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Effect of Groundwater Flow and Thermal Conductivity on the Ground Source Heat Pump Performance at Bangkok and Hanoi: A Numerical Study

Arif Widiatmojo, Youhei Uchida and Isao Takashima

Abstract

In recent decades, the fast-growing economies of Southeast Asian countries have increased the regional energy demand per capita. The statistic indicates Southeast Asian electricity consumption grows for almost 6% annually, with space cooling becoming the fastest-growing share of electricity use. The ground source heat pump technology could be one of the solutions to improve energy efficiency. However, currently, there are limited data on how a ground source heat pump could perform in such a climate. The thermal response test is widely used to evaluate the apparent thermal conductivity of the soil surrounding the ground heat exchanger. In common practice, the apparent thermal conductivity can be calculated from the test result using an analytical solution of the infinite line source method. The main limitation of this method is the negligence of the physical effect of convective heat transfer due to groundwater flow. While convection and dispersion of heat are two distinctive phenomena, failure to account for both effects separately could lead to an error, especially in high groundwater flow. This chapter discusses the numerical evaluation of thermal response test results in Bangkok, Thailand, and Hanoi, Vietnam. We applied a moving infinite line source analytical model to evaluate the value of thermal conductivity and groundwater flow velocity. While determining the ground thermal properties in a high accuracy is difficult, the moving infinite line source method fulfills the limitation of the infinite line source method. Further, we evaluated the five-year performance of the ground source heat pump system coupled with two vertical ground heat exchangers in Bangkok and Hanoi. The results suggest the importance of groundwater flow to enhance the thermal performance of the system.

Keywords: Ground source heat pump, tropical region, Southeast Asia, space cooling, moving infinite line source, thermal response test

1. Introduction

The population of Southeast Asia was almost 640 million in 2016 and is expected to increase to 760 million by 2040, assuming 0.7% annual population growth.

Urbanization is an essential factor that affects total energy consumption [1–3]. The residential sector accounts for the second-highest electricity demand after the industrial sector, growing by an average annual rate of 7.5%, owing mainly to the increasing number of appliances. The introduction of energy-efficient products can restrain household energy demand. The Japan Refrigeration and Air Conditioning Industry Association (JRAIA) reported that in 2016, Vietnam and Thailand were the second and third countries with the highest air conditioner demand in Southeast Asia, with 1.98 million and 1.56 million units per year, respectively. Indonesia ranked first with 2.3 million units in the same year [4]. Annual regional air conditioner demand increased from 12.2 million units/year in 2011 to 16.4 million units/year in 2016, equivalent to an average of 6.1% increase per year.

Researches have been focused on the possibility of introducing the Ground Source Heat Pump (GSHP) in the region. Even though GSHP is a mature technology, the application of GSHP in the tropical climate, such as Southeast Asia, faces several problems. The use of GSHP is mainly for cooling, eliminating the balance between heat rejection and heat extraction. The ground temperature is relatively higher and within the range of air temperature.

Yasukawa et al. conducted underground temperature surveys by measuring vertical groundwater temperature from several monitoring wells in Thailand and Vietnam [5]. They concluded that despite the differences between ground temperature and air temperature were low. However, there are still advantages of utilizing GSHP for space cooling. Further, they remarked that space heating might be possible for a short winter period in Hanoi, Vietnam.

In their subsequent study, Yasukawa et al. presented the pilot study of GSHP at Kamphaengphet province, Thailand. They confirmed the applicability of the system with series of experimental tests [6].

Several studies have focused on providing further information on GSHP applicability in the regions. Widiatmojo et al. evaluated the performance of GSHP systems coupled with horizontal/shallow Ground Heat Exchanger (GHE). They also performed cost analysis to estimate the payback time against Air Source Heat Pump (ASHP). Shimada et al. examined the different operational conditions based on field experimentation and numerical simulation. While in another publication, Sasimook et al. presented the experiments and performance comparison of GSHP and ASHP. They highlighted the GSHP advantage, especially in higher thermal load [7, 8]. Although most of the studies above remarked the possibility of GSHP application in Southeast Asia, none of these addresses the effect of groundwater on the performance of GSHP.

This chapter discusses numerical simulation results to evaluate the Thermal Response Test (TRT) conducted in Bangkok, Vietnam, and Hanoi, Vietnam. The numerical simulation uses the Moving Infinite Line Source (MILS) analytical method to account for thermal conductivity and groundwater flow. Further, we extend the simulation to estimate the GSHP performance for five years of operation considering different parameters obtained using the Infinite Line Source (ILS) and the MILS methods.

2. Thermal response test

The Thermal Response Test (TRT) is a standard method to determine the ground thermal conductivity. From the TRT result, the apparent thermal conductivity of the ground surrounding the GHE can be calculated. A standard method to evaluate the apparent thermal conductivity from the TRT result is the Infinite Line Source (ILS) method [9, 10]. The ILS approach is based on the Kevin line source

theory. This method calculates the temperature response of an infinite constant heat source analytically, assuming an infinite, isotropic, and homogeneous soil medium. This method also neglects the axial (vertical) heat transfer along the borehole. Considering the relationship between average fluid temperature, $\overline{T_f}$ (C) at a time t (s) with the borehole wall temperature at a radius r_b (m), constant heat–transfer rate per unit length of borehole, q (W m^{-1}) and borehole heat resistance, R_b (mK W^{-1}), the ILS solution is written as follows:

According to Carslaw and Jaeger [11], the temperature increase of a medium at a radial distance r (m) from an infinite line source with a constant heat exchange rate, q (Wm^{-1}), is expressed as:

$$T(r,t) - T_0 = \frac{q}{4\pi\lambda}E\left[\frac{r^2}{4Dt}\right] = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4Dt}}^{\infty}\frac{e^{-u}}{u}du \qquad (1)$$

