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A Study on the Operational Condition of a Ground Source Heat Pump in Bangkok Based on a Field Experiment and Simulation

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Abstract: The deployment of highly efficient cooling equipment is expected to promote energy savings and greenhouse gas emissions reductions in the tropics. A ground source heat pump (GSHP) has high energy-savings potential for use in Bangkok, Thailand. This study aimed to elucidate the operational conditions of a GSHP when used in Bangkok which was expected to achieve a higher efficiency than an air source heat pump (ASHP) over the long term. An operational experiment on a pilot facility in Bangkok and a simulation over a three-year GSHP operation were conducted. As a result of the operational experiment and simulation, the proposed operational condition was that the 90th percentile value of the hourly heat pump (HP) inlet temperature did not exceed 5 °C above that of the hourly annual ambient temperature during the third year of operation. When a GSHP designed based on this condition was utilized for a small government building, the required number of boreholes were 24, 4, and 3 for air-conditioned areas of 200, 40, and 25 m^2, respectively, which achieved 40% energy savings. Thus, a small-scale GSHP in Bangkok designed based on the proposed condition can achieve high efficiency within space limitations.

Keywords: Bangkok; ground source heat pump; air source heat pump; system coefficient of performance; HP inlet temperature

1. Introduction

The energy demand in Thailand is expected to increase owing to its future economic growth. The Ministry of Energy in Thailand has reported that their energy demand is expected to increase by 78% compared with 2014 by 2036 [1]. Thus, Thailand has set a goal of reducing greenhouse gas (GHG) emissions by 20–25% compared with the 2030 baseline established in the Paris Agreement, which was adopted in 2015 [2]. In Thailand, energy consumption accounts for approximately 70% of GHG emissions, of which approximately 40% are emitted by energy industries such as those involved in power generation [3]. Therefore, to achieve the goal of reducing GHG emissions, it is essential to promote the deployment of energy-savings equipment.

Thailand, which is located in the tropics, has a warm climate throughout the year with no period when the monthly average maximum atmospheric temperature falls below 30 °C. According to an indicator called cooling degree days, Bangkok, the capital city of Thailand, is the second warmest metropolitan city in the world [4]. Considering the high humidity in Bangkok as well, there is a cooling demand throughout the year; thus, air conditioning accounts for a large portion of the energy consumption. For instance, approximately 24% of the electricity consumption in Thailand stems from the commercial sector, of which more than half is consumed by commercial buildings [5]. Approximately 60% of the power consumption of commercial buildings stems from air conditioning [6]. Therefore, the deployment of highly efficient air conditioning systems is essential for Thailand to promote energy savings and reduce GHG emissions.

Ground source heat pumps (GSHPs) are known as highly efficient air conditioning systems which transfer the heat between the indoors and subsurface by using a heat exchanger embedded in the subsurface (i.e., ground heat exchanger, for example, open loop or closed loop). Alternatively, a conventional air conditioning system (i.e., an air source heat pump (ASHP)) transfers the heat between indoor and outdoor. In mid- and high-latitude regions, such as Europe, the USA, Japan, and China, GSHPs operate in an environment in which the temperature difference between the heat sink and the room is smaller than that of an ASHP. Thus, the power consumption of a HP compressor can be reduced to increase the efficiency. For example, case studies on GSHPs in Japan and Spain exhibited a 69% and 37% ± 18% reduction in electricity consumption for the whole cooling season compared with using an ASHP, respectively [7,8]. From the above discussion, GSHPs are an appropriate option for the "Trias Energetica" concept: minimizing the energy demand, utilizing sustainable energy sources, and using fossil energy as efficiently as possible [9].

The subsurface temperature in the tropics is higher than that in other regions and constant throughout the year; thus, GSHPs have been considered incompatible for the tropics. However, a geological survey of the Chao Phraya Plain, Thailand, showed that the subsurface temperature at a depth of 50 m is lower than the atmospheric temperature during the daytime [10]. For example, the subsurface temperature at a depth of 20–50 m is in the range of 29–31 °C, whereas the average daily maximum atmospheric temperature from March to June surpasses 33 °C in Bangkok. Given the existence of aquifer and groundwater flow, the subsurface in this plain has considerable potential to be utilized as a cold heat source for HP systems. Based on this geological survey, a pilot study of the GSHP in Thailand was conducted to demonstrate its energy-savings potential. As a result, a GSHP with vertical- and horizontal-type borehole heat exchangers (BHEs), which is a type of a ground heat exchanger, reduced the electricity consumption by approximately 30% and 18% compared with that of an ASHP, respectively [11,12]. Moreover, the GSHP in Bangkok reduced the life-cycle CO_2 emissions by approximately 28% compared with the ASHP according to a life-cycle inventory analysis of its use in a commercial building [13]. Thus, a GSHP is useful for energy savings and GHG emission reduction, even in Bangkok, which is located in the tropics.

However, the pilot study conducted in Thailand [11,12] did not elucidate "the performance of the GSHP for the specific heat sink temperature" and "the subsurface temperature increases on long-term GSHP operation". The efficiency of the GSHP/ASHP during cooling operations is decreased by increasing the heat sink temperature, i.e., HP inlet temperature/atmospheric temperature [14]. Owing to the high subsurface temperature, which is unlike other regions, the performance of the GSHP in Bangkok may not always be higher than that of the ASHP. Even further, the long-term GSHP operation may be at risk of subsurface temperature increase. Therefore, it is essential to elucidate "the efficiencies of the GSHP and ASHP according to the heat sink temperature" and "the subsurface temperature increase on long-term GSHP operation".

A subsurface temperature increase cannot be observed during a few months of operation but requires a few years of operation or simulation [15]. Several studies have been conducted on the long-term subsurface temperature changing in regions with a warm climate. In Greece, the effect was observed upon 8 years of GSHP operation [16]. In Shanghai, Hong Kong, and Qatar, the influence was predicted by a few years of operational simulation which was validated based on experiments [17–19]. These regions have a heating demand in winter, and the subsurface temperature for these regions, except for Qatar, is approximately 20 °C. However, Bangkok does not have heating demand throughout the year, and its subsurface temperature is in the range of 29–31 °C. Even for warm climate regions, in the tropics, such as in Bangkok, there is a unique operational environment. Therefore, we could not apply the results of previous research for predicting the subsurface temperature increase during long-term GSHP operation in Bangkok.

Moreover, the groundwater level and the existence of groundwater flows vary for each region; thus, the underground thermal properties are not the same even in the tropics, especially the thermal conductivity. Therefore, a simulation that uses the subsurface thermal properties for Bangkok is necessary to predict the subsurface temperature increase in Bangkok.

According to the above, the objective of this study was to elucidate the operational conditions for a GSHP in Bangkok to achieve high efficiency compared with the ASHP for long-term use via the following two studies:

(1) An experimental investigation was conducted by using the same pilot facility in the previous study in Bangkok [11] to elucidate the efficiency of a GSHP and ASHP according to the heat sink temperatures.
(2) A simulation was conducted that utilized the analytical solution of the heat conduction equation to predict the subsurface temperature increase due to the GSHP operation over the long term.

2. Materials and Methods

2.1. Experimental Investigation

2.1.1. Description of the Experiment Facility

An operational experiment was conducted on the 2nd floor of the Parot Racha building at Chulalongkorn University which is located in the central area of Bangkok, Thailand [11] (Figure 1). An experimental room with a total floor area of 15 m^2 was equipped with both a GSHP and ASHP. The experimental apparatus was divided into three main pieces of equipment: (1) a BHE, (2) an HP, and (3) a data acquisition system.

Figure 2 presents a schematic illustration of the experimental apparatus.

