

Investigation on the Operating Performance of Hybrid Ground Coupled Heat Pump Systems: a Case Study in Hong Kong

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ABSTRACT: A pilot project of the hybrid ground-coupled heat pump system with hot water supply reported in this paper was developed in October, 2006 in Hong Kong for research purposes. The HGCHP system can offer space cooling and/or space heating accompanied with hot water supply for residential or public buildings. A data collection system was established to record most of the operating variables. The operating performance has been discussed and evaluated based on the recorded data. Furthermore, the impact of the heat transfer within the ground heat exchanger on the surrounding soil has been discussed according to the recorded temperatures within the boreholes. The results demonstrate that this system has higher energy efficiency for providing space cooling and hot water. The experiments also indicate that the alternative cooling/heating modes and discontinuous operation are favorable for the heat transfer process in the ground heat exchangers. Therefore, the HGCHP system with DHW supply is a preferable alternative for hot-climate areas like Hong Kong when space cooling and DHW are needed at the same time.

Keywords: Hybrid ground-coupled heat pump, domestic hot water, heat transfer

INTRODUCTION

During the last two decades, the technology of ground-coupled heat pumps (GCHPs) has been developed and a large number of GCHPs have been installed in residential and

commercial buildings around the world, offering spacing cooling and heating [1]. However, higher capital cost of excessively larger ground heat exchanger (GHE) or limited land area has restricted to a large extent the wider applications of this technology in cooling-dominated buildings, which reject more heat to the ground than that extracted from the ground on an annual basis in hot-climate areas. In recent years, some concerns have been raised about the application of the hybrid ground-coupled heat pump (HGCHP) system with a supplemental heat rejecter in cooling-dominated buildings. Incorporating a supplemental heat rejecter can reduce a fair amount of heat rejected into the ground and then effectively balance the ground thermal loads, which can consequently reduce the capital cost of the system and improve the operation performance.

A number of studies in terms of the HGCHP system with a fluid cooler or a cooling tower have been analyzed and simulated in detail by Kavanaugh, S.P. [2] and Ramamoorthy M. [3]. The function of the fluid cooler or cooling tower is to handle the excess cooling requirement. Obviously, this method can reduce the GHE size and lower the capital cost; however, it may cause a thermal pollution to the environment and can not increase the operating efficiency.

One economical and practical way to reduce the high capital cost of the system is to preheat a portion of domestic hot water using the excess condensation heat through the addition of a desuperheater to the heat pump unit [4]. A desuperheater is a small, auxiliary heat exchanger that uses superheated gases from the heat pump's compressor to heat water. In summer, when the HGCHP system is in the cooling mode, the desuperheater merely uses excess heat that would otherwise be expelled to the ground to heat domestic water in this manner virtually for free. In winter or some transitional seasons when the cooling requirement is unnecessary, the system can be shifted into heating mode to produce hot water. Kavanaugh, S.P. reported a similar project of the GCHP system with a desuperheater and concluded that the cost savings were very considerable based on the utility bill [5].

For the practical applications of the HGCHP system in residential buildings in hot climates, the alternative cooling and heating modes over a short-time period, which can flexibly meet cooling and hot water demands, become the primary running scheme. In view of the thermal behavior of the GHE, the alternative operating modes can increase significantly the heat transfer efficiency in the borehole field, especially in the hot-weather areas.

Furthermore, most of the HGCHP systems are generally at the discontinuous operations which can alleviate to some extent the heat buildup in the ground. The main objective of this work is to quantitatively examine the performance of the HGCHP system in various operating modes over a short-time period and thereby to investigate the thermal influence of the alternative and discontinuous operations of the heat pump unit on the performance of the GHE and surrounding soil.

SYSTEM DESCRIPTION

System Configuration

For the research purposes aforementioned, a pilot project of the HGCHP system was installed to offer space cooling and domestic hot water for a wooden house in a park in Hong Kong in October 2006, as shown in Figure 1. The heating mode in this project is only used to produce hot water for daily life as there is little heating requirement for buildings in Hong Kong. This project consists of a water-to-water heat pump equipped with a desuperheater and coupled to a GHE mixed with vertical and inclined boreholes. The heat pump unit with the cooling and heating capacity of 4.5 kW and 4.9 kW respectively was mounted in the plant room. Three water circulating pumps are of the constant flow rates (Model: UPS 25-125 180). The capacity of the hot water tank is 260 liter with a pressure rating of 7MPa. A fan coil unit is located on the wall of the wooden house, which has three wind speeds with the maximum capacity of 4.5 kW in cooling mode.