T_0 (C) is the initial ground temperature, D (m^2 s), the thermal diffusivity, and E is the exponential integral function. Assuming that the following condition is satisfied:

$$t > 5\frac{r^2}{D} \qquad (2)$$

Eq. (1) can be re-written as:

$$\overline{T_f}(t) - T_0 = (T_f(r_b,t) + qR_b) - T_0 \cong qR_b + \frac{q}{4\pi\lambda}\left[ln\left(\frac{4Dt}{r_b^2}\right) - \gamma\right] \qquad (3)$$

where, R_b (mK W^{-1}) is the borehole thermal resistance, r_b (m) is the borehole radius λ (W m^{-1} K^{-1}) is the thermal conductivity, D (m^2 s) is the thermal diffusivity, Υ (−) is Euler constant, and T_0 (C) is the soil temperature at initial (t = 0). $\overline{T_f}$ (C) is the average circulation fluid temperature calculated by:

$$\overline{T_f} = \frac{(T_{bh-in} + T_{bh-out})}{2} \qquad (4)$$

where, T_{bh-in} and T_{bh-out} (C) are GHE fluid inlet and outlet temperature, respectively. Eq. (3) can be re-arranged into the linear form of fluid temperature against the natural logarithmic value of time as:

$$\overline{T_f}(t) \cong \frac{q}{4\pi\lambda}ln(t) + \left(qR_{bh} + \frac{q}{4\pi\lambda}\left[ln\left(\frac{4Dt}{r_{bh}^2}\right) - \gamma\right] + T_0\right) = m\ ln(t) + c \qquad (5)$$

From the fluid temperature gradient against the natural logarithmic value of time, m (C), obtained from TRT measurement, the value of apparent thermal conductivity, λ_{app} (W m^{-1} K^{-1}) can be calculated as:

$$\lambda_{app} = \frac{q}{4\pi m} \qquad (6)$$

In the ILS method, the effect of convective heat transfer as a result of groundwater convection is not considered. The value of apparent thermal conductivity represents both diffusive and convective heat transfer. Accordingly, it is recognized that the value of apparent thermal conductivity is larger than the value of effective

thermal conductivity, λ_{eff}. The heat transfer due to convection of groundwater flow and heat conduction are two different physical phenomena. Thus, the use of apparent thermal conductivity (heat conduction) for calculating the thermal performance of vertical ground heat exchangers can lead to some serious errors, especially for the longer time-scale and high-velocity groundwater flow.

While groundwater flow is an important parameter, measuring the groundwater velocity is practically difficult. Besides, the ground layers are inhomogeneous. The practical way to measure the groundwater velocity is the pumping test. However, the pumping test is expensive as it requires an additional borehole for the observation well.

The TRT measurements were carried out in Bangkok, Thailand and Hanoi, Vietnam. These were the first and second measurements to be carried out in Southeast Asia [12]. The measurements were conducted in the existing GSHP systems. In Bangkok, TRT measurement was performed in an installed GSHP system at Chulalongkorn University, Bangkok campus. The measurement was also performed in the GSHP system installed at the Vietnam Institute of Geosciences and Mineral Resources (VIGMR), Hanoi. The measurement procedures were similar for both sites. **Figure 1** shows the measurements at Bangkok and Hanoi.

Both measurements applied the constant heating rates q = 39.72 Wm^{-1} and q = 35.91 Wm^{-1} for Bangkok and Hanoi, respectively. By evaluating the TRT results using the ILS method, the apparent thermal conductivity was calculated as λ_{app} = 1.82 W m^{-1} K^{-1} and λ_{app} = 1.42 W m^{-1} K^{-1} for Bangkok and Hanoi, respectively. The data regarding the effective thermal conductivities and groundwater velocities in both GSHP sites are unavailable. Further details on the measurements can be found in another publication [12].

Figure 1.
TRT measurement at the GSHP sites: Chulalongkorn University, Bangkok (left) and VIGMR, Hanoi (right).

3. Moving infinite line source

To consider the effect of groundwater flow, we evaluated the TRT measurement results in Bangkok and Hanoi by applying the Moving Infinite Line Source (MILS) theory. According to Diao et al., the temperature increase at a radial position, φ(rad), from a line source is expressed as [13]:

$$T(r, \varphi, t) - T_0 = \frac{q}{4\pi\lambda} \exp\left(\frac{u_{eff} r}{2D} \cos \varphi\right) \int\limits_0^{r^2/4Dt} \frac{1}{\eta} \exp\left[-\frac{1}{\eta} - \frac{u_{eff}^2 r^2 \eta}{16D^2}\right] \mathrm{d}\eta \qquad (7)$$

where, $\eta = 4D(t-t')/r^2$, u_{eff} (m²s⁻¹) is the effective velocity of groundwater flow assuming local thermal equilibrium, calculated by:

$$u_{eff} = u\frac{\rho_w c_w}{\rho c} \tag{8}$$

Here, u (ms⁻¹) is the seepage velocity, ρ_w (kgm⁻³) and c_w (Jkg⁻¹ K⁻¹) are the volumetric mass density and the specific heat of water, respectively. The following relationship defines the volumetric mass density and specific heat of the medium:

$$\rho c = (1 - \varepsilon)\rho_s c_s + \varepsilon\rho_w c_w \tag{9}$$

Where ρ_s (kgm⁻³) and c_s (Jkg⁻¹ K⁻¹) are the volumetric mass density and the specific heat of the soil matrix, respectively. Eq. (7) calculates the temperature of the soil medium at an arbitrary position adjacent to the line source. The following equation represents heat balance between average fluid temperature and borehole wall temperature [14]:

$$\overline{T}_f(t) = \frac{1}{2\pi}\int_0^{2\pi} T(r_{bh}, \varphi, t)\mathrm{d}\varphi + qR_{bh} \tag{10}$$

where R_{bh} (mKW⁻¹) is the borehole heat resistance.

The simulation using the MILS analytical solution is valid under the following assumptions:

- The soil medium homogenous and infinite

- The ground physical and thermal properties are independent of time and temperature

- The effect of ambient temperature and the boundary between ground and surface are negligible

- The initial ground temperature is uniform

4. Discussion

Figure 2 shows the TRT measurement results and the numerical simulation using Eq. (7) by setting the u_{eff} = 0 and apparent thermal conductivity similar to those calculated using the ILS method. Additional parameters for the numerical simulations are listed in **Table 1**. The discrepancies between simulations and measurements at the beginning are likely the indication of heat transfer within boreholes, which have different thermal properties than the surrounding soil [14]. It is essential to ensure the apparent thermal conductivity adequately represents the value of soil mass. Typically, only the last few hours of results are considered for the linear fitting of Eq. (5).