Borehole Heat Exchanger (BHE)

The device had two boreholes with a depth of 50 m and a diameter of 23 cm, and each borehole was set 6 m apart. The borehole on the left was indicated by No. 1 and the one on the right by No. 2. High-density polyethylene (HDPE) pipes called U-tubes with an outer diameter of 32 mm were inserted into these two boreholes to circulate the heat transfer fluid (brine). Approximately 20% of propylene glycol solution was utilized for the brine. Utilizing propylene glycol solution was designated by the manufacturer of the GSHP. Borehole heat exchanger No. 1 had two pairs of U-tubes inserted to a depth of 10 and 15 m in series; BHE No. 2 had one pair of U-tubes inserted to a depth of 50 m. The space between the U-tube and borehole was filled with river sand which was saturated with water for the case below the groundwater level.

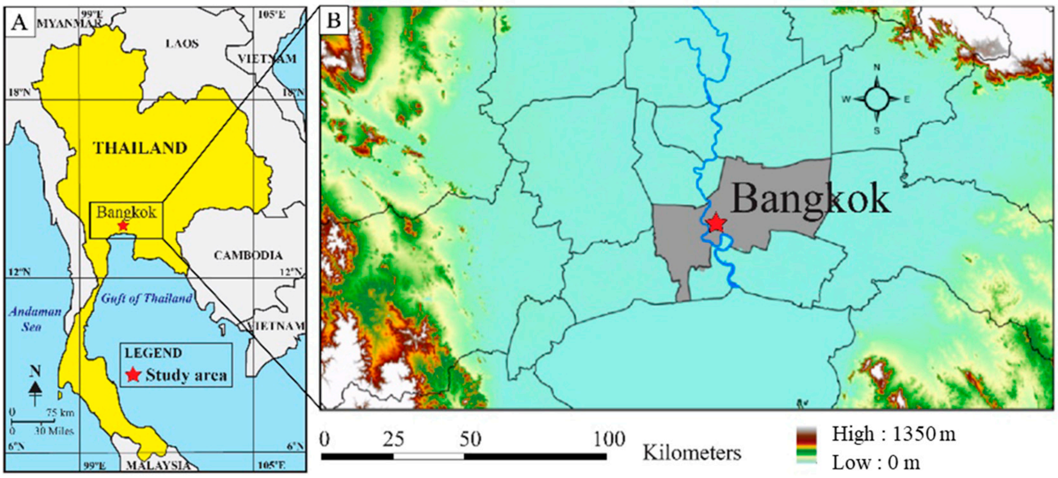

Figure 1. Location of the ground source heat pump (GSHP) experiment facility: (**A**) index map of Thailand; (**B**) Chulalongkorn University (star) in Bangkok. (Retrieved and modified from Chokchai et al. (2018) [11], Figure 1).

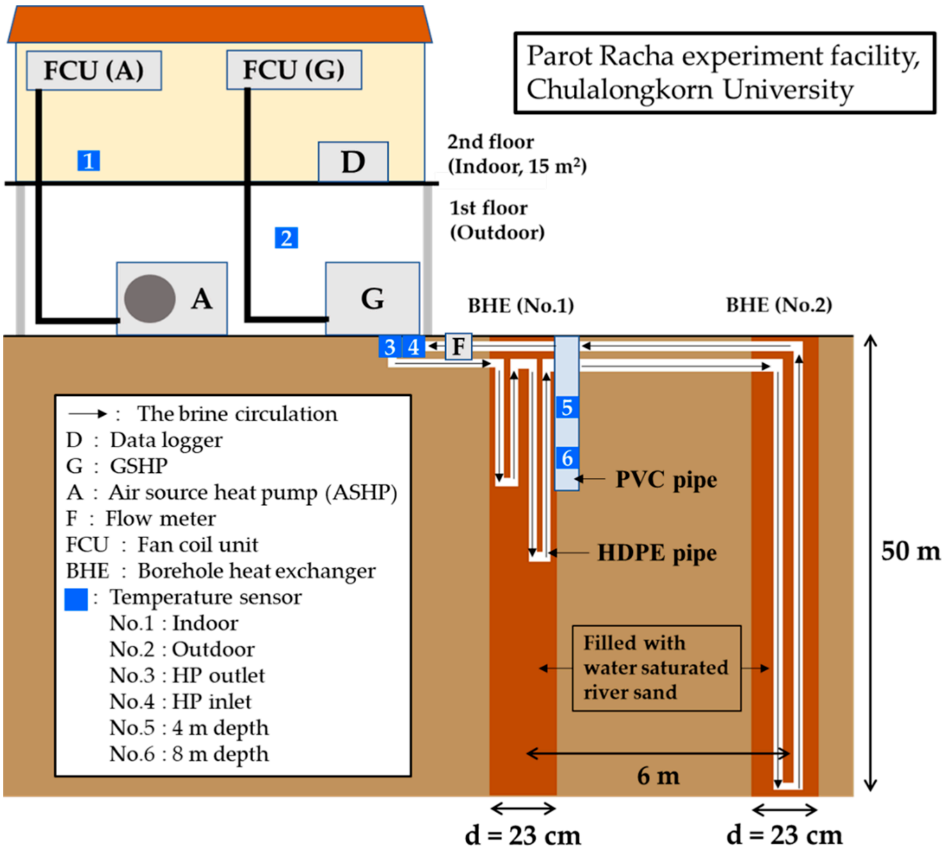

Figure 2. Schematic illustration of the experimental apparatus.

In general, U-tubes are recommended to be inserted to a same depth and connected in parallel for preventing the uneven flow and heat injection rates in each U-tube. However, this experimental facility is designed to conduct experiments based on various U-tube arrangements. This study utilized a part of the experimental facility. Therefore, the BHE utilized in this study was different from conventional ones.

Heat Pump (HP)

The GSHP utilized for the experiment was a Corona CSH-C4000G, and the ASHP was a Panasonic CS-PC12QKT. Both systems were controlled by an inverter. Table 1 presents a specification of both HP.

Table 1. The specification of the ASHP and GSHP.

Detail	ASHP	GSHP
Brand	PANASONIC	CORONA
Model	CS-PC12QKT	CSH-C4000G
Rated cooling capacity (W)	3600	4000
Rated cooling COP	3.5	4.0
Refrigerant	R410A	

This study aimed to make a comparison of efficiency between a GSHP and an ASHP by utilizing household products. Since every product has a specific performance, the results obtained by this study may not be fully generalizable. However, given the similar cooling capacity of each, we considered that the HP we selected was acceptable to demonstrate the difference of efficiency between the GSHP and ASHP. The HP units, which are composed of a compressor and condenser, were placed outdoors on the 1st floor. A fan coil unit (FCU), which works as an evaporator, was placed inside the experimental room on the 2nd floor. Figure 3 presents photographs of the experimental room and the HP units.

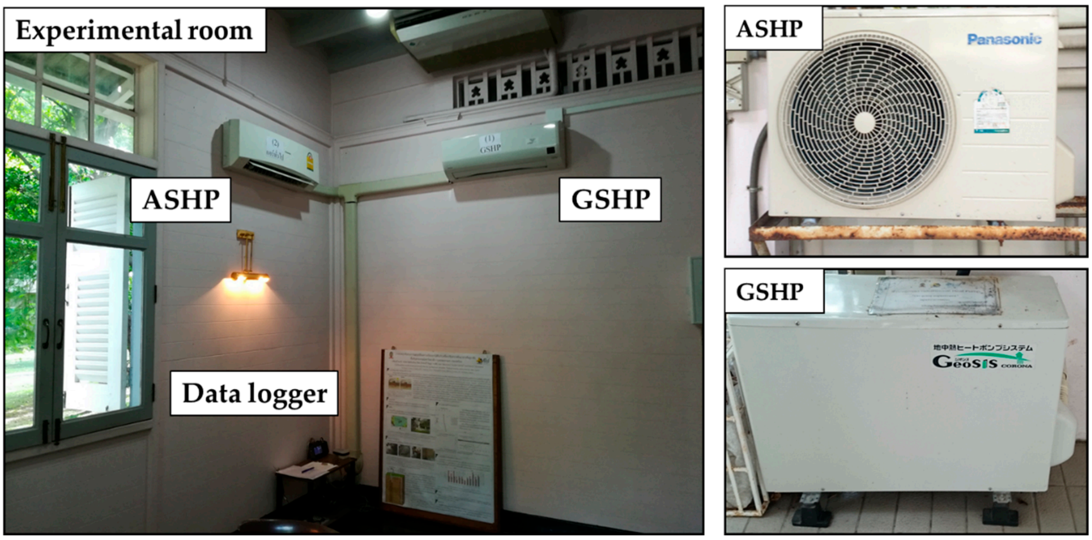

Figure 3. Photographs of the experimental room and the HP units.

