upper and lower temperatures at FL+0 m to 1.8 m in the human activity zone is ±0.5 K at noon (the temperature directly above the floor is 23.0 to 23.4°C), except on Monday, but the temperature near the floor is 1.0 K lower than the average temperature at 10 am (the lowest temperature directly above the floor is 22.0 to 23.4°C), more than ±1.0 K. This is the range in which a temperature difference is felt at the foot on the floor. This can be improved by starting the heating earlier every morning or by using continuous heating.

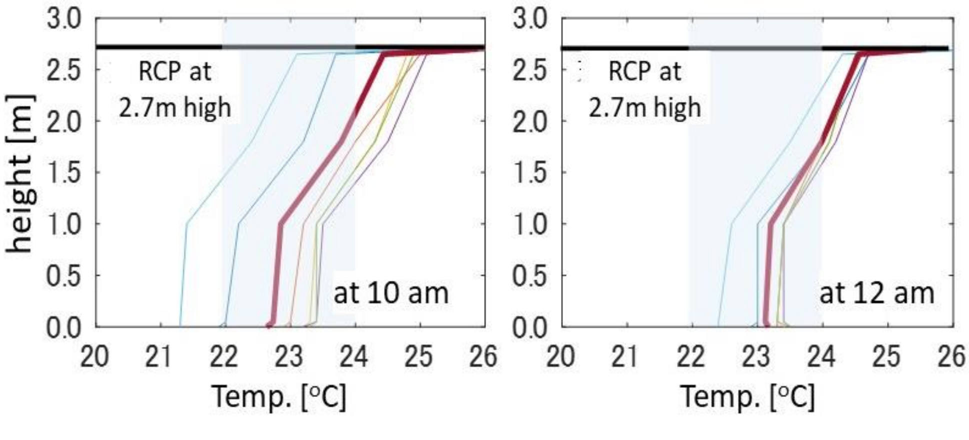


Fig. 10 Variations of average vertical room temperature profile at certain time from February 1 to February 12, 2020.

6. Evaluation of continuous heating operation

6.1 Energy conservation

Continuous heating operation was tested in order to compare the energy consumptions and indoor thermal environment with those of intermittent heating operation in the period with similar weather conditions in winter as shown in Table 3.

Table 3 Weather conditions during each heating conditions.

	Continuous1	Continuous2	Intermittent
Date	16th Dec. 2020	15th Jan. 2021	19th Jan. 2021
Ave. air temp.[°C]	-4.0	-3.3	-3.0
Max. Temp.[°C]	-2.1	-1.8	-0.6
Min. Temp.[°C]	-6.2	-7.1	-6.6
Sunlight hours [hr]	4.4	1.5	6.0
Global solar radiation [MJ/m^2]	6.76	5.13	8.00
Snow fall depth [cm]	4	-	4

The results are shown in Fig. 11. In the continuous2 test, the evaporation temperature of the heat pimp was set to 7 °C, and the circulation pump speed was controlled by an inverter, which gives the temperature difference between the supply and return temperatures of the heat pump circuit was 4 K to 5 K. As a result, both COP and SCOP were improved up to 12%. The heating operation time was 22 hours per day. The COP of the heat pump machine was 4.16, and SCOP was 3.70, both 12 % higher than the values in intermittent operation. This result indicates that in an externally well insulated building and huge heat storage capacity, continuous heating can lead the reduction of energy consumption and increasing the thermal comfort by setting the proper circulation pump flow rate and the heat pump evaporation temperature.

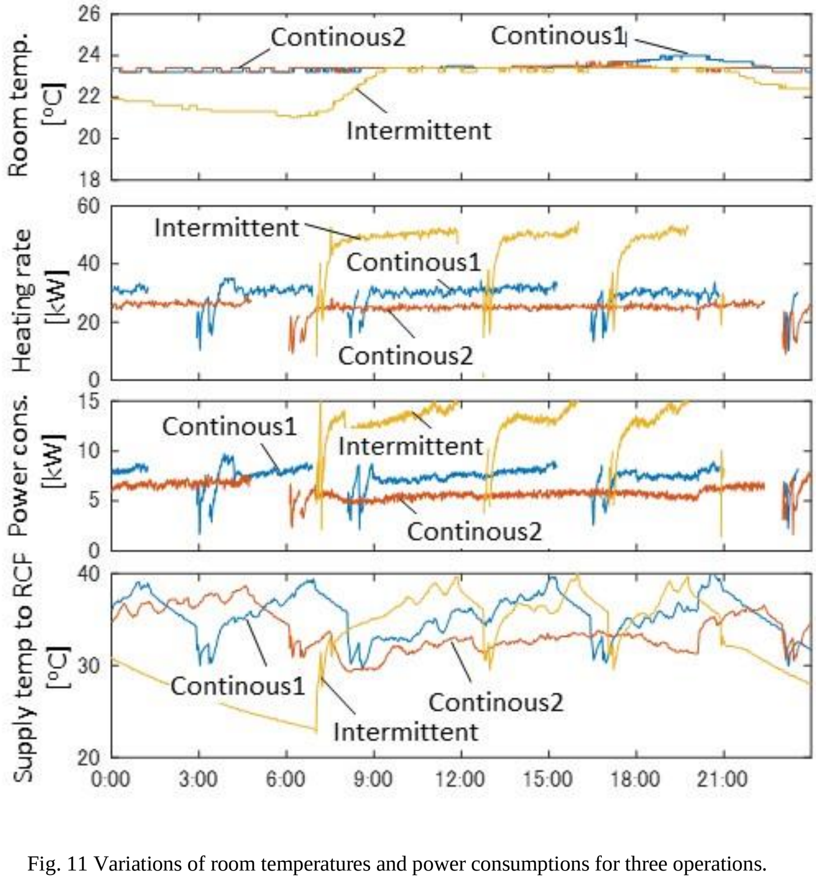


Fig. 11 Variations of room temperatures and power consumptions for three operations.