4.1 Estimation groundwater flow velocity and effective thermal conductivity

By using the MILS method, the groundwater flow can be taken into account. However, the determination of groundwater velocity remains a problem. A
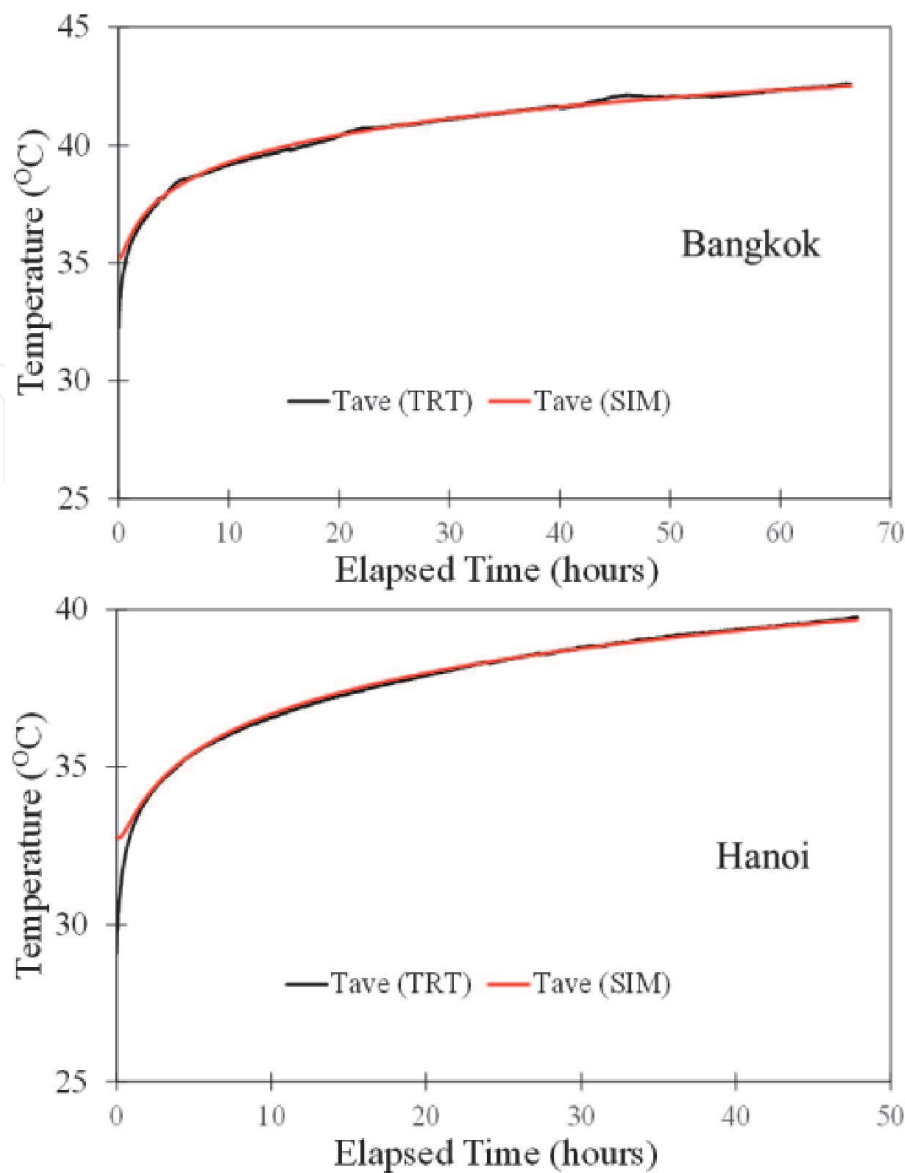
Figure 2.
The average fluid temperatures obtained from TRT measurements and the simulation results using Eq. (7).

	T_0 (°C)	R_{bh} (mK W^{-1})	q (Wm^{-1})	λ (Wm^{-1} K^{-1})	D (m^{2}s)
Bangkok	29	0.156	39.72	1.82	7.58e-7
Hanoi	27	0.16	35.91	1.42	5.07e-7

Table 1.
Simulation parameters for TRT data using Eq. (7) (u_{eff} = 0).

numerical approach incorporating a parameter optimization method has been proposed [14, 15]. In this study, a similar numerical procedure was performed in Matlab employing the *fminsearch* function. The *fminsearch* is a pre-programmed function to search the minimum unconstrained multivariable function using the derivative-free method. The parameter estimation from the TRT results employs the *fminsearch* function to find the minimum value of Root Mean Square Error (RMSE) between the MILS model and the TRT result [14].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\overline{T_{f(sim)}}(i) - \overline{T_{f(meas)}}(i)\right)^2}{N}} \qquad (11)$$

The initial values of the fitting parameters are given; thermal conductivity, effective groundwater velocity, and borehole heat resistance. Three values are provided for each parameter, resulting in a total

$$\overline{T}_{f(sim)}$$

of 27 combinations. Some of the results from different combinations yield similar results. To summarize the results, we select some representative values from these combinations, as shown in **Table 2**.

Figure 3 compares TRT results and the simulation results considering the optimized parameters listed in **Table 2** for both sites. The simulation results fit well with the TRT measurements. The higher RMSE error for the Bangkok site is due to the fluctuations of the measured data. As expected, the MILS models predict smaller thermal conductivities than those calculated using the ILS method for all cases. The smaller thermal conductivities are because the MILS models account for the effect of groundwater flow. It is interesting to note that the H1, H2 and H3 yield a similar value of thermal conductivity and RMSE but differs in groundwater velocities. The predicted velocities are low, and their effect on the calculated temperature response is not significant. In addition, each model shows the convergence of borehole thermal resistance values, except for the case of B1. Overall, the differences between the simulated temperatures are close to each other and visually difficult to be distinguished.

4.2 Effect of groundwater flow and ground thermal conductivity on the performance of ground heat exchanger

In the previous discussion, the effect of different thermal conductivities and groundwater velocities over the short TRT measurement period is not distinct. To further examine the impact of these parameters on the fluid temperatures, we extend the simulation period to one year. The simulations assume constant heating rates similar to the field TRT measurement. The simulation results are shown in **Figures 4** and **5** for Bangkok and Hanoi models, respectively. The calculations considering the thermal conductivity values obtained using the ILS method are also presented. For the Bangkok cases, the discrepancies due to the various estimated thermal conductivities and effective groundwater velocities are clearly observable. The B3 and B4 cases, which have the lowest predicted effective groundwater velocities, show higher average fluid temperatures. Meanwhile, B1 and B2 cases yield lower average fluid temperatures.