Data Acquisition System

A thermistor from SEMITEC, AT103, was used to observe the outdoor and indoor temperatures (No. 1 and 2 in Figure 2). Sensors No. 1 and No. 2 were placed so as not to expose them to the airflow from the FCU and to the sunlight, respectively. The brine temperature at the HP inlet and outlet (No. 3 and 4 in Figure 2) was observed using the platinum resistance thermometers, from CHINO, R040. The error for these temperature sensors was verified to be 0.1 °C or less in the range of 26–42 °C via calibration before installing. The subsurface temperature was observed using the thermistor (AT103) which was placed inside the polyvinyl chloride (PVC) pipe adjacent to BHE No. 1. The thermistor placed inside the PVC pipe was at a depth of 8 m (No. 6 in Figure 2) during the experiment from September to October 2018. However, because the temperature data from sensor No. 6 were inaccurate, we replaced it with a new sensor for the experiment from February to April 2019. At that time, the sensor (No. 5 in Figure 2) was wrapped in vinyl for waterproofing and placed at a depth of 4 m, not 8 m. An electromagnetic type flow meter (0.6% error) from KEYENCE, the FD-M series, was used to observe the flow rate of the brine.

The data from all sensors were gathered and obtained using the data logger, from GRAPHTEC, GL220, which was placed in the experimental room. The data logger was also used to measure the electricity consumption of the overall system by use of converter. All data were recorded at an interval of 1 min.

2.1.2. Experimental Conditions

The operational experiments were conducted from September to October 2018 (rainy season) and from February to April 2019 (hot and dry season). Table 2 presents the experimental conditions. The settings for the GSHP and ASHP were 25 °C and a constant air volume during the experiment. The experiment was not conducted on weekends.

Table 2. Operational experimental conditions.

<table>
<tr><th colspan="6">September and October 2018 (Rainy Season)</th></tr>
<tr><td rowspan="3">September</td><td>5th~11th</td><td>9:00~12:00: ASHP</td><td>12:00~15:00: GSHP</td><td colspan="2">15:00~22:00: ASHP</td></tr>
<tr><td>12th~19th</td><td>8:00~12:00: GSHP</td><td>12:00~15:00: GSHP+ASHP</td><td colspan="2">15:00~16:00: GSHP</td></tr>
<tr><td>24th~28th</td><td colspan="4">8:00~16:00: GSHP</td></tr>
<tr><td rowspan="3">October</td><td>1st~5th</td><td>9:00~12:00: GSHP</td><td>12:00~15:00: GSHP+ASHP</td><td colspan="2">15:00~22:00: GSHP</td></tr>
<tr><td>8th~12th</td><td colspan="4">24 Hours Operation: GSHP</td></tr>
<tr><td>16th~19th</td><td>9:00~10:00: GSHP</td><td>10:00~12:00: ASHP</td><td>12:00~16:00: GSHP</td><td>16:00~22:00: ASHP</td></tr>
<tr><th colspan="6">February to April 2019 (Hot and Dry Season)</th></tr>
<tr><td>February</td><td>26th~1st</td><td rowspan="2">9:00~10:00: GSHP</td><td rowspan="2">10:00~12:00: ASHP</td><td rowspan="2">12:00~16:00: GSHP</td><td rowspan="2">16:00~21:00: ASHP</td></tr>
<tr><td rowspan="3">March</td><td>4th~8th</td></tr>
<tr><td>11th~15th
18th~22nd</td><td colspan="3">9:00~16:00: GSHP</td><td>16:00~21:00: ASHP</td></tr>
<tr><td>25th~29th</td><td colspan="4" rowspan="2">9:00~21:00: GSHP</td></tr>
<tr><td rowspan="2">April</td><td>1st~5th</td></tr>
<tr><td>9th~11th</td><td colspan="4">24 Hours Operation: GSHP</td></tr>
</table>

September and October 2018 (Rainy Season)

For the conditions from 5 to 11 September, the ASHP operation was performed in the morning and evening, whereas the GSHP operation was performed during the daytime. For the conditions from 12 to 19 September and from 1 to 5 October, the GSHP and ASHP operations were performed at the same time from 12:00 to 15:00 when a large cooling load was expected. For the conditions from 16 to 19 October, the GSHP operation was performed during the time that was expected to require a substantial cooling load to minimize the electricity consumption as much as possible while preventing an increase in the subsurface temperature.

February to April 2019 (Hot and Dry Season)

For the conditions from 26 February to 8 March, the same conditions as from 16 to 19 October was used to verify the difference between the rainy and hot seasons. After this condition, the GSHP operation time was changed every 2 weeks to 8, 12, and 24 h per day.

2.1.3. Analysis on the GSHP and ASHP Operation

To analyze the efficiency of the GSHP and ASHP as a function of the heat sink temperature, the heat dissipation rate and cooling load must be calculated using the operational experimental data. This section describes the calculation methodology of the heat dissipation rate, cooling load, and efficiency. The heat exchange rate per unit length of BHE (HER) was utilized as the indicator of the heat dissipation rate. The system coefficient of performance (Sys-COP) was used as an indicator of efficiency. Table 3 presents the terminology used in this paper.

Table 3. Nomenclature for Equations (1)–(11).

Nomenclature		**Subscripts**	
C	specific heat (J/(kg °C))	ashp	air source heat pump
COP	coefficient of performance (-)	b	brine
E	electric power (W)	c	cooling load
H	hydraulic head (m)	com	compressor
HER	heat exchange rate (W/m)	fan	fan (ASHP condensor)
L	length of BHE (m)	fcu	fan coil unit
m	flow rate (m^3/min)	gshp	ground source heat pump
Q	thermal energy rate (W)	h	heat dissipation
r	radius (m)	in	heat pump inlet
Sys-COP	system coefficient of performance (-)	m	motor
t	time	out	heat pump outlet
T	temperature (°C)	p	pump
Greek symbols		s	subsurface soil
λ	thermal conductivity (W/(m K))	to	total
μ	efficiency (-)		
ρ	density (kg/m^3)		

Heat Exchange Rate Per Unit Length of BHE (HER)

The hourly average heat dissipation to the subsurface was calculated from the brine temperature difference between the HP inlet and outlet as follows:

$$Q_{\mathrm{h}} = \frac{1}{3600} \times \sum_{t=t'}^{t'+60} m_{\mathrm{b}}(t)\rho_{\mathrm{b}}C_{\mathrm{b}}(T_{\mathrm{b,\,out}}(t) - T_{\mathrm{b,\,in}}(t)) \tag{1}$$

where Equation (1) refers to the average amount of heat dissipation for 1 h to a value per second. The density and specific heat of the brine were 1023 kg/m^3 and 3951 J/(kg °C), respectively, from the thermal properties of 20% solutions of propylene glycol. These values were obtained by the software "GroundClub version 1.0.0.30", a performance prediction tool for the GSHP which was utilized for the simulation in the latter part of this study. The *HER* was calculated as follows:

$$HER = \frac{Q_{\mathrm{h}}}{L_{\mathrm{to}}} \tag{2}$$

where L_{to} was 65 because the total length of the U-tube was 65 m.

