# STUDY ON GROUND SOURCE HEAT PUMP SYSTEM APPLYING PHC FOUNDATION PILES AND SHORT TERM THERMAL ENERGY STORAGE

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**Abstract:** This paper describes the design concept of an energy efficient heat pump system installed in a hospital in Chiba prefecture of Japan. Several kinds of heat pumps and thermal energy storage including Ground Source Heat Pump (GSHP) system were applied for heating, cooling and hot water supply. The GSHP system is operated in heating mode at night time and in cooling mode at daytime during the summer season. This alternate operation mode change is a short term heat storage system using the ground as thermal storage. By introducing short term alternate thermal energy storage operation, the efficiency of GSHP system which usually suffers from the performance degradation over long period due to the ground temperature rise is expected to improve. In this paper, applied heating and cooling system, soil conditions, operating concept, conceptual drawing are described followed by the performance analysis based on the actual operation data.

**Key Words: GSHP, PHC foundation, Short term heat storage, Totally electrified**

## 1 INTRODUCTION

There were few buildings with Ground Source Heat Pump (GSHP) system using foundation piles as heat exchangers in Japan at the beginning of this project, except for some cases in the cold region. This is considered because the GSHP system was not popular among the engineers and also they couldn't come to an idea to use foundation piles as part of the heat source system. But by using the foundation piles as heat exchanger of GSHP system, excavation cost for the heat exchanger becomes unnecessary, leading to advantages not limited to initial cost reduction. Therefore such design practice should be considered worth being listed among various design alternatives.

A major characteristic of GSHP system is that the thermal storage capacity is considerably different from other energy heat sources. This degrades the system efficiency over long term continuous HVAC operation despite the higher efficiency at the beginning of the seasons.

Some papers say that it is effective to balance the amount of thermal storage in the summer and discharge in the winter.

The effect of the long term seasonal thermal storage operation of the GSHP system is widely acknowledged in Europe and there are numerous introduction examples. However, studies about short term system of night and day thermal storage have not been found.

The GSHP system in this project focused to the thermal heat storage characteristic of the ground, which can be the cause of the degraded annual heat source system efficiency and the GSHP system is designed to switch to cooling operation during the daytime and heating operation during the nighttime in the summer season. The purpose of this alternate cooling and heating operation is to recover the ground thermal condition, so the cooling operation stores warm heat into the ground in the daytime and the heating operation for preheating hot water supply recovers warm heat from the ground at the night. This switching operation is supposed to recover the soil temperature and for the ground temperature and the cooling operation can be considered as warm heat storage and heating operation is cold heat storage. In other word, the most significant characteristics of this system is that by day-night alternate the thermal storage operation, the negative factor for the heat source can be reversed to positive factor.

This paper intends to introduce the new system as part of studies on the short term thermal storage GSHP system, showing results of study on energy saving effect and reporting the actual operation and presenting a solution for the degradation of the cooling efficiency during the summer season in warm region.

## 2 DESCRIPTION OF HEAT SOURCE SYSTEM

### 2.1 Description of the Building

The hospital is specialized in rehabilitation department to deal with physical impediment by cerebro-vascular diseases, so the operating room is not provided. In addition, this hospital provides intensive rehabilitation plans for patients from early period of onset, the hospital is trying to make patients return to their original life early. The hospital of total floor area of 13,946.9m$^2$, 4 stories and 200 beds, is located in Chiba prefecture and was opened on April 2008.

### 2.2 Description of the Heat Source System

The heat source system is basically intended for simultaneous hot and cold water supply because it is necessary to control room temperature delicately for patients, who have thermal sensing disability. And the heat source system for air conditioning and hot water supply is all electrified to reduce the CO2 emission. Table 1 shows the summary of main heat source equipment.

The piping system is 4-pipe system to provide cold and hot water simultaneously. Air handling units (AHU) and fan coil units (FCU) have 2 coils to control each room temperature arbitrarily.

The characteristic energy conservation concepts of the heat source system are shown in the followings. Figure 1 shows the schematic of the heat source system.