Interestingly, the average fluid temperature converges into an asymptotic value for the highest effective groundwater velocity (B1 case) after few days. It reveals the critical role of the convective heat transfer to the ground heat exchanger performance over an extended period.

		λ_{fit}	u_{eff}	R_{bh}	RMSE
Bangkok	B1	1.45	1.82E-06	0.1388	0.0706
	B2	1.68	4.55E-07	0.1486	0.0770
	B3	1.69	1.01E-07	0.1493	0.0777
	B4	1.69	1.37E-07	0.1493	0.0776
Hanoi	H1	1.34	2.88E-10	0.1537	0.0258
	H2	1.34	2.96E-09	0.1537	0.0258
	H3	1.34	1.14E-07	0.1536	0.0258
	H4	1.34	1.14E-08	0.1537	0.0258

Table 2.
List of parameters from the MILS fitting simulation against the TRT data.
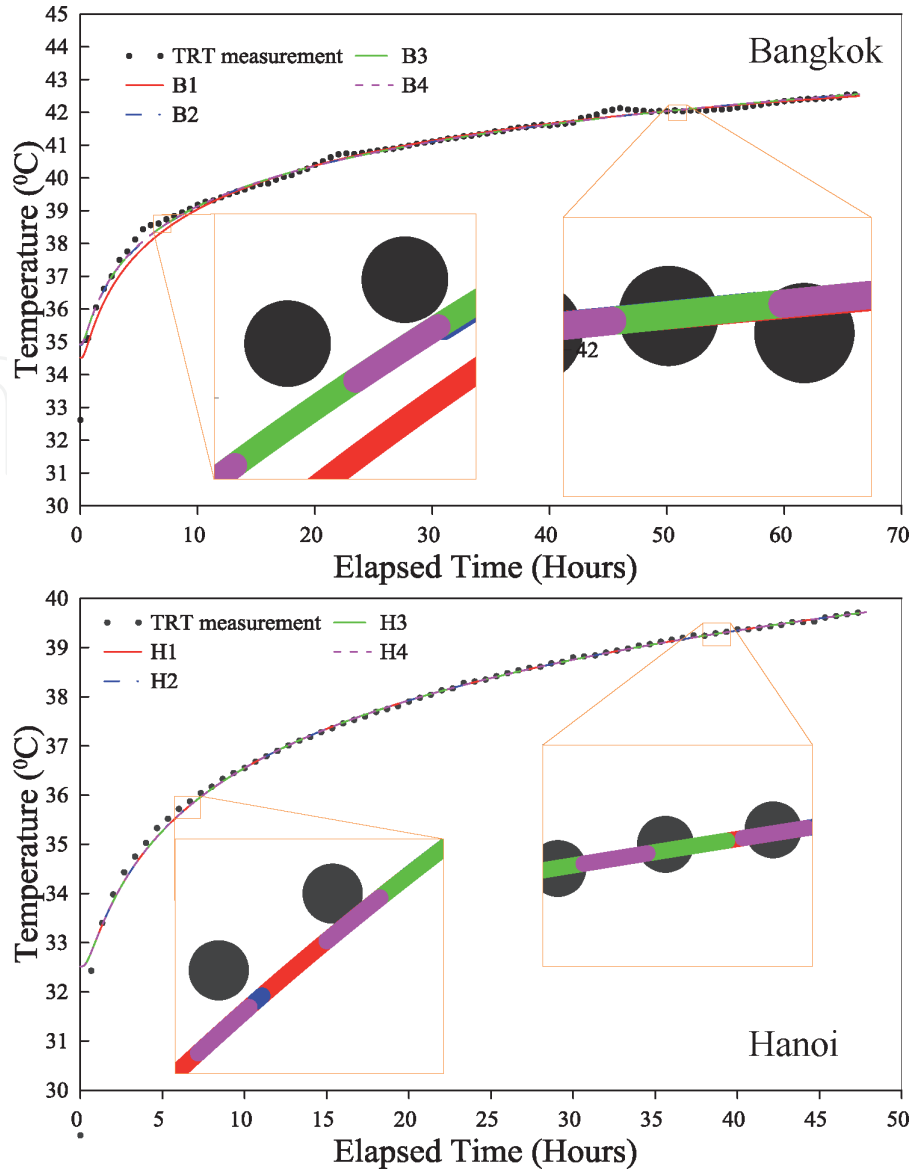
Figure 3.
The average fluid temperatures from TRT measurements and the best fits MILS simulation using parameters as listed in **Table 2**.

Figure 5 shows the differences over the extended period for the Hanoi numerical model. While H1, H2, and H4 yield almost similar values of average fluid temperatures, the highest predicted effective groundwater velocity, the H3 case, shows the lower average fluid temperature.

Figures 6 and **7** show the contour plots representing the soil temperature increase after a year of constant heating. The ground heat exchanger is located at the center coordinate (0,0), and the grid intervals are shown in meter-unit. The groundwater flows to the positive x-direction (in **Figure 6 right** and **Figure 7 right**). The left-hand part in both **Figures 6** and **7** is the simulation result in case the apparent thermal conductivity calculated by the ILS method is used (u_{eff} = 0). In comparison, the right-hand part is the simulation result using the optimized value of thermal conductivity and groundwater velocity (B2 and H3 cases). The maximum temperature and the shape of isothermal lines for Bangkok show that the case with groundwater velocity u_{eff} = 4.55E-07 ms^{-1}, despite its lower thermal conductivity, provides better thermal performance than the case with u_{eff} = 0. On the contrary, the numerical results for Hanoi cases (**Figure 7**) show the opposite due to the low groundwater velocity.