Cooling Load

The amount of heat dissipation is equal to the sum of the cooling load and electricity consumption of the compressor. Thus, the hourly average cooling load was expressed as follows:

$$Q_{\mathrm{c}} = Q_{\mathrm{h}} - E_{\mathrm{com}} \tag{3}$$

However, although the electricity consumption of the overall system was recorded, the data acquisition system in this study could not record the electricity consumption of the compressor itself. Because the GSHP was composed of a compressor, circulation pump, and FCU, the electricity consumption of the overall system was expressed as follows:

$$E_{\text{gshp}} = \frac{1}{3600} \times \sum_{t=t'}^{t'+60} E_{\text{gshp}}(t) \ = E_{\text{com}} + E_{\text{fcu}} + E_{\text{p}} \quad (4)$$

Here, substituting Equation (4) for (3) and transforming it, we obtain:

$$Q_{\text{c}}{}' = Q_{\text{c}} - E_{\text{fcu}} = Q_{\text{h}} - \left(E_{\text{gshp}} - E_{\text{p}}\right) \quad (5)$$

where Q_c' is the value of the cooling load minus the electricity consumption of FCU (E_{fcu}). We utilized Q_c' as a substitution for the cooling load in this study because Q_h, E_{gshp}, and E_p could be obtained and estimated from the experimental data. E_p, the electricity consumption of the circulation pump, could be estimated by the relationship between the flow rate and hydraulic head which was stated in the technical data book for the GSHP. Thus, E_p is given by:

$$E_{\text{p}} = \frac{0.163}{\mu_{\text{p}}\mu_{\text{m}}} \times m_{\text{b}}\rho_{\text{b}}\text{H} \quad (6)$$

where m_b, the flow rate of the brine, was 27 L/min almost continuously when the operation was stable. According to the description in the technical data book, the hydraulic head was 6 m when the flow rate was 27 L/min. Assuming that the efficiency of the pump was 0.5 and the efficiency of the motor was 0.9, the E_p was 60 W. We conducted the sensitivity analysis on the cooling load (Q_c') with the E_p in the range of ±50% over the value of 60 W. As a result, the average fluctuation rate of the Q_c' was ±2.62%, implying the robustness of Q_c' over E_p was confirmed. After confirming this robustness, we set the electricity consumption of the circulation pump at 60 W.

Figure 4 presents the relation between Q_c' and the hourly average outdoor temperature. Because the storage load was treated within an hour after the beginning of operation, the cooling load during that time was becoming large regardless of the outdoor temperature. Thus, the data obtained during operation within an hour after the beginning of service was not included in Figure 4.

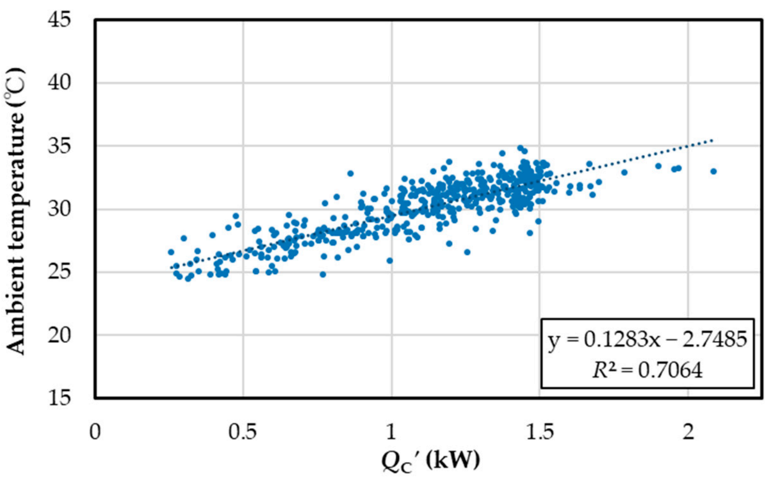

Figure 4. The relationship between Q_c' and the hourly average outdoor temperature.

The cooling load was roughly proportional to the outdoor temperature. Thus, for the case when the absolute temperature curve of the outside converged to an error range of ±0.25% of the curve of another duration, we considered the transition of hourly cooling load for each duration equal. Although the cooling load during the ASHP operation was impossible to calculate from the obtained data directly, we estimated it from the GSHP operational data for the case when the outside temperature curve converged to an error range of ±0.25%. For example, the outside temperature curve on 4 March 2019 converged to an error range of ±0.25% of that on 27 March 2019. In this case, the hourly cooling load from 10:00–12:00 and 16:00–21:00 on 27 March 2019 was utilized for estimating that of the ASHP operation on 4 March 2019 (see Table 2).

System Coefficient of Performance (Sys-COP)

The coefficient of performance (COP) is a standard indicator for evaluating the heat pump efficiency which refers to the ratio of the air conditioning load that can be processed by electricity consumption of compressor per unit. Given that the FCU and circulation pump also consumes electricity, utilizing the electricity consumption of the compressor is not sufficient to demonstrate the performance. Thus, we defined the system coefficient of performance (Sys-COP) as an indicator for evaluating the overall system efficiency which included not only electricity consumption of compressor but also FCU and circulation pump. The *Sys-COP* of the GSHP and ASHP were obtained as follows:

$$Sys-COP_{\mathrm{gshp}} = \frac{Q_{\mathrm{c}}}{E_{\mathrm{gshp}}} = \frac{Q_{\mathrm{c}}}{E_{\mathrm{com}} + E_{\mathrm{fcu}} + E_{\mathrm{p}}} \quad (7)$$

$$Sys-COP_{\mathrm{ashp}} = \frac{Q_{\mathrm{c}}}{E_{\mathrm{ashp}}} = \frac{Q_{\mathrm{c}}}{E_{\mathrm{com}} + E_{\mathrm{fcu}} + E_{\mathrm{fan}}} \quad (8)$$

In this study, we utilized Q_{c}' as a substitution for Q_{c}. In this case, *Sys-COP* using Q_{c}' was expressed as follows:

$$Sys-COP_{\mathrm{gshp}}' = \frac{Q_{\mathrm{c}}'}{E_{\mathrm{gshp}}} = \frac{Q_{\mathrm{c}} - E_{\mathrm{fcu}}}{E_{\mathrm{com}} + E_{\mathrm{fcu}} + E_{\mathrm{p}}} \quad (9)$$

$$Sys-COP_{\mathrm{ashp}}' = \frac{Q_{\mathrm{c}}'}{E_{\mathrm{ashp}}} = \frac{Q_{\mathrm{c}} - E_{\mathrm{fcu}}}{E_{\mathrm{com}} + E_{\mathrm{fcu}} + E_{\mathrm{fan}}} \quad (10)$$

2.2. Simulation of Long-Term GSHP Operation

2.2.1. Determining the Subsurface Thermal Properties

To predict the long-term subsurface temperature changes as a function of the GSHP operation, we must understand the thermal properties at the subsurface of the BHE. Notably, the apparent thermal conductivity of the subsurface includes the effect of heat advection by groundwater flow; thus, it is a significant thermal property that influences the subsurface temperature change.

The thermal response test (TRT) is a test for obtaining the apparent thermal conductivity of the subsurface in situ. The TRT was conducted by circulating the brine through the BHE with heating constantly and measuring the brine temperature response [20]. After the test, mathematical models for the analysis of the heat conduction equation for a cylindrical coordination system were utilized to evaluate the temperature response to obtain the thermal conductivity. The following equation is the heat conduction equation for a cylindrical coordination system:

$$\frac{\partial T_{\mathrm{s}}}{\partial t} = \frac{\lambda_{\mathrm{s}}}{\rho_{\mathrm{s}} C_{\mathrm{s}}}\left(\frac{\partial^2 T_{\mathrm{s}}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{\mathrm{s}}}{\partial r}\right) \quad (11)$$

In this experimental facility, the TRT was performed at BHE No. 2 from 13 to 16 February 2018. This TRT was the first attempt in the tropics. The TRT was conducted for almost 66 h while providing 2 kW of heating load, which is 40 W/m of *HER*, to BHE No. 2. Water was utilized as the brine for this TRT alternative to propylene glycol solution. The line source model was applied to analyze the temperature response of the brine [21]. As a result of the analysis, the apparent thermal conductivity of the subsurface at BHE No. 2 was found to be 1.82 W/(m K) [22].