#### 2.2.1 Selection of the “top runner” equipment

The most energy efficient products were selected for the heat source system.

#### 2.2.2 Focus on high efficiency characteristic at partial load

Because the air cooled heat pump (HHP) has higher efficiency at partial load and the variable part of the load is provided by HHP, total efficiency of the heat source system was improved.

#### 2.2.3 Multiple hot water supply temperature setting

The hot water is preheated to 40 deg C in the summer by GSHP during the summer and by air cooled heat pump(EHP) in other seasons. The preheated hot water (40 deg C) is heated by high temperature supply type air cooled heat pump (HWHP) to 60 deg C. Total efficiency of hot water supply is improved because GSHP system efficiency is high. This hot water supply system was combined heating and preheating, so the initial cost of the system is lower than that of dedicated HWHP heating system because the cost of such system is still high.

### 2.2.4 Effective use of power rate system
The operation matched with the power rate system lead to the reduced running cost.

### 2.2.5 Introduction of the GSHP system
The detail concept of the GSHP system is described in following pages.

### 2.2.6 Dual supply of hot water for air-conditioning
The hot water for the floor heating pipe supplied from the GSHP is separated from the central hot water supply system (fluid temp is 45 deg C).The GSHP supply temperature is set to 35 deg C, lower than that of central system, contributing to improved COP of the GSHP system.

**Table1 Heat Source Equipments Specification**

| Description | Qty. | Specification | Location |
|---|---|---|---|
| High performance air cooled heat pump chiller (HHP) | 11 | Total cooling capacity：1,177kw<br>Total heating capacity：1,298kw | RF |
| High performance air cooled heat pump chiller (EHP)（Only for heating) | 3 | Total heating capacity：354kw | RF |
| High performance air cooled screw type heat pump chiller(SHP)+ Ice Thermal Storage Tank (SHP) | 1 | Cooling capacity:490kw<br>Max stored heat capacity：3,498kwh<br>※With three ice storage tanks | Cooling Tower ~~unit~~: RF<br>Chiller: Main machine room<br>Ice storage tank: Outdoor |
| Ground Source water cooled Heat Pump chiller（GSHP） | 1 | Cooling capacity:50kw<br>Heating capacity:62kw | Main machine room |
| Air cooled heat pump chiller for hot water supply（HWHP） | 3 | Heating capacity:52kw | RF |