Despite the advantage of MILS, the reverse analysis involving parameter optimization performed in this study results in several combinations of parameters. The
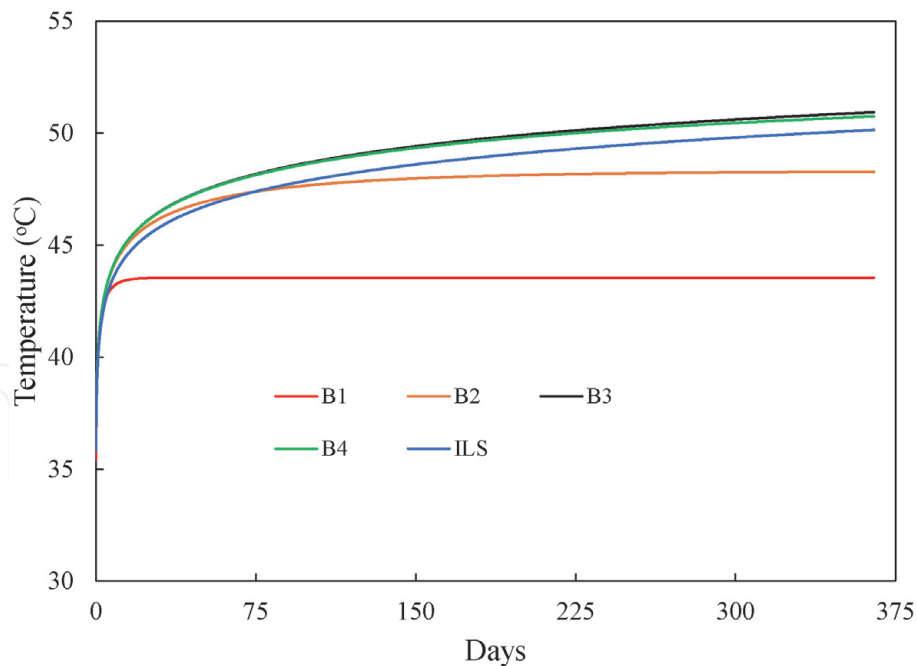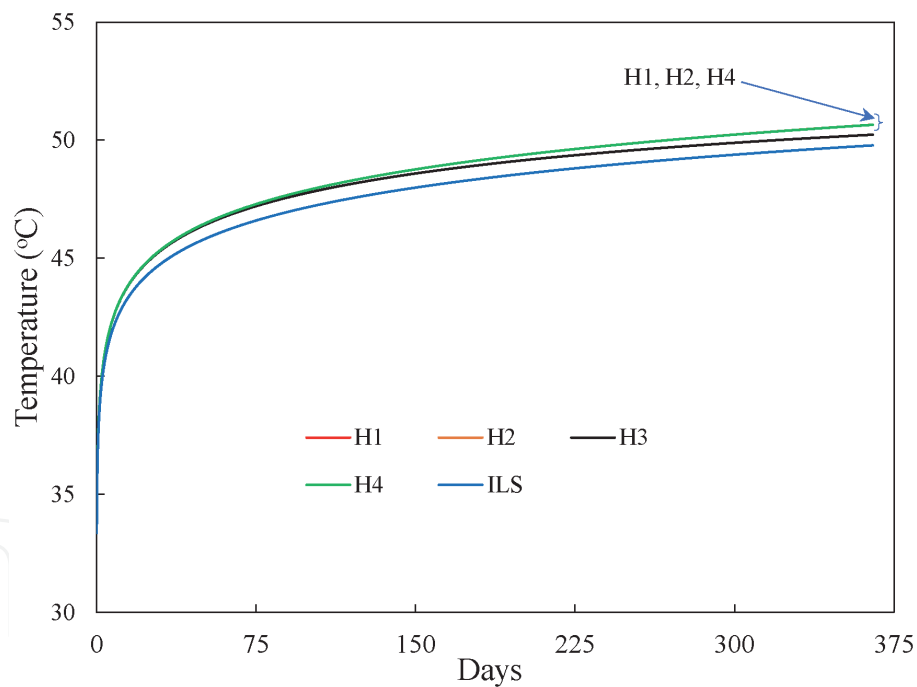
Figure 4.
Effect of different parameters (thermal conductivity and effective groundwater velocity) to a year cycle of average fluid temperature under a constant heat rejection rate (q = 39.72 Wm^{-1}) for Bangkok case.

Figure 5.
Effect of different parameters (thermal conductivity and effective groundwater velocity) to a year cycle of average fluid temperature under a constant heat rejection rate (q = 35.91 Wm^{-1}) for the Hanoi case.

improvement should be emphasized on the TRT method to provide data to narrow down the resulting combinations into the best possible solutions. One of the most feasible methods is providing different heating rates for a TRT site.