To confirm the validity of the obtained thermal conductivity, we simulated the brine temperature response by using the same condition as that used for the TRT. This validation methodology is called history matching. There are two mathematical models for history matching: an analytical and a numerical model [23]. The numerical model can handle the inhomogeneity of the subsurface and the advection effect of groundwater flow. However, the hydrogeological characteristics of a wide area are required to understand how to set the boundary condition so that the settings for the numerical simulation require time and money compared with the analytical solution. Therefore, the analytical model was utilized for the history matching in this study.

In addition to the line source model described above, there is another analytical model based on a cylindrical source function that is called the cylindrical source model [24]. The line source model cannot consider the heat capacity of the brine or the geometry of BHE, because it regards the BHE as a line heat source. In contrast, the cylindrical source model can consider both and can simulate the temperature response with higher accuracy than the line source model. It should be annotated that the cylindrical source model neglects the heat capacity of BHE elements. However, the effect of the heat capacity of BHE elements appears on the brine temperature response within few hours after starting TRT, while the apparent thermal conductivity is not calculated utilizing the data at that duration. Thus, given that the purpose of the TRT was obtaining the apparent thermal conductivity, we considered that neglecting the heat capacity of BHE elements did not affect the results. Based on the above discussion, we adopted the cylindrical source model to conduct history matching. The software "GroundClub ver 1.0.0.30", whose basic theory is the cylindrical source model, was utilized [25–27]. The boundary condition for Equation (11) was a heat flux generated on the surface of borehole (55.4 W/m^2), and the initial condition was an average subsurface temperature (29.5 °C). The brine inlet and outlet temperature were calculated from the equation (retrieved and modified from Equation (13) in Reference [25]) as follows:

$$\rho_b C_b V_b \frac{dT_b}{dt} = -m_b \rho_b C_b (T_{b,\,in} - T_{b,\,out}) + K_b A (T_s - T_b) \tag{12}$$

where V_b is the volume of the brine; K_b is the overall heat transmission coefficient between the surface of the borehole and the brine; and A and T_s are, respectively, the surface area and surface temperature of the borehole.

Table 4 presents the specifications and thermal properties of BHE No. 2. Figure 5 presents the results of the history matching.

Table 4. The specifications and thermal properties of BHE No. 2.

The specifications of BHE No. 2	The type of BHE	Single U-tube
	Brine	Water
	Diameter (m)	0.23
	Depth (m)	50
	Type of backfill material	Water saturated river sand
	Backfill material thermal conductivity (W/(m K))	2.0
The specifications of U-tube pipe	Material	HDPE
	Outer diameter (mm)	32
	Inner diameter (mm)	26
	U-tube pipe thermal conductivity (W/(m K))	0.38
Subsurface soil thermal properties	Effective thermal conductivity (W/(m K))	1.82
	Heat capacity (kJ/(m^3 K))	2600
	The initial average temperature (°C)	29.5

Although some errors were observed between the simulation and the TRT results after starting the TRT, the simulation result was in good agreement with the TRT results approximately 12 h after starting the TRT. The average error for the first 12 h was 1.00%, while the after that it was 0.24%. Generally, the influence of thermal conductivity did not appear instantly after starting the TRT but after some time after running the TRT [20]. Moreover, the subsurface temperature profile at BHE No. 2

was in the range of 29 °C to 30.5 °C, and the heat capacity of 2600 kJ/(m^3 K) was a typical value for quaternary formations [11]. Thus, the history matching results demonstrated that the apparent thermal properties obtained by the TRT were the actual values for BHE No. 2.

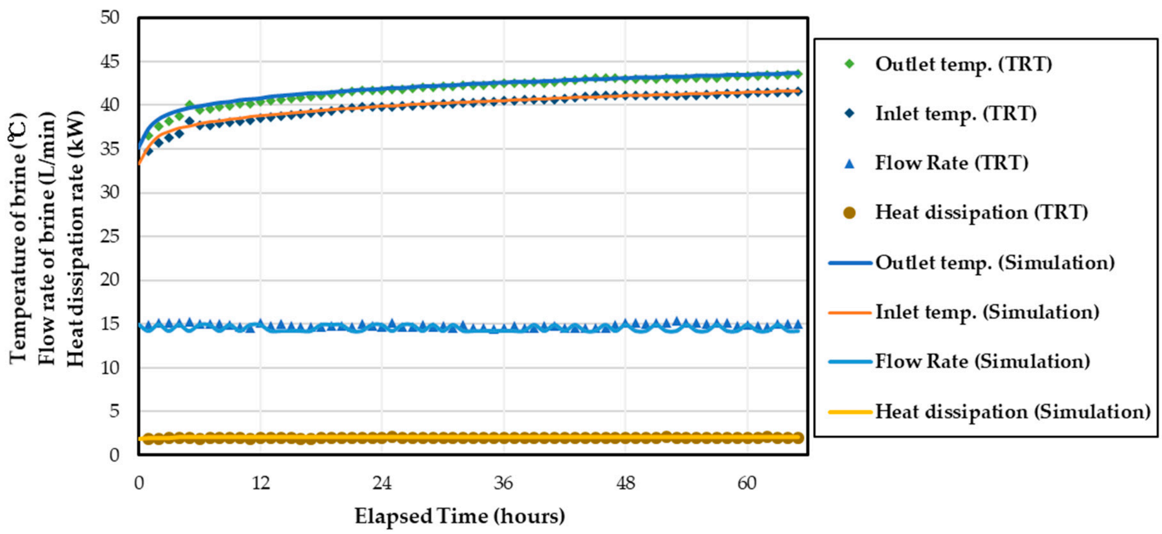

Figure 5. Thermal response test (TRT) history matching results.

2.2.2. Simulation Parameters

The subsurface temperature change was simulated assuming long-term GSHP operation using BHE No. 2, of which the thermal properties were validated as discussed in the previous section. The same software, "GroundClub version 1.0.0.30", was utilized for the simulation. The high reproducibility of this simulation software has been verified by comparison with the measured values from annual operation [28]. The average BHE surface temperature was used as an indicator of the subsurface temperature because the BHE surface was adjacent to the ground.

According to the GSHP design guidelines provided by the Ministry of Land, Infrastructure, Transport, and Tourism, Japan, the standard average *HER* is in the range of 50 to 70 W/m for office buildings [29]. In Thailand, there is no heating demand, only a cooling demand throughout the year; thus, the allowable *HER* is expected to be smaller than in Japan. According to the above discussion, we set three *HER* values of 20, 30, and 40 W/m. These *HER* values were assumed to be constant during the GSHP operation. The GSHP operation times per day were set to 5, 9, and 14 h, and the operation days per week were set to 5 and 7 days. Thus, we set a combination of a total of 18 patterns. The simulation was conducted assuming 3 years of the GSHP operation.

3. Results and Discussion

3.1. Experimental Investigation

3.1.1. Subsurface Temperature Change

Figure 6 presents the measurement results at the HP inlet and outlet, the subsurface temperature, and the result for *HER* under the operational conditions that are shown in Table 2.