Fig. 1: An on-site photo of the project

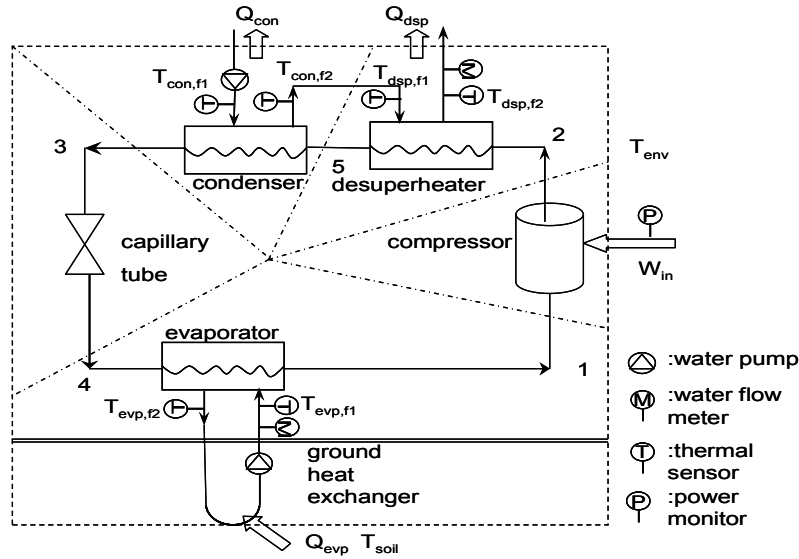


Fig. 2: Schematic diagram of the HGCHP system (in hot water mode).

Figure 2 illustrates the primary components and experimental instruments of the system, where the refrigerant flow is in the heating cycle depicted by the arrow direction. In heating mode, as shown in Figure 2, the evaporator is connected to the GHE and the desuperheater and the condenser are used to produce hot water. The desuperheater and condenser can be treated as two similar heat exchangers connected in series in terms of the refrigeration cycle analysis. In case of the cooling mode, the condenser is connected to the GHE while the evaporator is connected to the fan coil unit and the desuperheater is used to preheat hot water. The hot water first goes through the condenser before entering the desuperheater in order to improve the heat transfer rate within the condenser and desuperheater.

Ground heat exchangers

As stated above, the borehole field in the project consists of two vertical and two inclined boreholes with a tilted angle of 20° arranged in a rectangular configuration. The distance between two adjacent boreholes on the ground surface is 4m. Each borehole has the diameter of 110mm and the depth of 30m. The U-tubes are the high-density polyethylene pipe with the outer diameter 32mm (SDR 11). The horizontal supply and return headers are buried at a depth of 1 meter. It is noted that the purpose for drilling the inclined boreholes in this project is to alleviate the thermal interference among them in the ground while occupying less land

area on the ground surface than the vertical GHEs [6]. However, the advantages of the inclined boreholes will exhibit at least after one year's operation; therefore, it is not discussed in this paper.

The local average ground temperature a few meters below the ground is about 21.5 °C in January. The thermal properties of the local ground were estimated according to the geological report offered by the drilling contractor. It is worthwhile to stress that the ground water level is about 16m below the ground surface, which is quite beneficial to the heat transfer in the borehole field. The thermally-enhanced grout material, superplasticized cement-sand, was used to backfill three boreholes for research purpose and the mixture fine sand and silt was used to seal the last borehole for comparisons.

EXPERIMENTAL RIG AND DATA PROCESSING

Temperature Sensors and Other Instruments

To investigate and analyze the performance of the HGCHP system applied in the sub-tropical area, a set of data acquisition system was established in the system. As shown in Figure 2, six three-wire thermal-resistant sensors (Pt100) are located in the water pipes to measure the water temperature at the inlet and outlet of the three water loops. One Pt100 sensor was bound tightly to the U-tube pipes in a 7-meter interval along the borehole depth in order to analyze the heat diffusion in the surrounding soil. All the Pt100 sensors have an accuracy of $\pm 0.2^{\circ}\text{C}$. Three turbine flow meters (model: LW15) are used to measure the water flow rates in the three water loops. The flow meters, whose flow range is within 0.6-6 m^3/h , had been calibrated by the manufacturer to $\pm 0.5\%$ of full scale. The power consumption of the compressor and water pumps are measured using a power monitor which has an accuracy of $\pm 0.5\%$ of rated value.