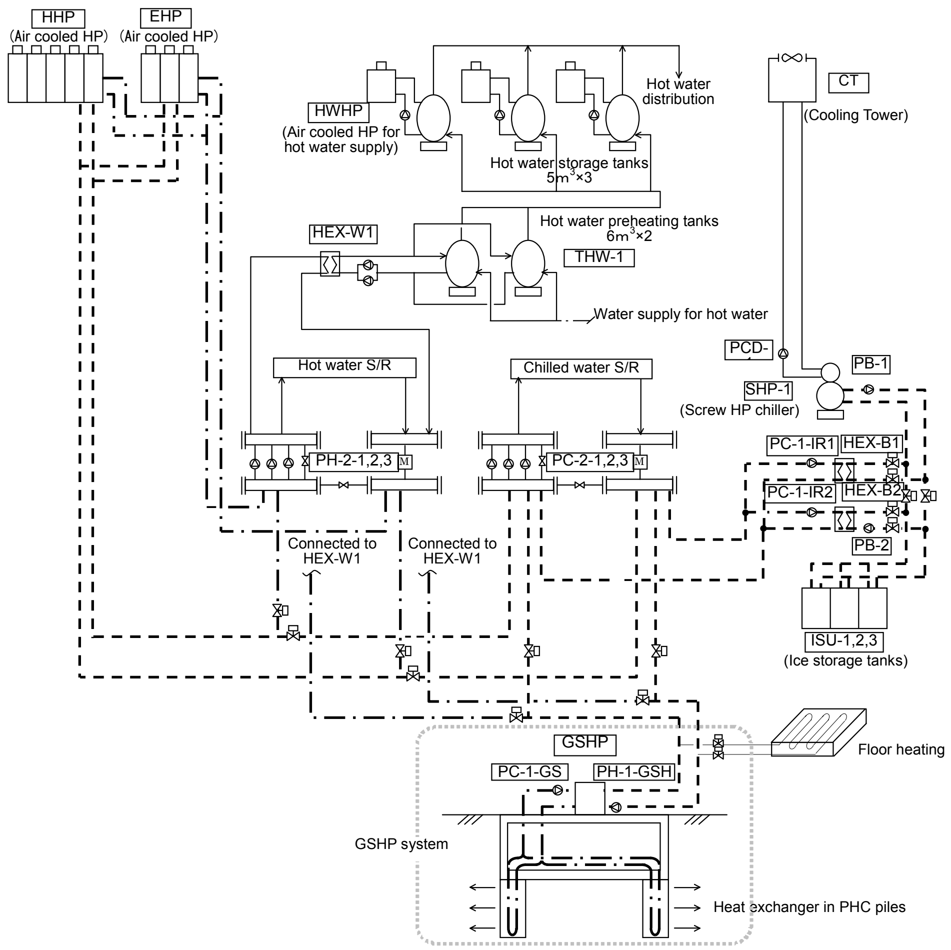


**Figure 1 Schematic of the heat source system**

# 3 DESCRIPTION OF THE GSHP SYSTEM

## 3.1 The Concept of Connection between the GSHP System and the Central Heat Source System

At first, the GSHP system was planned as a heat source for rehabilitation area and entrance area floor heating. The design heat source capacity of the GSHP system was 50kW, estimated from the floor heating area (about 800m$^2$) and assumed average unit floor heating load (60W/m$^2$). Moreover, the GSHP system was planned to connect with the central heat source system in order to enable more effective operation. Figure 2 shows the operation concept of the GSHP system set to switch “the winter season and the summer season” operation and “the daytime and the nighttime” operation. Table 1 shows the final heat source capacity.
The GSHP system is operated as floor heating heat source and is isolated from the central heat source system in the winter season. In the summer season, the GSHP system is operated as a pre-heating machine for hot water at night time. At that time connection of the HEX-W1 (shown in the Figure 1) is isolated from heating pipes of the central heat source system. In the daytime, the GSHP system is operated as the chilling machine of the central heat source system and at that time it is connected to the chilled water header.

