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Geothermal Heat Pump System for Air Conditioning in Hong Kong

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ABSTRACT

In Hong Kong, electrical energy consumption for air conditioning of buildings is very high. Since most central air conditioning systems are air-cooled, there has been much concern about the need for appropriate energy conservation strategies and solutions for the "heat island effect" due to heat dissipation from the air conditioning condensers of the crowded buildings. Although experience in cold climate countries has shown that geothermal heat pump systems are more efficient than other types of systems for building environmental control, there has never been any study or project of geothermal heat pump systems carried out for the sub-tropical environment of Hong Kong.

Recently, the Hong Kong government has initiated a pioneering project for the Wet Land Garden in the New Territories in which a geothermal heat pump system is employed for central cooling and heating of the associated buildings. In order to predict the performance of the geothermal system under Hong Kong weather conditions, a computer modelling and simulation study is carried out using the TRNSYS software package and a vertical U-tube ground loop heat exchanger model. Useful results are obtained for the long-term performance for cooling only and combined cooling and heating throughout the year. Great improvements in performance are achieved for the latter case. Further analyses of the results can help determine whether geothermal heat pump systems are economically viable and environmentally friendly in Hong Kong.

1. INTRODUCTION

Geothermal heat pump systems rely on the earth for heat rejection or heat absorption in order to achieve space cooling or heating. Experience in cold climate countries has shown that geothermal heat pump systems are more efficient than other types of systems for building environmental control. There are also other advantages including high reliability, low maintenance requirements and minimal environmental impacts. Storage effect due to accumulation of heat or coldness in the earth can however be a problem if proper system design is not followed. This can lead to substantial degradation in performance after five to ten years of operation. Careful and proper design of ground-coupled heat exchangers must be followed and there are many useful references on this topic (Kavanaugh and Rafferty (1997), Shonder (2000) and Kavanaugh (2003)). However, there has not been any geothermal heat pump system installed in Hong Kong where the climate is sub-tropical. The Architectural Services Department of the SAR Government of Hong Kong has recently initiated an innovative project for the Wet Land Garden in the New Territories in which a geothermal heat pump system is employed for central cooling and heating of the associated buildings. In this research project, the challenge is to find out whether geothermal heat pumps are suitable for application under Hong Kong weather conditions.

2. COMPUTER MODELLING OF GROUND-COUPLED HEAT PUMP SYSTEM FOR BUILDING AIR CONDITIONING

In order to study the applicability of geothermal heat pump systems for building air conditioning purposes under Hong Kong weather conditions, the TRNSYS component-based computer simulation software package (Klein et al. (2002)) is chosen for developing the system components and carrying out system performance analyses. The total design heat dissipation of the ground loop heat exchanger is about 1640 kW. By symmetry of the area available for U-tube heat exchanger boreholes, half of this capacity, i.e. 820 kW is used in the actual computer simulation setup.

2.1 Heat Pump Component

Typical water-to-air heat pumps are used, which have the water-to-refrigerant coil linked to the ground-source water loop and the air-to-refrigerant coil linked to a forced air system. The performance characteristics of a commercially available heat pump with a cooling capacity of 88 kW each are defined for the component model for detailed computer simulation studies.

2.2 Ground Heat Exchanger Component

Vertical U-tube ground loop heat exchangers are used, which are made of polyethylene tubing having an inner radius of 17.27 mm and a centre-to-centre half distance of 25.4 mm. They are installed and embedded inside 234 boreholes, each 50 m deep, with bentonite and quartz sand grout. A borehole spacing of 10 m is used. The ground heat exchanger component model employed is developed by the University of Lund, Sweden (Hellstrom (1991)).

2.2.1 Geological Data

The site is located at the north-west part of the New Territories of the Kowloon Peninsula. Since actual site measurements of soil properties are not available, the geological data for Yuen Long district are utilized (CED-HKSAR (1992)). Specifically, the thermal conductivity and the specific heat capacity of the ground layer are taken to be 2.60 W/m K and 2322.29 kJ/m^3 K respectively. The initial temperature of the undisturbed ground is taken to be 17.6°C.

2.3 Weather Component

The meteorological data of dry-bulb temperature and relative humidity for Hong Kong from 1975 to 1995 are obtained from the Hong Kong Observatory and pre-processed by a C++ program for conversion to the required format for the TRNSYS simulation program.

2.4 Pump, On-Off Function and Plotter Components

A typical water pump component model is used to simulate the water flow through the ground heat exchangers. Other supporting models used include the on-off function and the on-line plotter components models.