4.3 Long-term GSHP performance in Bangkok and Hanoi

One of our main interests in the GSHP potential application in Southeast Asia is to estimate the GSHPs long-term sustainability. Thus, it is essential to examine further the effect of different ground thermal properties on the long-term
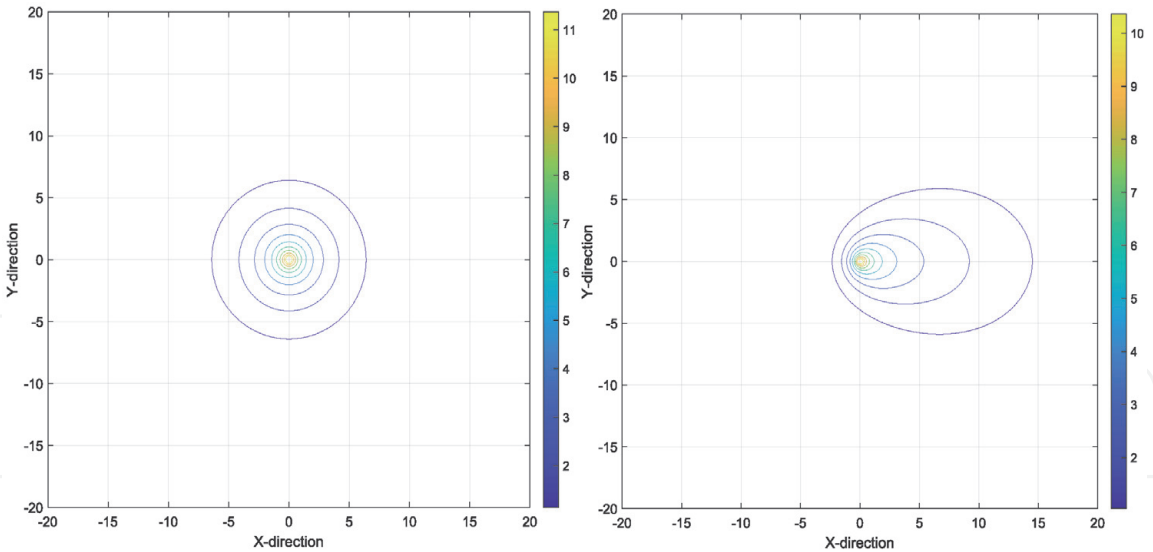
Figure 6.
Contour plot showing the soil temperature increase after a year of constant heating for the Bangkok site; (left: Q = 39.72 Wm^{-1}, λ = 1.82 Wm^{-1} K^{-1}, u$_{eff}$ = 0 ms^{-1}; right: Q = 39.72 Wm^{-1}, λ = 1.68 Wm^{-1} K^{-1}, u$_{eff}$ = 4.55E-07 ms^{-1}).
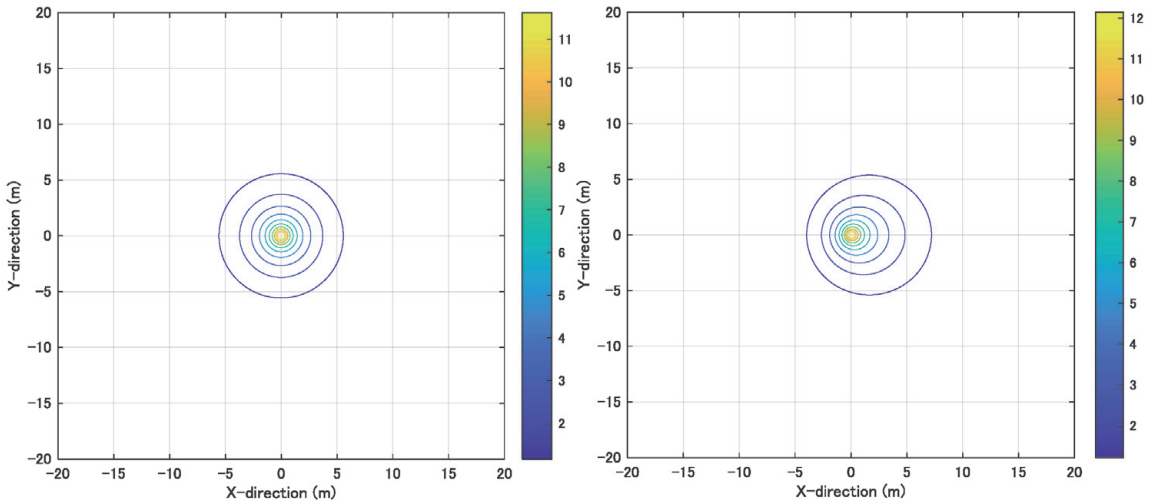

Figure 7.
Contour plot showing the soil temperature increase after a year of constant heating for the Hanoi site; (left: Q = 35.91 Wm^{-1}, λ = 1.42 Wm^{-1} K^{-1}, u$_{eff}$ = 0; right: Q = 35.91 Wm^{-1}, λ = 1.34 Wm^{-1} K^{-1}, u$_{eff}$ = 1.14E-07 ms^{-1}).

performance of GSHPs. So far, the MILS analytical model is only limited to a single ground heat exchanger. Here, we propose a simple modification to the described analytical models to simulate two ground heat exchangers.

The maximum number of ground heat exchangers in the numerical model depends on the symmetrical arrangement of boreholes and whether the model considers the groundwater flow. The simplest numerical model disregarding the effect of groundwater flow can simulate up to four ground heat exchangers. The numerical model can simulate a maximum of two ground heat exchangers if the groundwater flow is considered. In such a case, the boreholes must be arranged perpendicular to the groundwater flow direction.

The calculation of the temperature field uses the superposition method. Once the average fluid temperature for one of the boreholes is calculated, the total average fluid temperature flowing from/to the heat pump can be calculated owing to its symmetrical arrangement. The following additional equation is required to calculate the unknown inlet and outlet temperatures, $T_{bh\text{-}in}$ and $T_{bh\text{-}out}$.

$$T_{bh-in} - T_{bh-out} = Q/_{\rho_f \vartheta c_f} \qquad (12)$$

Where Q (Watt) is the heat rejection rate from heat-pump to the ground, ρ_f (kgm^{-3}), ϑ (m^{3}s^{-1}) is the volumetric flowrate of heat exchanger fluid, and c_f (Jkg^{-1} K^{-1}) is the specific heat capacity of heat exchanger fluid. The inlet and outlet temperatures can be calculated by combining Eqs. (4) and (12).

The long-term simulation model considers a GSHP system with a heat rejection rate of 5 kW. The heat pump connects to two vertical 50 m-long ground heat exchangers in a parallel flow configuration. A parallel flow configuration means that the heat exchanger fluid flows from the heat pump into each borehole at a proportional flow rate (see **Figure 8**). Thus, the heat exchange rate per unit length is identical for both ground heat exchangers. In the present study, the GSHP is assumed to be used only for cooling purposes (heat rejection) and operates only 8 hours a day (8 am to 4 pm) during weekdays. These assumptions are to represent the typical behavior of air conditioner use in standard office buildings. In addition, the simulation period is five years. The numerical models disregard the effect of ambient air temperature fluctuations on the cooling load.

A standard parameter to evaluate the thermal performance of GSHP is the Coefficient of Performance (COP). The COP is a ratio between the total rate of cooling or heating to the required electrical input. While the COP is affected by various factors, a simple approximation is possible via a correlation with the heat pump's fluid temperature (T_{bh-out}) [16]. Such correlation can be obtained from the performance tables provided by the manufacturer. **Figure 9** shows the correlation between COP and T_{bh-out} for a heat pump with a rated capacity of 5.27 kW. This correlation is specific for a 15.8 L min^{-1} fluid flowrate and 27°C dry-bulb and 19°C room air temperature at the 13.45 m^{3}min^{-1} flow rate (air flowrate in the fan-coil unit).