The difference in sensitivity of the subsurface temperature was observed between conditions (a) and (b). There are two possible reasons for this difference. One is that the waterproof process on the thermistor differed between conditions (a) and (b). Another is that the difference in the depth of the measurement point appeared as a difference in sensitivity because the PVC pipe was presumed to have moved away from the BHE as it became deeper. Although the sensitivities of these two-measurement data were different, the response of the subsurface temperature corresponded to the GSHP operation. Thus, we considered that the observed subsurface temperature was reliable.

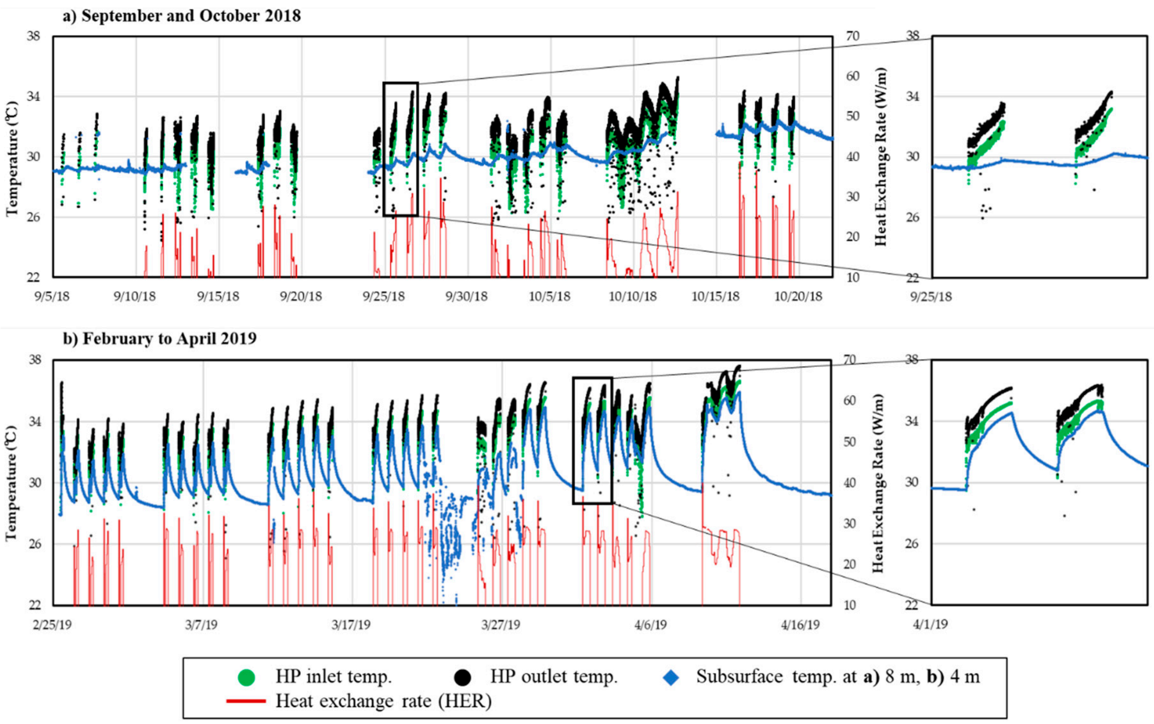

Figure 6. The measurement results for the operational experiment: (**a**) September to October 2018; (**b**) February to April 2019.

The HP inlet/outlet temperature and *HER* were higher during condition (b) than during condition (a). That is because the ambient temperature from February to April in Bangkok is higher than that from September to October; thus, the cooling load from February to April was more substantial than that from September to October.

3.1.2. Performance Analysis of the Heat Source Temperature

The *Sys-COP*′ of the GSHP was in the range of 2.4 to 4.6, and that of the ASHP was in the range of 1.6 to 3.6.

A scattering in *Sys-COP*′ was observed when there was the same Q_c' for both systems. This scattering indicates that the efficiency of HP varied as a function of the heat sink temperature. Figure 7 presents the *Sys-COP*′ of the GSHP and ASHP corresponding to their heat sink temperatures, which were classified at every 0.1 kW in the range of 1.1 to 1.5 kW. Here, the heat sink temperature on the GSHP and ASHP refers to the HP inlet and ambient temperature, respectively.

The *Sys-COP*′ for both systems were inversely proportional to their heat sink temperatures; thus, the efficiencies of both systems decreased as the heat sink temperatures increased. Since the slope of the ASHP was larger than that of the GSHP, the *Sys-COP*′ difference between the GSHP and ASHP increased in accordance with the heat sink temperature. In the case of the same *Sys-COP*′, the heat sink temperature for the GSHP was higher than that for the ASHP. For instance, when the *Sys-COP*′ was three, the heat sink temperature for the GSHP was 5 °C higher than that for the ASHP. This indicates that the efficiency of the GSHP was higher than that of the ASHP for the same heat sink temperature.

Ito et al. [30] demonstrated that the compressor of the water source heat pump (WSHP) consumes electricity equivalent to that of the ASHP when the HP inlet temperature is 10 °C higher than the ambient temperature. In an actual case, the heat sink temperature difference at which the performances of the GSHP and ASHP are equal becomes less than 10 °C, because the circulation pump consumes electricity. For example, a previous study suggested that the COP of the GSHP may be larger than that of the ASHP until the subsurface temperature is 5 °C above the ambient temperature [10]. This is consistent with the results of this study. Therefore, we found that the GSHP had a higher efficiency than the ASHP at least until the HP inlet temperature was 5 °C above the ambient temperature.

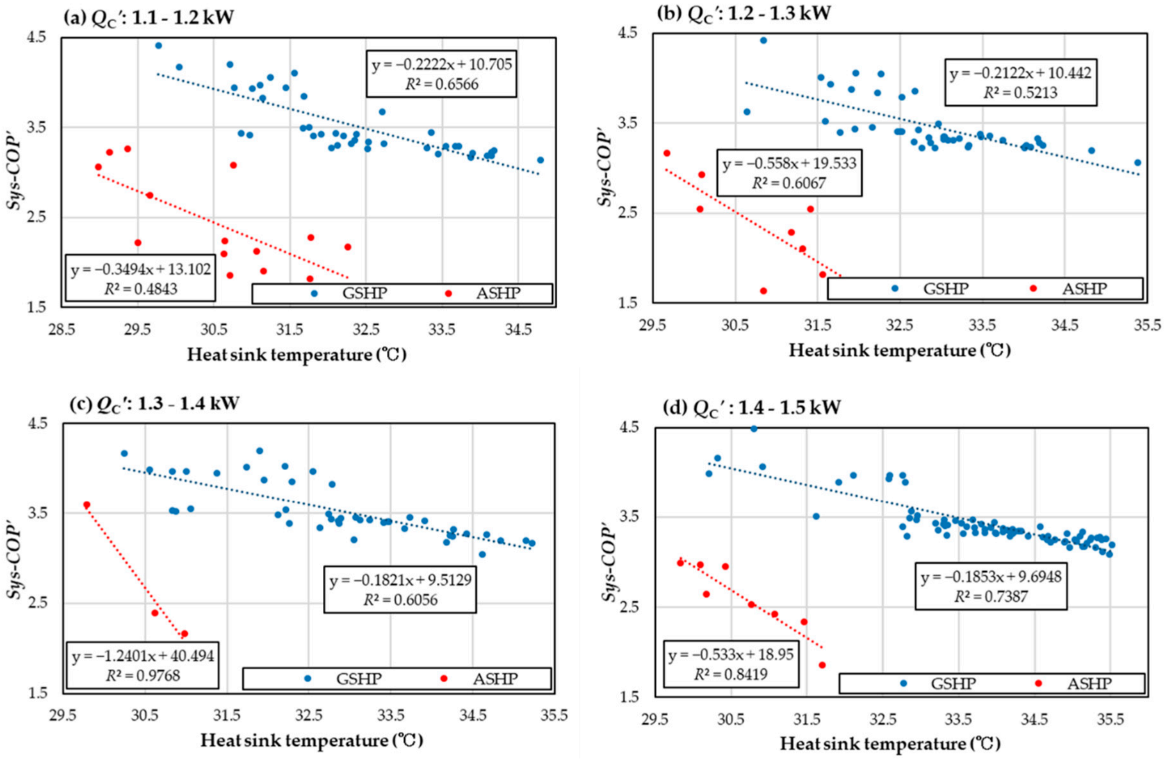

Figure 7. The relationship between the heat sink temperature and *Sys-COP*′. When Q_c′ was in the range of (**a**) 1.1 to 1.2 kW; (**b**) 1.2 to 1.3 kW; (**c**) 1.3 to 1.4 kW; and (**d**) 1.4 to 1.5 kW.