3. COMPUTER SIMULATION OF SYSTEM PERFORMANCE

Computer simulation is employed to study the performance of the geothermal heat pump system using TRNSYS Version 15.2 with intelligent graphical interface for system configuration and interlinking of the system components. The simulation covers a period of seventeen years using hourly weather data in order to be able to study the long-term performance due to changes in the ground condition.

3.1 Cooling Only

The geothermal heat pump system is first configured for central cooling only. The simulation results are shown in the following Figures 1 and 2 for the first three-and-half years for the sake of clarity. Discussions about the overall trend of the results are given in Section 4.1.

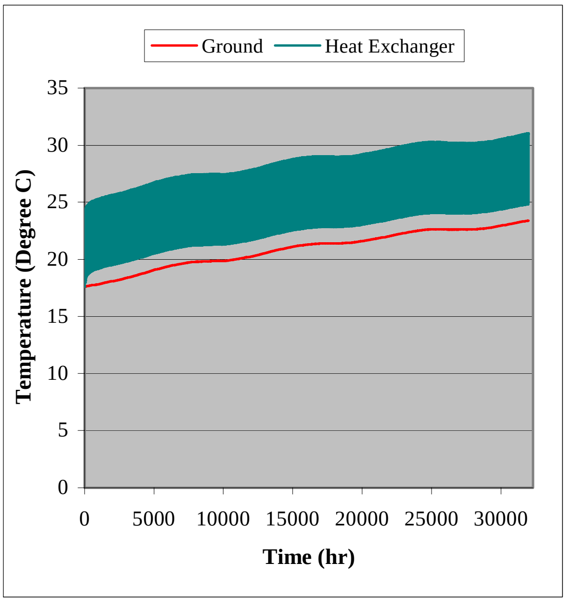

Figure 1: Graph of Ground and Heat Exchanger Outlet Temperatures Vs Time (Cooling Only)

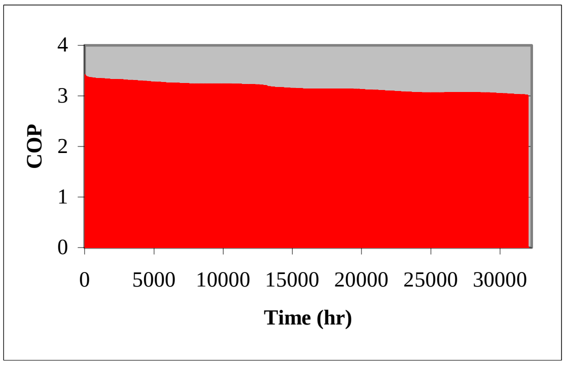

Figure 2: Graph of COP Vs Time (Cooling Only)

Sensitivity studies of the effects of borehole separation, borehole depth, number of boreholes and total borehole length are also performed. The results obtained are shown in Figures 3 to 6. The implications of the sensitivity analysis are discussed in Section 4.1.