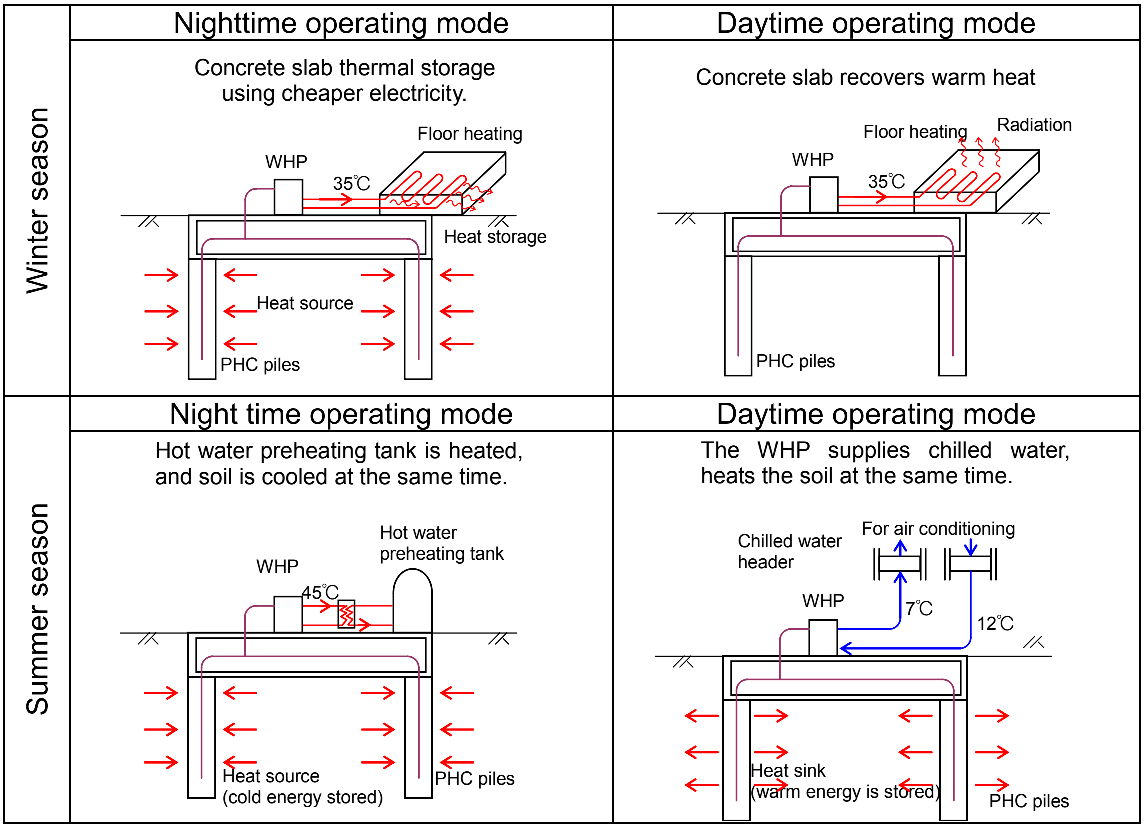


**Figure 2 A concept diagram of the GSHP system operation**

## 3.2 Overview of the Underground Part of the GSHP System

The columnar section in Figure 3 shows the soil condition from the ground level (GL) to about 20m depth that is almost occupied by silt and sand. Therefore the soil thermal conductivity was estimated as 1.3W/(m･K) for the analysis. But the thermal response test (TRT) was performed during the construction period and the apparent thermal conductivity was analyzed from the result of the TRT. The numerical analysis was performed again from this result. The result is described in later section.
39 pre-cast concrete piles (PHC piles) with 20m depth were used as ground heat exchangers. The piles for heat exchangers (energy piles) were selected by the efficiency of piping

connections. The energy piles were zoned for three heat source areas, each with 13 piles and at similar distance from the main machine room where the heat source was installed. The heat exchangers were installed into the piles by 20m depth. The heat exchangers were made of high density polyethylene 20mm I.D. U tubes and for each pile, two U tubes were installed.

The double U tubes were connected in series in a pile and each energy piles were in parallel connection to heat source pipes in the pit area. Because each energy pile is in parallel connection, it is possible to continue operation even if some heat exchangers fail. The piping connections of each energy piles are reverse return system in order to control the heat source water equally for each energy piles. The heat source water pipes were connected to the header in the main machine room from each of 3 heat source areas, the pipes were connected to the GSHP machine, and each pipe was equipped with flow meters and pressure meters.