Figure 8.
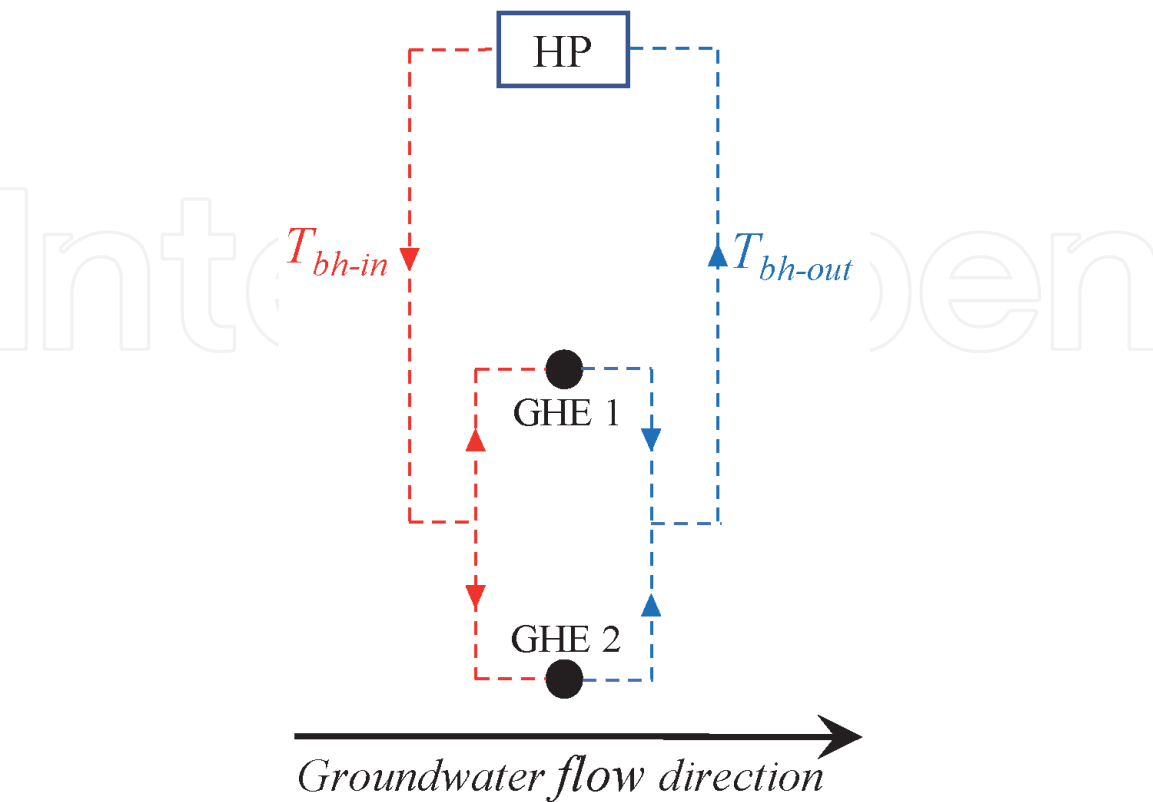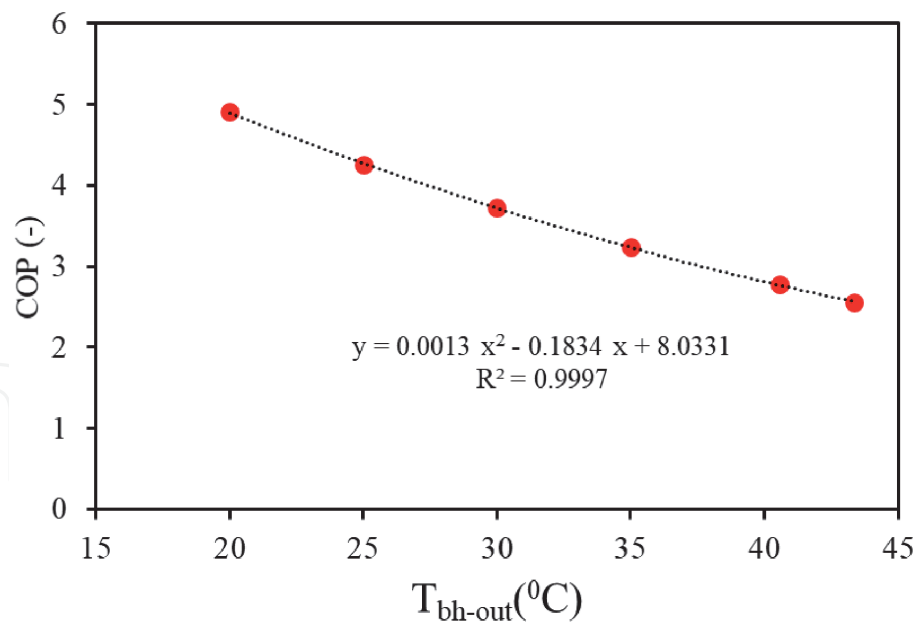*Schematic figure of the numerical model for long-term performance evaluation.*

Figure 9.
A relationship between $T_{bh\text{-}out}$ *and COP of a heat pump, obtained from the performance table supplied by the manufacturer.*

Figures 10 and **11** present the fluid temperature leaving the ground heat exchanger ($T_{bh\text{-}out}$) and the calculated COP, respectively. The initial ground temperature and ground thermal properties are similar to those applied in the previous simulations (see **Tables 1** and **2**). The simulation results considering the thermal properties calculated using the ILS method show higher fluid temperatures than the simulations with the groundwater flow (case B4 for Bangkok and H3 for Hanoi). At the end of the five-year operation, the final fluid temperature for Bangkok are 41.77°C and 41.1°C for ILS and B4 cases, respectively. While, the final fluid temperatures for Hanoi are 41.89°C and 40.86°C for ILS and H3 case, respectively. Note that the thermal conductivities for B4 and H3 cases are lower than those calculated using the ILS. **Figure 12** compares the iso-temperature plot of B4 and H3 cases after five years. The B4 case with higher thermal conductivity and groundwater velocity provides a better heat transfer rate.