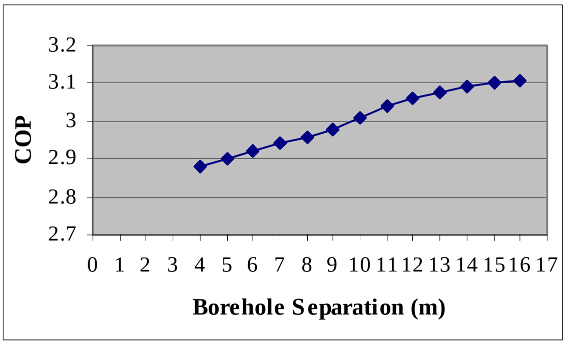

Figure 3: Graph of COP Vs Borehole Separation

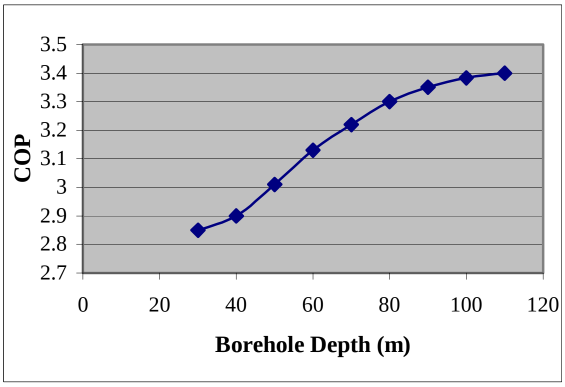

Figure 4: Graph of COP Vs Borehole Depth

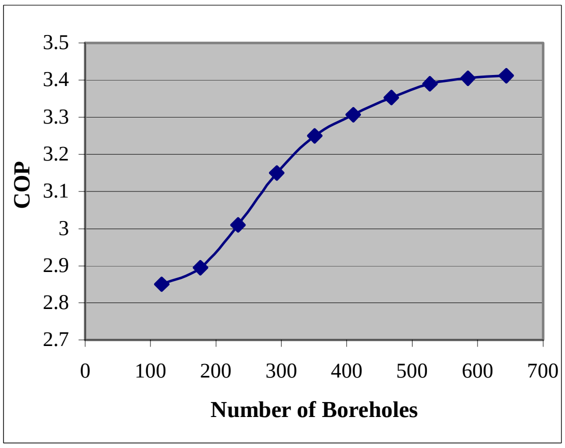

Figure 5: Graph of COP Vs Number of Boreholes

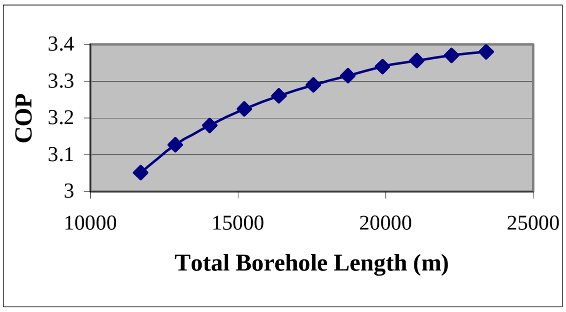

Figure 6: Graph of COP Vs Total Borehole Length

3.2 Cooling and Heating

The geothermal heat pump system is then configured for combined cooling and heating modes for different seasons throughout the year. The simulation results for the ground and heat exchanger temperature variations and the heat pump coefficient of performance for the first three-and-half years are shown in Figures 7 and 8. Discussion of the results is given in Section 4.2.

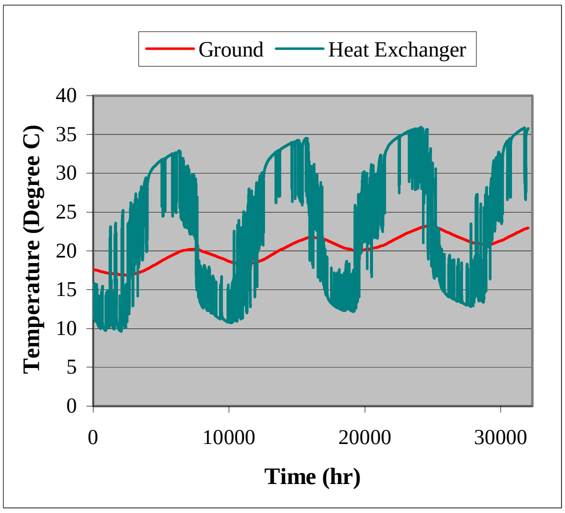

Figure 7: Graph of Ground and Heat Exchanger Outlet Temperatures Vs Time (Cooling and Heating)

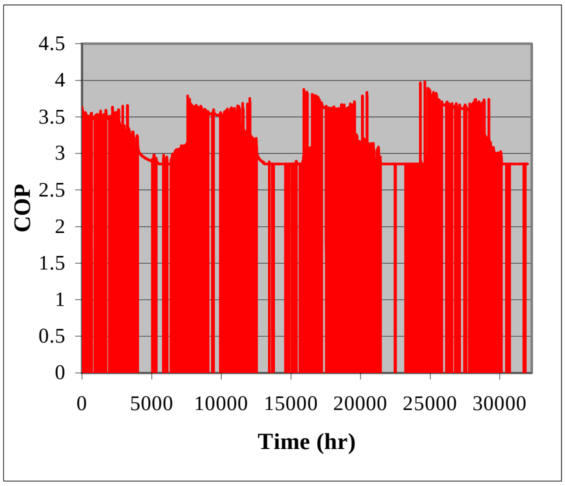

Figure 8: Graph of COP Vs Time (Cooling and Heating)

Similar sensitivity studies as for the cooling only mode of operation are also performed. The general patterns of the results are similar to the previous case and are not shown here for the sake of brevity.