3.2. Simulation of Long-Term GSHP Operation

Figure 8 presents the results of 3 years of simulation with the average BHE surface temperature under three conditions. Here, the three conditions were 20, 30, and 40 W/m of *HER* with an operation time of 9 h per day and 5 days per week.

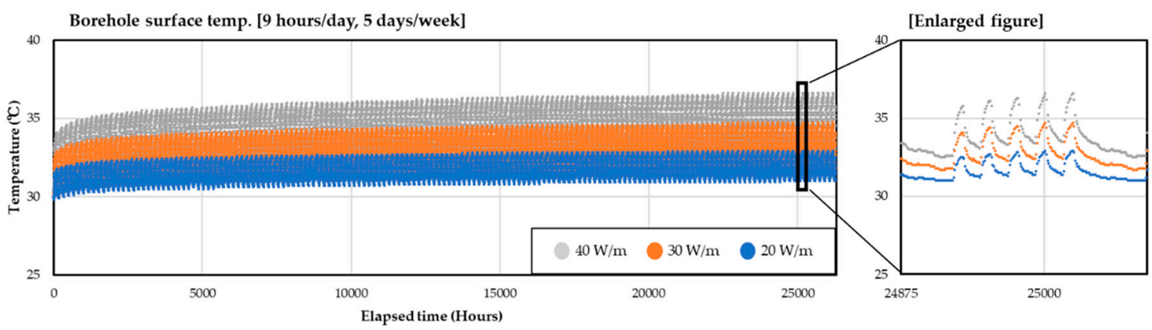

Figure 8. The three-year simulation of the BHE surface average temperature.

The increase in the BHE surface temperature was slow after the first year of operation for the three *HER* conditions. Although the required duration for mitigating the increase in the BHE surface temperature varied with every situation, the increase was slow at least within the 2 years after starting the operation for all 18 simulation tests. Therefore, the operational condition should be designed according to the heat sink temperature after the increase in subsurface temperature becomes moderate, not by the absence of an increase in the subsurface temperature. By combining the results obtained in the previous section, we found that it is crucial to design and operate the GSHP so that the HP inlet temperature does not exceed 5 °C above the ambient temperature after the increase in the subsurface temperature is mitigated. Thus, we compared the 90th percentile value of hourly HP inlet temperature during the third year of operation and that of the hourly annual ambient temperature.

The 90th percentile value of hourly annual ambient temperature in Bangkok is 33 °C according to the reference year weather data published in "EnergyPlus" [31]. Therefore, the 90th percentile value of the HP inlet temperature during the third year of operation should not exceed 38 °C. Table 5 presents the 90th percentile values and maximum at the HP inlet temperatures during the third year of operation for all 18 tests.

Table 5. The 90th percentile values and maximum temperatures at the HP inlet during the third year of operation.

HER	Operation Time per Day (5 days/week)	90th Percentile Value Temp. at HP Inlet (°C)	Maximum Temp. at HP Inlet (°C)
20 W/m	5 h	32.9	33.9
	9 h	34.7	35.2
	14 h	36.1	36.5
30 W/m	5 h	35.1	36.7
	9 h	37.9	38.6
	14 h	40.1	40.6
40 W/m	5 h	37.4	39.5
	9 h	41.3	42.2
	14 h	44.3	45.1
	Operation Time Per Day (Everyday)		
20 W/m	5 h	33.8	34.2
	9 h	35.5	35.7
	14 h	37.1	37.3
30 W/m	5 h	36.5	37.2
	9 h	39.2	39.5
	14 h	41.7	42
40 W/m	5 h	39.3	40.2
	9 h	43	43.4
	14 h	46.7	47.1

As can be observed in Table 5, the conditions in which the 90th percentile value of the HP inlet temperature did not exceed 38 °C were as follows:

(1) When operating the GSHP 5 days per week:

When the *HER* was 20 W/m, operating the GSHP for less than 14 h per day;

When the *HER* was 30 W/m, operating the GSHP for less than 9 h per day;

When the *HER* was 40 W/m, operating the GSHP for less than 5 h per day.

(2) When operating the GSHP every day:

When the *HER* was 20 W/m, operating the GSHP for less than 14 h per day;

When the *HER* was 30 W/m, operating the GSHP for less than 5 h per day.

The above conditions are the operational conditions for a GSHP in Bangkok that can achieve higher efficiency than an ASHP over the long term.

When the proposed conditions were applied to three reference government building models designed by the energy audit information in Thailand, the required number of BHEs are as follows.

Three reference government building models were named Types 1, 2, and 3 with air-conditioned areas of 200, 40, and 25 m^2 [6]. We calculated the required number of BHE if these three buildings adopted the GSHP (COP: 3) as a substitution for a split-type ASHP (COP: 1.76) in Bangkok. This replacement refers to achieving an approximately 40% energy savings. The BHE was assumed to have the same specifications as BHE No. 2 (single U-tube). The working hours per day were considered to be 9 h. The building was considered to be closed on weekends and holidays (workdays: 245 days per year). Cooling load and heat dissipation load were calculated from the annual electricity consumption of air conditioning system. According to Table 6 in Reference [6], the annual electricity consumptions of air conditioning system were 29,835, 4874 and 3372 kWh for building Types 1, 2, and 3, respectively. From the above conditions of air conditioning, 30 W/m of *HER* was used as the operational condition of the GSHP. In Bangkok, the depth of BHE is recommended to be 50 m [11]. Thus, we considered that one BHE could treat 1.5 kW of heat dissipation, caveating that the thermal interference among adjacent boreholes was not taken into account for the calculation.

As a result of the calculation, the required numbers of BHEs were 24, 4, and 3 for building Types 1, 2, and 3, respectively. It is difficult to interpret the obtained results from an economic point of view because an economic analysis has not been conducted for the case of Bangkok. However, given that the BHEs will be arranged in a grid every 5 m in general, we consider it feasible to install a BHE inside a site such as a car park.

4. Conclusions

This study aimed at elucidating the operational conditions for a GSHP in Bangkok to achieve higher efficiency than an ASHP over the long term. An operational experiment on a pilot facility and simulation of 3 years of the GSHP operation were conducted. The simulation model was validated by the TRT in the pilot facility. The following results were obtained.

The GSHP had a higher efficiency than the ASHP at least until the HP inlet temperature was 5 °C above the ambient temperature.

The BHE surface temperature increase was stagnated over the first 2 years in the 3 years simulation.

Considering the high temperature during the daytime in Bangkok, the obtained result clarifies the high potential of the GSHP to reduce the energy consumption of a building over the long term. Combining the above-obtained results, we propose operational conditions for utilizing GSHPs in Bangkok as follows.

The 90th percentile value of the hourly HP inlet temperature shown should not exceed 5 °C above that of the hourly annual ambient temperature during the third year of operation.

We applied this condition when designing our GSHP which was introduced in a small government building as a substitution for an ASHP. As a result of this design, the required BHEs were not large for the building to achieve an approximately 40% energy savings. This may be feasible because we can install them inside a site such as in a car park. Thus, a small-scale GSHP in Bangkok may result in a high efficiency over the long term within space limitations.