The results also suggest the significant role of groundwater convection in lowering the fluid temperature. For the application of GSHP in tropical countries with high initial ground temperature, the role of groundwater flow is ultimately essential.
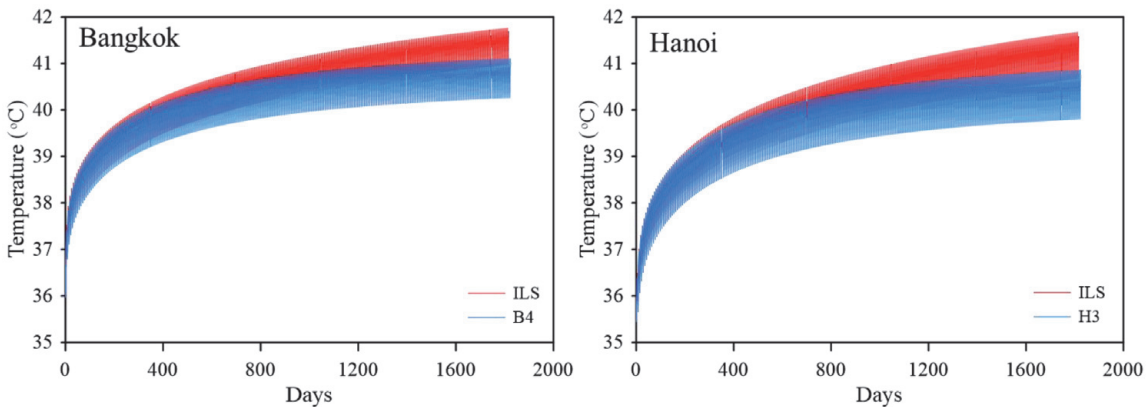

Figure 10.
Fluid temperature flowing from the ground heat exchanger ($T_{bh\text{-}out}$*) for five-years GSHP operational period.*
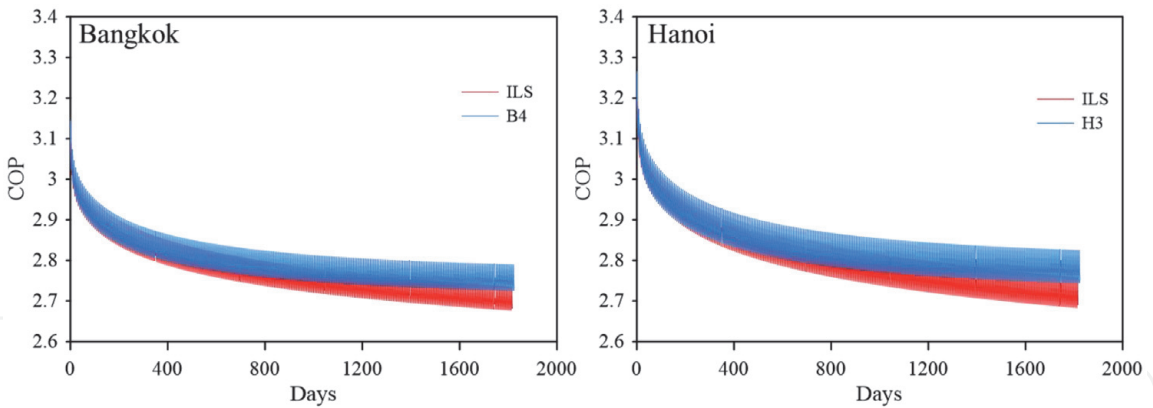
Figure 11.
COP of the GSHP system for a five-year GSHP operational period.
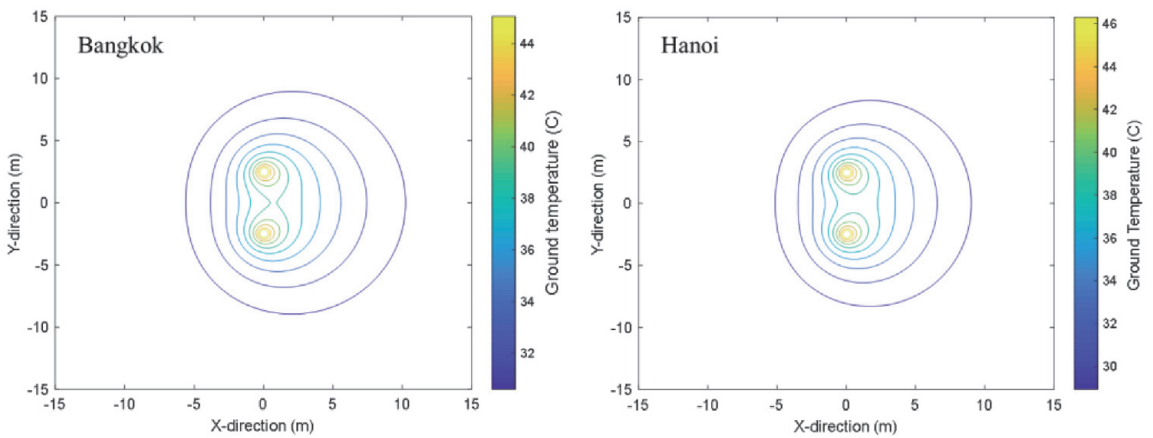

Figure 12.
Contour plot showing the soil temperature increase after a five-year GSHP operation; the thermal parameters for B4 and H3 cases are used for Bangkok (left) and Hanoi (right), respectively.

5. Conclusion

The application of GSHP in tropical countries, such as Thailand and Vietnam, encounters several problems. One of the main problems is the insufficient data on how GSHP could perform under such a climate. We carried out the numerical analysis of the TRT measurement results conducted in Bangkok, Thailand and Hanoi, Vietnam.

The MILS analytical method provides a better numerical analysis to evaluate the TRT result than the commonly used ILS method. The inverse analysis of TRT result using the MILS method with parameter optimization resulted in multiple solutions of unknown parameters: groundwater flow velocity, thermal conductivity, and borehole thermal resistance. The groundwater velocity and thermal conductivity are parameters with significant variations, while the borehole thermal resistance indicates a stable convergence into a single value. Simulations considering parameters obtained using the MILS and ILS method do not show a clear difference over a short-term TRT period. In the extended period of simulations, more than a year time scale, the differences are evident. The results also suggest the importance of groundwater flow in the long-term performance of GSHP, especially in tropical regions with high soil background temperatures. Over-reliance on the ILS method and the use of apparent thermal conductivity, especially for the site with high groundwater flow, can lead to a severe error.

Further, we extended the MILS simulations by incorporating two borehole heat exchangers and a simple approximation of COP to evaluate the GSHP performance over five years under different ground thermal parameters. The COP decreases over a more extended period because of the thermal imbalance resulting from the absence of heat extraction. The simulation results also suggest that the groundwater flow can effectively reduce the decreasing rate of COP.

Acknowledgements

Author details

Arif Widiatmojo[1*], Youhei Uchida[1] and Isao Takashima[2]

1 Renewable Energy Research Center, National Institute of Advanced Industrial Science and Technology, Koriyama-shi, Fukushima-ken, Japan

2 Mining Museum, Akita University, Akita-shi, Akita-ken, Japan

*Address all correspondence to: arif.widiatmojo@aist.go.jp

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