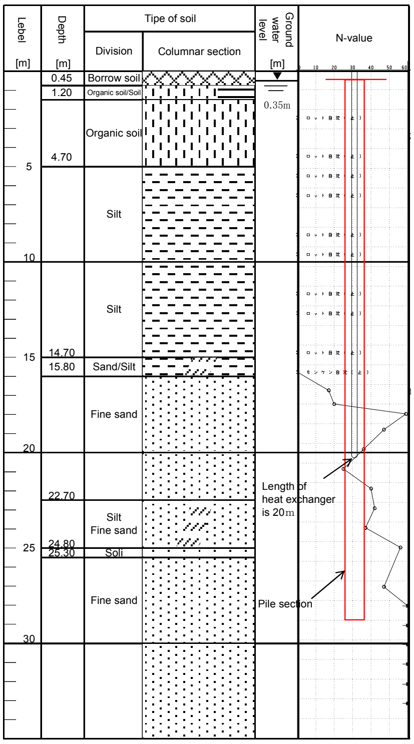


**Figure 3 The columnar section and soil condition**

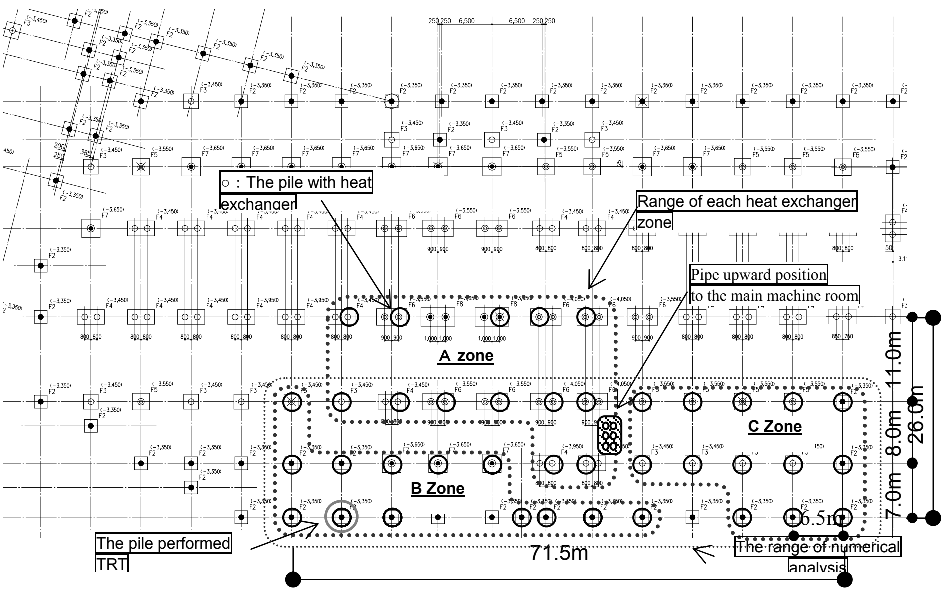


**Figure 4 Location of the heat exchanger installed in piles**

### 3.3 Outline of Thermal Response Test(TRT)

TRT was carried out after the heat exchangers were installed into piles and foundation construction around them was completed. Figure 4 shows the measurement results. The average flow rate was 8.7 L/min and the average heat injection was 1.26kW (63W/m per unit length of the energy pile) during TRT. The heat source fluid supply temperature was raised for about 12 deg C, from about 18 deg C to 30deg C, in 23 days. The average temperature difference between supply and return of heat source water was about 2.5 deg C. The heat balance of TRT was equivalent to heat released to the ground by cooling operation for one month. The return fluid temperature was maintained at approximately 30 deg C, and it was expected that it would result in relatively efficient cooling.

The effective thermal conductivity $\lambda$ was estimated from the equation (1) based on the line source theory using the k value calculated by temperature change after 240 hours.

$$\lambda = Q / 4\pi k L \quad (1)$$

With k, the average heat injection Q, and the effective length of heat exchanger L (=20m), the effective thermal conductivity was 4.84 W/m/K. This result was about twice the actual value of general gravel. The reason of high $\lambda$ was considered due to the ground water flow effect etc. and this condition was considered good for GSHP system.

### 3.4 GSHP System Operation Concept

The GSHP system operation concept is shown in Figure 2. The GSHP system is described in terms of system operation concept.

In the winter season, the GSHP supplies hot water to floor heating pipes in the concrete slab. The GSHP heats the concrete slab with the cheaper night time electricity rate at night time. This operation is heat storage. The stored heat is used for base heating and the GSHP supplies hot water for additional heating in the day time. The GSHP is separated from the central heat source system and supplies hot water as the dedicated heat source for floor heating during the winter season. This is to prevent the low temperature burning of the senior patients, as the supply water temperature of the GSHP is 35 deg C while that of the central system is 45 deg C. Therefore this setting is aimed at the ensuring safety of low temperature burn prevention of the senior patients. Moreover, it improved COP of GSHP and contributed to energy saving by separating itself from the central system and lowering the supply hot water temperature.