Data Acquisition System and Uncertainty

All sensors and transducers can output analog signals of direct current (DC) in the forms of voltage, resistance, or frequency. These analog signals can then be converted into the digital signals by a data acquisition system which consists of a PCI card (Model PCI-8360V),

and some transformers. Finally, the data acquisition system can then convert the digital signals into the real physical values of the measured parameters using a pre-compiled program inside the module. The time interval of collecting data can be optionally set according to real conditions or research purposes.

An uncertainty analysis is performed using the method described by Holman [7]. Suppose the calculated variable R is a given function of the independent variables x_1, x_2, \dots, x_n . Based on the uncertainties of independently measured variables (x_1, x_2, \dots, x_n), the uncertainty of the calculated variable can be estimated using the classic root-sum-square formula:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

where

w_i = the uncertainty of the independently measured variable x_i

$\frac{\partial R}{\partial x_i}$ = sensitivity coefficient, the partial derivative of the calculated variable R with respect to

the measured variable x_i

The cooling or heating capacity of the HGCHP system can be obtained using the temperature difference on the water side:

$$Q = m_w c_p (t_{w,in} - t_{w,out}) \quad (2)$$

Thus, the uncertainty of the cooling or heating capacity is predicted approximately at 5~7%, depending largely on the accuracy of measured water temperatures.

System performance efficiency

In the HGCHP system, the hot water can be taken as a free by-product in the cooling mode. Therefore, the coefficient of performance (COP) in cooling mode can be revised according to its definition from ASHRAE Handbook (ASHRAE, 2000):

$$COP = \frac{Q_{evp} + Q_{des}}{W_{in}} \quad (3)$$

And the COP for heating mode is given by:

$$COP = \frac{Q_{des} + Q_{con}}{W_{in}} \quad (4)$$

where, Q_{evp} is the cooling capacity, Q_{des} is the heat absorbed by the hot water in the desuperheater and Q_{con} is the heat released into the condenser.

RESULTS AND DISCUSSIONS

Experimental Operating Schedule

Following the objectives aforementioned, the HGCHP system was set under three different operation modes over a short-time period, i.e. cooling mode, hot water heating mode and cooling with hot water mode. The experiments were undertaken from 11:11 to 15:11 on January 19th 2006. All the needed data including water temperatures, pipe wall temperatures, water flow rates and system power consumption were recorded every minute. To investigate the thermal behavior of the GHE, the temperatures on the U-tube pipes wall were continuously recorded for a few hours (until 24:00) after the system was shut down. Four operating periods were covered during the experiments, as shown in Table 1.

Table 1 Operating schedule of the HGCHP system during the experiments

No.	Operating Time	Operating mode
I	11:11~11:22	Hot water heating
II	11:25~11:33	Cooling only
III	11:34~14~51	Cooling with hot water heating
IV	14:51~15:11	Hot water heating

The operating performance of the system (i.e. COP) and the heat transfer rates of the GHE can be readily calculated through the recorded data, such as the temperatures, water flow rates and power consumption. The results are presented in Figures 3 through 6.

Results Discussion

The average temperatures on the outside wall of the U-tube pipes in the two vertical boreholes are depicted respectively from the starting time to the midnight, as shown in Figure 3. The pipe wall temperatures oscillated significantly during the four periods and then decreased gradually with time. After about 8 hours of off-time, the pipe wall temperature was almost close to the initial value before the system started. This is very essential to the heat transfer efficiency of the GHE and thereby to the whole system.

Fig. 4 presents the average heat transfer rate per unit length of the borehole during the four periods, where the heat rejection is shown as positive and heat extraction as negative. Obviously a higher heat flux is observed in hot water mode (periods I and IV), which had an average value of about 60W/m. However, the heat transfer rate in the cooling mode (period II) was approximated to be 50W/m, which was evidently lower than that in heating mode. Note that the amount of the heat rejected into the ground for cooling with hot water supply mode depends largely on the heat rejected to the hot water. It can be seen from Figure 4 that the heat rejection into the ground rose gradually with the reduction of the heat rejected to the hot water (i.e. the increase of the hot water temperature) during the period III. Based on the measured data, the desuperheater can capture up to 60% of the total condensation heat to produce hot water in the system, which reveals it was slightly oversized by the manufacture.