4. DISCUSSIONS

4.1 Cooling Only

The simulation results show that for the first six years, the ground temperature and the heat exchanger outlet temperature continuously increase due to the accumulation of heat rejected from the geothermal heat pump system. The overall temperature increase within this period is about 7.5°C while the corresponding increase for the entire simulation period of seventeen years is about 12.4°C. The ground heat exchanger outlet temperature follows the same trend together with a short-term variation within a range of about 6°C according to the load profile. Figure 1 shows the temperature profiles for the first three-and-half years only for better clarity. Figure 2 shows the COP value for the corresponding period. Because of this ground temperature rise, the COP of the geothermal heat pump system drops to 2.81 for the seventeenth year from an initial value of 3.24 in the first year, as shown in Table 1.

Table 1: Comparison of COP Values of Heat Pump (Cooling Only)

Year of Operation	COP
1^{st} year	3.24
6^{th} year	2.90
17^{th} year	2.81

It is obvious that the current design of geothermal heat pump system is not acceptable on account of the substantial deterioration in the long-term system performance. Design improvements can be achieved by considering the effects of borehole separation, borehole depth, number of boreholes and total borehole length on the COP value. It can be noticed from Figures 3 to 6 that an increase in the various parameters will in general result in a corresponding increase in the COP value until the sensitivity curves tend to level off. Appropriate choice of the various parameter values can be made to ensure that the target COP value is achieved subject to the imposed constraints on availability of land and cost of borehole drilling etc.

Alternatively, in order to satisfy the constraints on system capital cost and land availability for installation of ground heat exchangers, a hybrid geothermal heat pump system design can be considered for cooling-dominated applications. In a hybrid system, an auxiliary conventional heat rejection system is used to dissipate the excessive heat which will otherwise cause unacceptable rise in the ground temperature. A number of studies have been made on the design methodologies, control strategies, simulated system performance and actual measured performance results for hybrid geothermal heat pump systems (Kavanaugh and Rafferty (1997), Kavanaugh (1998), Thornton (2000), Yavuzturk and Spitler (2000), Phetteplace and Sullivan (1998), Singh and Foster (1998)). It seems that a hybrid design can be employed to arrive at an optimized system in terms of first or life-cycle costs.

4.2 Cooling and Heating

To further investigate the performance of the geothermal heat pump system, both cooling and heating operation modes are employed for the different seasons throughout the year. Heating of the ground mainly occurs for the first five years, with an increase in ground temperature of about 5.4°C over this period. The total temperature rise for the entire seventeen years is about 7.4°C. The ground heat exchanger outlet temperature also follows the same pattern of temperature rise as in the case of cooling only, but can be about 10°C higher or lower than the corresponding ground temperature depending on whether the operation is for cooling or heating purposes. Figure 7 depicts the temperature profiles for the first three-and-half years while Figure 8 shows the COP profile for the corresponding period. It is noticed that the COP values changes only slightly from 3.29 in the first year to 3.20 after five years and finally to 3.25 for the seventeenth year. This is in line with the heat pump manufacturer's rated COP of 3.2. The geothermal heat pump design is thus feasible when it is applied to cooling and heating modes of operation.

Table 2: Comparison of COP Values of Heat Pump (Cooling and Heating)

Year of Operation	COP
1^{st} year	3.29
6^{th} year	3.20
17^{th} year	3.25

5. CONCLUSION

From the results of the simulation studies based on the assumed geological properties of the site and the local weather conditions of Hong Kong, it is quite clear that if the heat pump system is used for cooling only, acceptable sustained long-term performance cannot be achieved. This is due to rise of the ground temperature and the resultant drop in the heat pump COP. On the other hand, there are good improvements of the system performance if operation of the heat pump system is for cooling and heating. The cyclic heat rejection to and heat removal from the ground help maintain an acceptable steady ground temperature and sustained heat pump COP. It can therefore be concluded that the simulation results demonstrate it is feasible to adopt the use of geothermal heat pump systems for cooling and heating in Hong Kong.

Apart from technical feasibility, there are other factors such as energy efficiency, environmental impacts, service life, maintenance requirements which will influence the choice of a geothermal heat pump system over other types of cooling and heating systems. Since a geothermal heat pump system is generally expected to score high marks in the above considerations, it is envisaged that it will have a high potential for application in Hong Kong, given the current concern about the accumulation of rejected heat from air conditioning systems resulting in "heat islands", especially in the urban areas. The major difficulty lies in the availability of land for the installation of the ground heat exchangers. Further research work will be carried out to investigate whether it is feasible to embed the heat exchangers into the building foundation piles in order to minimize the land requirement.

6. ACKNOWLEDGEMENT

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