In the summer season, the GSHP is connected with the central heat source system. The GSHP supplies cold water during the daytime and the heat is released into the ground, raising the ground temperature. This can be considered the warm heat storage which is used for heating operation during the nighttime. The GSHP preheats makeup water tank for hot water supply with the cheaper midnight electricity rate. This recovers the hot heat stored in the ground during the daytime, and at the same time it can be considered as cold heat storage that will be used for the cooling on the next day.

This system switches storage and recovery of heat from the ground, the cooling operation during the daytime and the heating operation during the nighttime to improve other operation and this is the major concept of this heat source system. This concept converts the ground source characteristic that degrades the performance after long continuous operation into what improves the performance.

## 4 THE PERFORMANCE VERIFICATION OF THE GSHP SYSTEM

### 4.1 Performance Estimate by Numerical Analysis

The GSHP system was examined with numerical analysis and the system COP was estimated. Numerical analysis was carried out using the GSHP system design/performance

**Table 2 Estimated GSHP system COP**

| | | | | |
|---|---|---|---|---|
| Analysis condition | Season | Daytime/ Nighttime | CASE1<br>Summer : For only cooling<br>Intermediate season : No operation<br>Winter : Floor heating | CASE2<br>Summer : Cooling and hot water preheating<br>Intermediate season : No operation<br>Winter : Floor heating |
| | Winter | Nighttime | Floor heating for three hours | |
| | | Daytime | Additional operating Floor heating for 15 minutes after 12 hours | |
| | Summer | Nighttime | No operating | Hot water supply preheating |
| | | Daytime | Cooling operating, for 8 hours | Cooling operating, for 8 hours |
| Analysis results | Season | Object | CASE1<br>(Coefficient of performance) | CASE2<br>(Coefficient of performance) |
| | Winter | Floor heating | 5.7 | 5.5 |
| | Summer | Cooling | 3.7 | 4.2 |
| | | Hot water supply preheating | — | 4.5 |
| Notes | | ※COP (analysis result) is seasonal average.<br>※Conditions in the numerical analysis of hot water are preheated from 25℃ to 40℃, and quantity of water of 12m³.<br>※Hot water supply temperature for floor heating is 35degC.<br>※Average initial soil temperature is 16.6degC.<br>※Effective thermal conductivity of soil is 3.0w/m/K. | | |