Figure 5 illustrates the variation of the COP and the relative variations of chilled water and hot water temperatures with operating time during periods II and III. It can be seen from Figure 5 that the COP of the cooling mode for this system had a relatively lower value due to the energy losses caused by the refrigerant's pressure loss in the desuperheater. In this case, the COP sharply dropped to 2.6 ten minutes after start-up. Regarding the cooling with hot water mode, the COP was enhanced significantly considering the production of hot water. A maximum COP of 7.7 is achieved at the beginning of the period and then the value is reduced with the rise of the hot water temperature. It can be noticed that the COP can still be maintained at a higher value of 4.5 when the hot water temperature reached about 30°C.

Figure 6 illustrates the variation of the COP and the relative variations of hot water temperature during the periods I and IV. The COP ranged between 3.6~5.4 when the hot water temperature increased from 16°C to 47 °C during the two periods, which is quite higher

than that in cooling mode, which contributed to the relatively higher ground temperature and is favorable for heating mode.

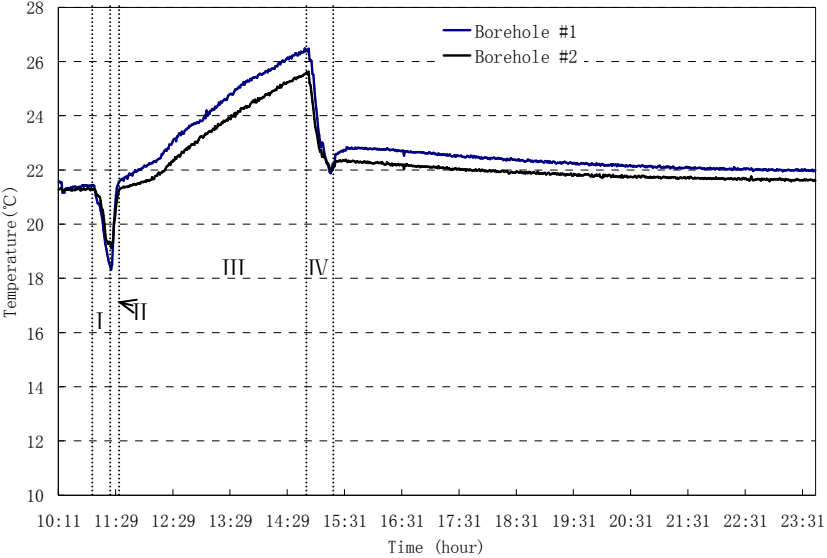


Fig. 3 The U-tube pipe wall temperatures variation with time

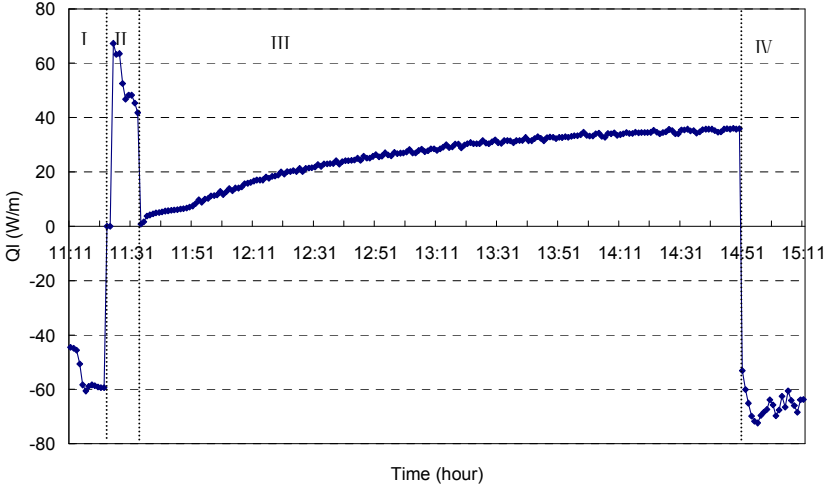


Fig. 4 Average heat transfer rate per unit length of borehole during the operation period