However, economic constraints have not been clarified by this study. Given the high initial cost of installing BHEs, budgetary constraints will be a serious issue for the deployment of GSHPs. Moreover, GSHPs cannot treat all cooling loads in large-scale buildings such as department stores and office buildings, because the required number of BHEs will be tremendous in a tropical climate. The cooperative operation of the ASHPs with a cooling tower may be a solution in the case of large-scale buildings. Therefore, in the future, an economic evaluation will be conducted on both small- and large-scale HVAC systems for use in Bangkok.

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References

1. IRENA. *Renewable Energy Outlook: Thailand*; International Renewable Energy Agency: Abu Dhabi, UAE, 2017; p. 45. ISBN 978-9-29-260035-8.
2. Office of Natural Resources and Environmental Policy and Planning. Available online: https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/Thailand/1/Thailand_INDC.pdf (accessed on 23 July 2019).
3. Office of Natural Resources and Environmental Policy and Planning. *Thailand's Second National Communication under the United Nations Framework Convention on Climate Change*; Ministry of Natural Resources and Environment: Bangkok, Thailand, 2010; pp. 45–46. ISBN 978-9-74-286865-9.
4. Sivak, M. Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries. *Energy Policy* **2009**, *37*, 1382–1384. [CrossRef]
5. Yungchareon, V.; Limmeechokchai, B. Energy Analysis of the Commercial Sector in Thailand: Potential Savings of Selected Options in Commercial Buildings. In Proceedings of the SEE International Conference, Petchaburi, Thailand, 19–21 May 2004; pp. 496–501.
6. Chirarattananon, S.; Taweekun, J. A technical review of energy conservation programs for commercial and government buildings in Thailand. *Energy Convers. Manag.* **2003**, *44*, 743–762. [CrossRef]
7. Sasada, M.; Takasugi, S.; Tateno, M. A Ground Source Heat Pump System in Central Tokyo; A Case Study of Retrofit for a Small Office Building. *J. Jpn. Soc. Eng. Geol.* **2011**, *51*, 265–272. [CrossRef]
8. Urchueguía, J.F.; Zacares, M.; Corberán, J.M.; Montero, A.; Martos, J.; Witte, H. Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. *Energy Convers. Manag.* **2008**, *49*, 2917–2923. [CrossRef]
9. Brouwers, J.; Entrop, A.G. New Triplet Visions on Sustainable Building, Action for sustainability. In Proceedings of the 2005 World Sustainable Building Conference (on CD-Rom), Tokyo, Japan, 27–29 September 2005; pp. 4330–4335.
10. Yasukawa, K.; Uchida, Y.; Tenma, N.; Taguchi, Y.; Muraoka, H.; Ishii, T.; Suwanlert, J.; Buapeng, S.; Nguyen, T.H. Groundwater temperature survey for geothermal heat pump application in tropical Asia. *Bull. Geol. Surv. Jpn.* **2009**, *60*, 459–467. [CrossRef]
11. Chokchai, S.; Chotpantarat, S.; Takashima, I.; Uchida, Y.; Widiatmojo, A.; Yasukawa, K.; Charusiri, P. A Pilot Study on Geothermal Heat Pump (GHP) Use for Cooling Operations, and on GHP Site Selection in Tropical Regions Based on a Case Study in Thailand. *Energies* **2018**, *11*, 2356. [CrossRef]
12. Widiatmojo, A.; Chokchai, S.; Takashima, I.; Uchida, Y.; Yasukawa, K.; Chotpantarat, S.; Charusiri, P. Ground-Source Heat Pumps with Horizontal Heat Exchangers for Space Cooling in the Hot Tropical Climate of Thailand. *Energies* **2019**, *12*, 1274. [CrossRef]
13. Shimada, Y.; Kurishima, H.; Uchida, Y. Life Cycle Environmental Evaluation on Introduction of Ground Source Heat Pump in Bangkok, Thailand. *J. Life Cycle Assess. Jpn.* **2019**, *15*, 269–281.
14. Safa, A.A.; Fung, A.S.; Kumar, R. Heating and cooling performance characterisation of ground source heat pump system by testing and TRNSYS simulation. *Renew. Energy* **2015**, *83*, 565–575. [CrossRef]
15. Rybach, L.; Eugster, W.J. Sustainability aspects of geothermal heat pump operation, with experience from Switzerland. *Geothermics* **2010**, *39*, 365–369. [CrossRef]
16. Michopoulos, A.; Zachariadis, T.; Kyriakis, N. Operation characteristics and experience of a ground source heat pump system with a vertical ground heat exchanger. *Energy* **2013**, *51*, 349–357. [CrossRef]

17. Zhai, X.Q.; Yu, X.; Yang, Y.; Wang, R.Z. Experimental investigation and performance analysis of a ground-coupled heat pump system. *Geothermics* **2013**, *48*, 112–120. [CrossRef]
18. Man, Y.; Yang, H.; Wang, J. Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like Hong Kong. *Appl. Energy* **2010**, *87*, 2826–2833. [CrossRef]
19. Kharseh, M.; Al-Khawaja, M.; Suleiman, M.T. Potential of ground source heat pump systems in cooling-dominated environments: Residential buildings. *Geothermics* **2015**, *57*, 104–110. [CrossRef]
20. Sanner, B.; Hellström, G.; Spitler, J.; Gehlin, S. Thermal response test–current status and world-wide application. In *Proceedings World Geothermal Congress*; International Geothermal Association: Antalya, Turkey, 2005.
21. Ingersoll, L.R.; Plass, H.J. Theory of the ground pipe heat source for the heat pump. *Heat. Pip. Air Cond.* **1948**, *20*, 119–122.
22. Uchida, Y.; Fujii, H. First thermal response test in Southeast Asia. *GSJ Chishitsu News* **2018**, *7*, 156–158.
23. Gehlin, S. *Thermal Response Test: Method Development and Evaluation*; Luleå Tekniska Universitet: Luleå, Sweden, 2002.
24. Ingersoll, L.R.; Zabel, O.J.; Ingersoll, A.C. *Heat Conduction with Engineering, Geological, and Other Applications*; McGraw-Hill: New York, NY, USA, 1954.
25. Nagano, K.; Katsura, T.; Takeda, S. Development of a design and performance prediction tool for the ground source heat pump system. *Appl. Therm. Eng.* **2006**, *26*, 1578–1592. [CrossRef]
26. Katsura, T.; Nagano, K.; Takeda, S. Method of calculation of the ground temperature for multiple ground heat exchangers. *Appl. Therm. Eng.* **2008**, *28*, 1995–2004. [CrossRef]
27. Katsura, T.; Nagano, K.; Narita, S.; Takeda, S.; Nakamura, Y.; Okamoto, A. Calculation algorithm of the temperatures for pipe arrangement of multiple ground heat exchangers. *Appl. Therm. Eng.* **2009**, *29*, 906–919. [CrossRef]
28. Katsura, T.; Nagano, K. Simulation Tool for Ground-Source Heat Pump System with Multiple Ground Heat Exchangers. *ASHRAE Trans.* **2018**, *124*, 92–101.
29. Ministry of Land, Infrastructure, Transport and Tourism, Japan. Available online: https://www.mlit.go.jp/common/001016159.pdf (accessed on 23 July 2019).
30. Ito, S.; Takano, Y.; Miura, N.; Uchikawa, Y. Studies of a Heat Pump Using Water and Air Heat Sources in a Series: Performance in Cooling Operation. *Trans. Jpn. Soc. Mech. Eng. Ser. B* **2001**, *67*, 2089–2096. [CrossRef]
31. Crawley, D.B.; Lawrie, L.K.; Pedersen, C.O.; Winkelmann, F.C. Energy plus: Energy simulation program. *ASHRAE J.* **2000**, *42*, 49–56.