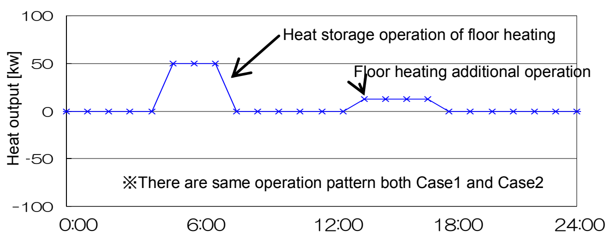


**Figure 5.1 Analysis condition of air conditioning load in the winter season**

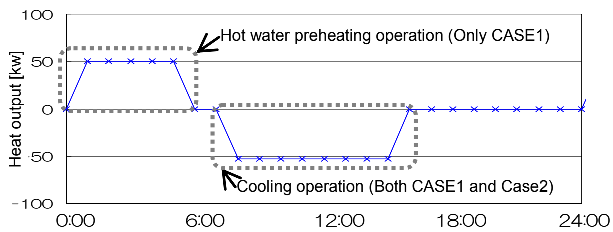


**Figure 5.2 Analysis condition of air conditioning load in the summer season**

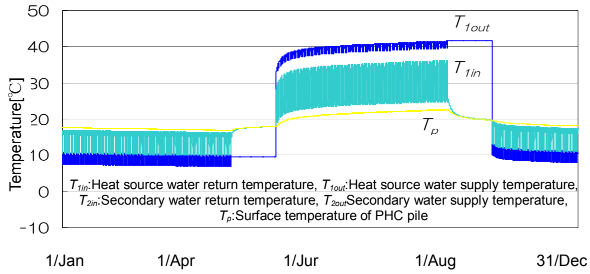


**Figure 6.1 Annual temperature of the heat source water (CASE1)**

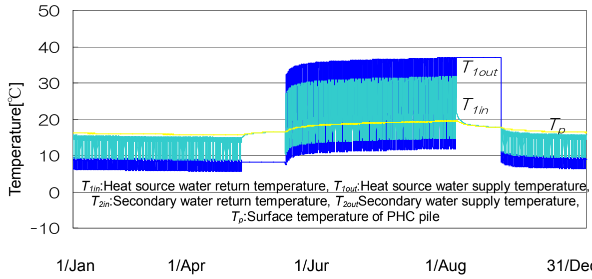


**Figure 6.2 Annual temperature of the heat source water (CASE2)**

prediction tool. The detail explanation of this tool refers to this reference (K. Nagano et al.) Although the effective thermal conductivity was 4.84 W/(m･K) by TRT, that was a very large figure. Since the confirmation of the equipment capacity was also part of the purposes, 3.0 W/(m･K) was used as the average data between 4.84 W/(m･K) by TRT and 1.3 W/(m･K) by estimation from boring data. The layout of piles with heat exchangers is shown in Figure 4. Figure 5.1 and 5.2 show the analysis condition of air conditioning load. The COP of GSHP was calculated from the GSHP performance diagram of the assumed product model and the temperature of return heat source water and that of the secondary supply water.

The result of numerical analysis was summarized in Table 2. Figure 6.1 and 6.1 show annual temperature of the heat source water. It showed that the heat source return water temperature was improved from 42 deg C in CASE1 to 38 deg C in CASE2 at the end of the summer. The reason was that the ground temperature condition was improved by switching daytime restoring and nighttime storing. As a result, improving the GSHP efficiency, the unit COP of the GSHP was expected to improve from 3.7 in CASE1, that was under usual operation condition for continuous cooling, to 4.2 in CASE2, that was characteristic condition of this system with switching cooling and heating. Figure 6.1 and 6.1 show the estimated annual temperature of the heat source water.

## 4.2 Operational Results with Different Operating Conditions

After two years since the building was opened, the operational measurement data was analyzed for the purpose of commissioning, with different operation conditions to improve the performance of the heat source system. Figure 7 to Figure9 shows the results of improved performance.

Figure 7 shows the GSHP heat balance of the ground in the summer of 2009. The heat stored in the ground was significantly larger in comparison with the recovered heat. The reasons were considered that hot water preheating load was small and actual cooling operation time (from 8 till 21 o'clock) was unnecessarily longer than the originally planned operation time (from 8 till 17 o'clock). The set condition of the GSHP system was changed in order to improve this condition. First, the GSHP cooling operation was terminated at 12 o'clock, when the ice storage system operation. This reduced the running time of the GSHP cooling operation and hence the storing heat for ground. Second, the hot water preheating temperature was set from 40 deg C to 45 deg C in order to improve the heat balance of ground and shift hot water heating operation to night time electricity rate time zone. The supply water temperature of the GSHP was also changed from 45deg C to 50deg C.

These changes contributed to the improvement of the heat balance between heat storing and heat recovering with the ground. One week average ratio of storing heat and recovering heat became 100:234[kWh] from 63:426[kWh] (Figure 7.1 & 7.2). As a result, the GSHP heat source water return temperature improved from 34.2 deg C to 30.2 deg C during the cooling operation (Figure 8.1 & 8.2). The energy pile inner temperature profile was improved as shown in Figure 9.1 and Figure 9.2.