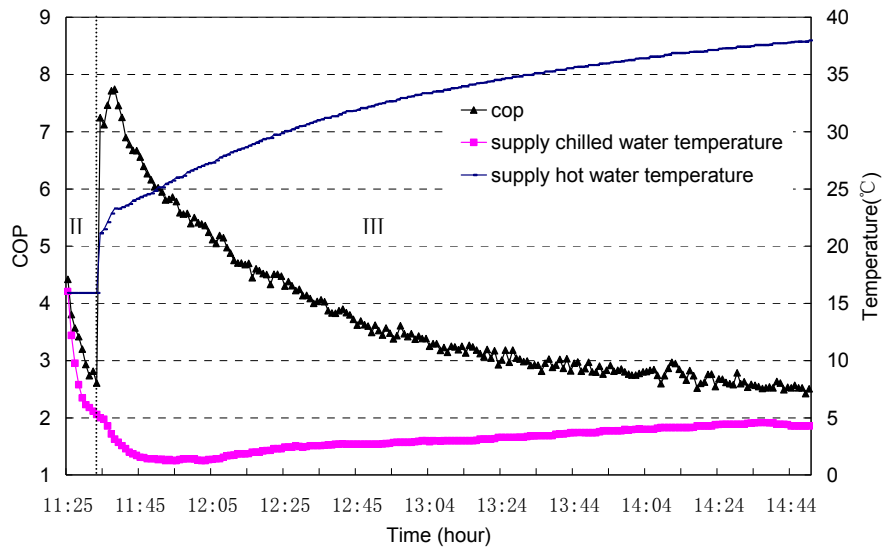


Fig. 5 Variations of COP and supply water temperatures in cooling modes

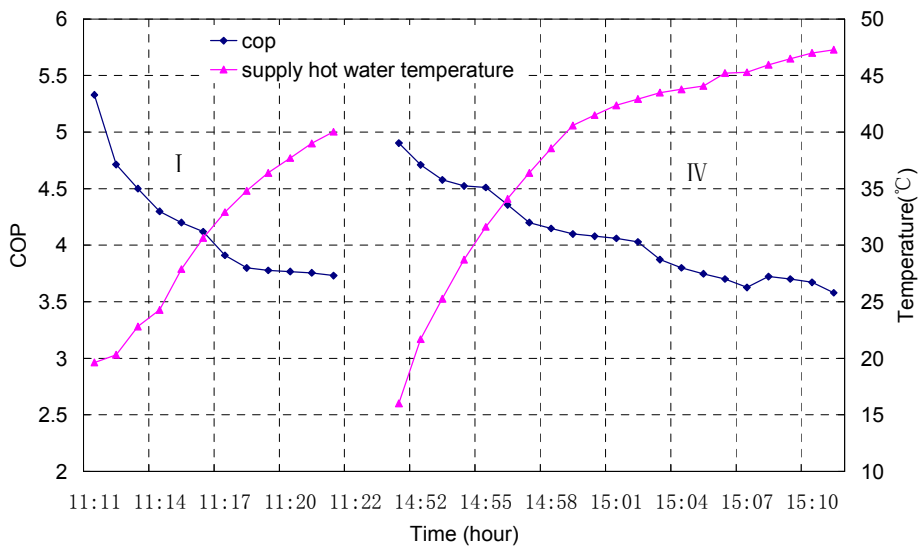


Fig. 6 Variations of COP and supply water temperature in hot water mode

CONCLUSIONS AND RECOMMENDATIONS

A pilot project of the HGCHP system with DHW supply has been developed for research purposes. The experiments with respect to the three operating modes have been undertaken during a short-time period. The measured results illustrate that the HGCHP system with DHW supply is suitable for hot-climate areas.

The results show that the HGCHP system can achieve higher performance efficiency in the hot water heating mode in hot-weather areas. Therefore, using the system to produce hot water has a considerable potential of energy saving compared to the conventional fossil fuel-fired or electrical–boiler hot water supply. Furthermore, the cooling with hot water heating mode is highly recommended in cooling season, which can not only save energy but also provide the domestic hot water.

Finally, the variation of the U-tube pipe wall temperatures illustrates that the discontinuous operation mode can effectively alleviate the heat buildup in the surrounding soil. Therefore, the discontinuous operation mode (such as operating during daytime while shut down at night or vice versa) is also recommended and it is feasible for commercial or residential buildings.

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