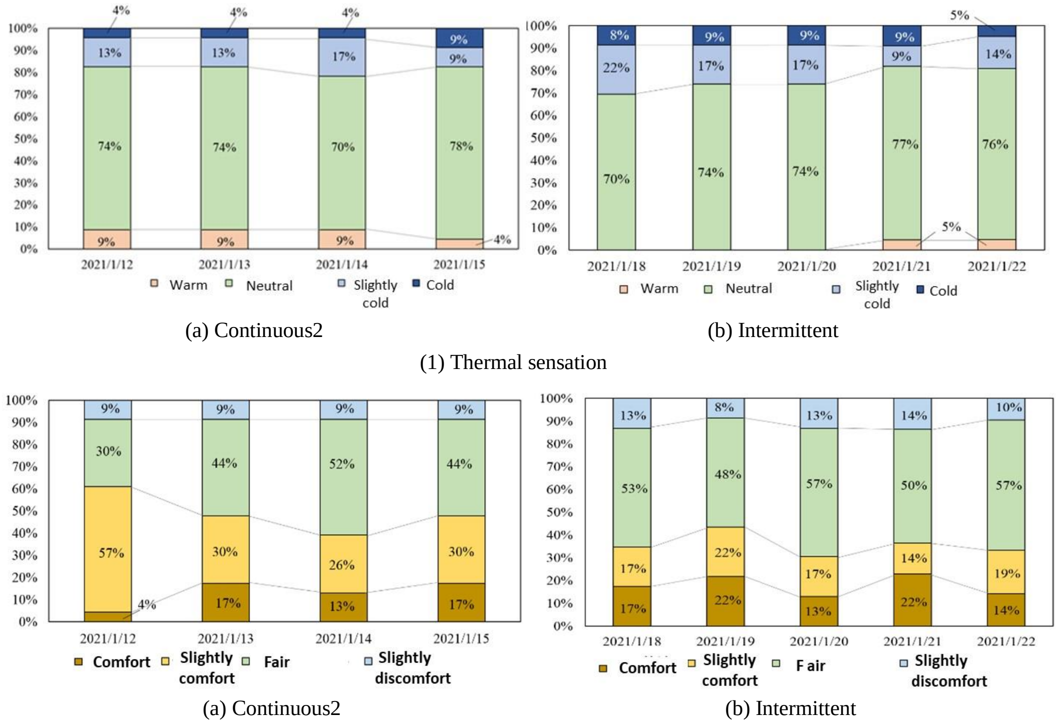
6.2 Thermal environment

The questionnaire was distributed to the workers every morning. Table 4 shows some characteristics of monitored workers. They were asked to fill in the average feeling of warmth and comfort on a 5-point scale, using integer values.

Table 4 Monitored workers in the office.

Sex		Male	Female
Total number of persons		19	4
Age/ persons	> 50	10	1
	40-50	5	1
	30-40	0	0
	20-30	5	2
Height / cm	Average	170	156
Weight / kg	Average	68	57

The results of the questionnaire survey are shown in Figure 12 for the daily distributions of thermal sensation, and comfort sensation. The average percentages of respondents who answered "cold" or "slightly cold" during the continuous and intermittent operation periods were 18% and 25%, respectively, which were 7% lower for the continuous operation period. Despite the better thermal sensation in continuous operation, the daily energy consumption of the two types was 129 kWh and 139 kWh, respectively. It is true that the power consumption of auxiliary equipment such as well water pumps and circulation pumps increase almost in proportion to the operation time as the operation time increases, but since the heat pump chiller itself operated in a highly efficient compressor speed band, the power consumption of the heat source including the auxiliary equipment power is also reduced. As a result, the SCOP (including power consumption of primary side pumps) of continuous operation was 12% higher than that of intermittent operation. On the other hand, it can be seen in the lower figures that the percentage of respondents who answered "slightly uncomfortable" was 9 % in continuous operation, while it was 12 % in intermittent operation. The average percentage of respondents who answered "comfortable" or "slightly comfortable" was 48% and 35%, respectively. This means clearly that the continuous operation gives the higher comfort level.



(a) Continuous2 (b) Intermittent

(1) Thermal sensation

(a) Continuous2 (b) Intermittent

(2) Comfort sensation

Fig. 12 Daily distributions of thermal sensation (1) and comfort sensation (2).

7. Conclusions

The building performance of the nZEB in a cold region in Hokkaido equipped with an open-loop groundwater source heat pump (GWHP) system and a radiant ceiling panel (RCP) was evaluated from both the energy conservation and the thermal environmental points of view. The primary energy consumption can be decreased by approximately 67% compared to that of the reference building by applying this system. It was shown this building could reach the ZEB-ready level from the measurement. The results showed that the suspended RCP system could achieve comfortable indoor thermal conditions during the year. The indoor temperature was maintained within the range of 22–26 °C. Finally, both energy consumption and thermal comfort of the continuous heating was compared to those of the intermittent operation. More stable indoor thermal environment was maintained and the COP and SCOP of the GWHP system was increased by 12%.

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