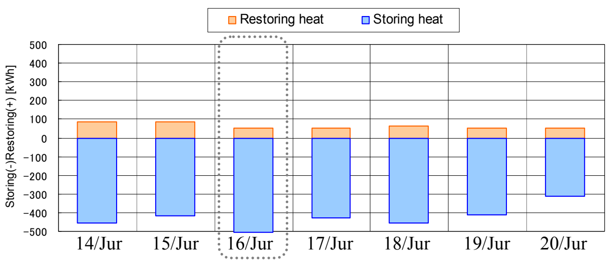


**Figure 7.1 Heat balance of the ground (from 14th to 20th, July)**

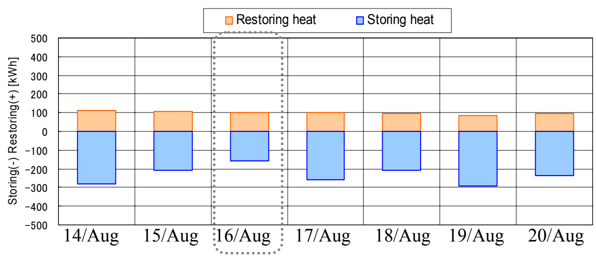


**Figure 7.2 Heat balance of the ground (from 14th to 20th, August)**

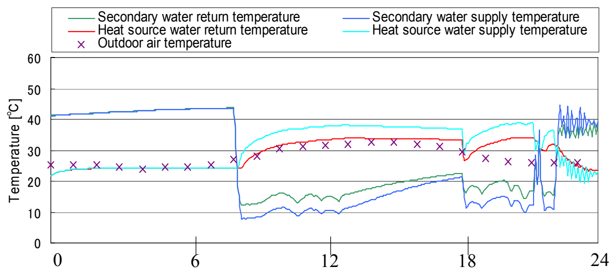


**Figure 8.1 Water temperature related to the GSHP (16th/Jur)**

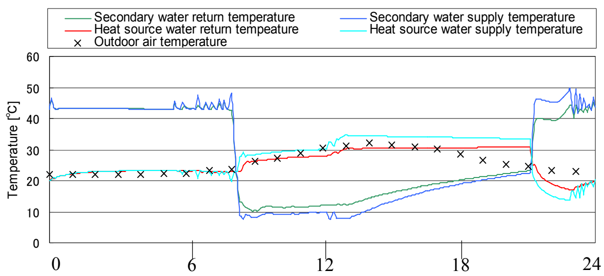


**Figure 8.2 Water temperature related to the GSHP (16th/Aug)**

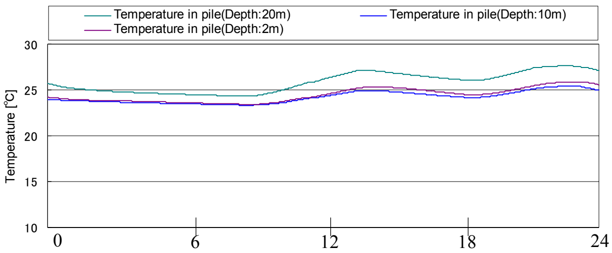


**Figure 9.1 Inner temperature profile of the pile (16th/Jur)**

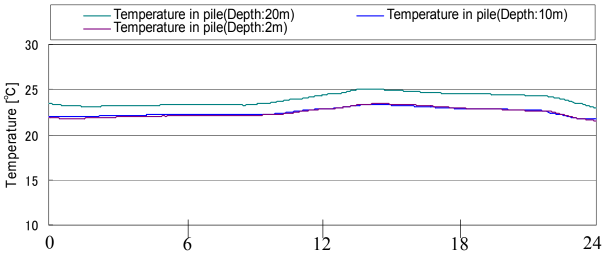


**Figure 9.2 Inner temperature profile of the pile (16th/Aug)**

## 5 CONCLUSIONS

This paper showed the effect of the GSHP system operation that switches cooling and heating during the daytime and the nighttime in the summer season, in other words the results of the numerical analysis as effect of short term heat storage and recovery of the ground. From the result of numerical analysis, it was estimated that the COP of the GSHP system in short term heat storage was more efficient than that of cooling-only operation in the summer season. It was shown in actual operation that the heat source water return temperature was improved by the operation condition change that improved heat balance of the ground in the summer season. As a result, a part of the potential development possibility of the GSHP system was clarified for the warm area where the cooling load in the summer season is considerably larger than the heating load in the winter season.

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