

A CLOSED LOOP GROUND SOURCE HEAT PUMP SYSTEM FOR SPACE HEATING AND COOLING IN BUILDINGS

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ABSTRACT

The UK is committed to reducing its emission of carbon dioxide, a major greenhouse gas, by 20% by the year 2010. Approximately 50% of the UK's total energy consumption is associated with buildings. This could be met by utilising 'environmentally-friendly' energy sources such as renewable energy. Ground source heat pump (GSHP) systems could be employed in buildings for space heating and cooling and also for provision of hot and cold water. The main benefit of using GSHPs is that the temperature of the subsurface is not subject to the large variations experienced by air, currently the most common energy source for heat pumps, and therefore more efficient systems are possible. A closed loop GSHP system has been installed at the Marmont Renewable Energy Research Centre of the School of the Built Environment. The system consists of a reverse cycle water-to-air heat pump coupled to three vertical ground- loops (one U-tube and two concentric tubes). Investigations of the thermal performance of this system were carried out for different ground heat exchanger designs in order to investigate their effect on the overall thermal performance of the system, which will help to develop more energy efficient and cost competitive ground source heat pump systems.

KEYWORDS

Ground Source, Geothermal, Heat Pump, Ground Heat Exchangers, Ground Loops, Renewable Energy, Space Heating and Cooling, Refrigeration, Building services

1. INTRODUCTION

There is a growing interest in renewable energy systems worldwide. This has been prompted by increased concern over fossil fuel depletion, environmental pollution and possible climate change implications resulting from our continued use of fossil and nuclear fuels. Buildings account for up to 50% of the UK's total energy consumption (Shorrock, 1992) and hence significantly contribute to pollutant emissions. A major part of this energy demand could be met by technologies utilising renewable energy sources such as solar, wind and ground energy.

A ground source heat pump (GSHP) system utilises the low-grade heat energy stored in the earth by upgrading it to a useful energy of a higher temperature, which may be employed for space heating and cooling in buildings. GSHP systems are energy efficient, cost competitive, environmentally friendly, quiet in operation, aesthetically pleasing and have long life expectancy with minimal maintenance (ASHRAE Application Handbook, 1999, Curtis, 1996, Gelder and Witte, 1999 and Morgan, 1997).

The term "ground source" is applied to a variety of heat pump systems that use ground soil, ground water or ground surface water as a heat source or heat sink (ASHRAE Application Handbook, 1999). The temperature of the subsurface is not subject to the large variations experienced by air, which is currently the most common energy source for heat pumps (see Figure 1). This makes the coefficient of performance (COP) of a GSHP system likely to be higher and more predictable

than that of a conventional air source heat pump system. Different types of soils have different thermal conductivity, density, specific capacity and moisture content. These factors would play an important role in determining the COP of a ground soil-source heat pump.

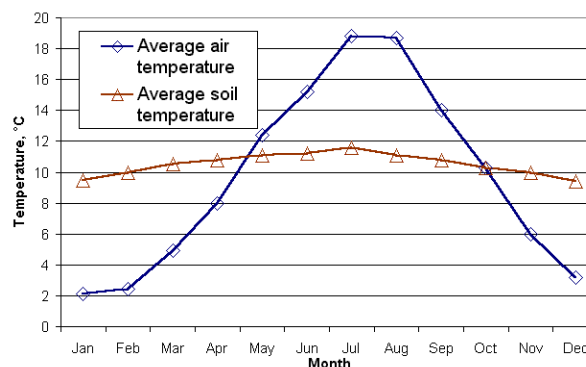


Figure 1 The subsurface temperature is stable all year round

The main component of a GSHP system is the heat pump unit, which is a device that extracts heat energy from a source at a low temperature and pumps it to a useful heat at a higher temperature (Heap, 1979). Heat pumping can be achieved by many thermodynamic cycles, e.g. vapour compression, vapour absorption and solid-vapour sorption. The great majority of heat pumps currently in operation work on the principle of the vapour compression cycle. The main components of such a cycle are the compressor, the condenser, the expansion valve and the evaporator (see Figure 2). The

compressor is usually driven by an electric motor or a combustion engine. There is a wide range of heat pumps, which may be classified according to the purpose of application, output, heat source type, heat pump process type etc. For instance, heat pumps may be classified according to the type of heat source/sink, e.g. air-to-air, water-to-air, water-to-water and air-to-water heat pumps.

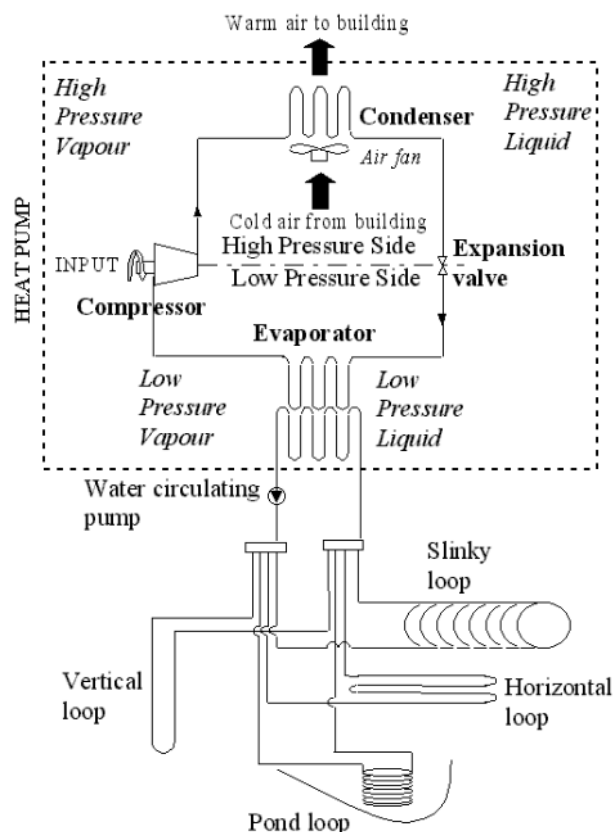


Figure 2 Schematic diagram of a vapour compression heat pump cycle coupled to different types of closed loop ground heat exchangers. Note: Heating mode only shown.

Several types of working fluids (refrigerants) may be used in vapour compression heat pump cycles. These refrigerants may be classified into different groups according to their chemical composition e.g., chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), blends, and natural fluids. A suitable refrigerant should have good thermodynamic properties i.e., high latent heat values in the system's temperature range. An ideal refrigerant should be easily condensed, with high thermal conductivity to enable good heat transfer. It should be chemically stable, non-toxic, non-flammable, non-corrosive and cost effective.

The GSHP absorbs or rejects heat to the ground soil via a loop, which acts as a heat exchanger. There are two types of loops: open and closed. The closed loops are

the most common ground heat exchangers. They consist of continuous loop of high density polyethylene pipe, filled with a water/antifreeze mixture and buried in the ground. Closed loops may be installed in three ways: horizontally, vertically, or in a pond/lake (see Figure 2). Open loops are installed where an adequate supply of suitable water is available (e.g., water from permeable rocks or aquifers) and open discharge is feasible. Water is extracted by a submersible pump and passed through the heat pump where it releases or absorbs heat, and is then discharged to a pond, lake or a 'return' well.

The thermal performance of a GSHP system may be assessed by its coefficient of performance (COP). The COP is the amount of useful heating or cooling that can be obtained from the GSHP unit to the energy consumed in delivering this heating or cooling (Grimm and Rosaler, 1998). The COP depends on the design of the heat pump and the temperature difference between the source and the sink. The COP of a heat pump improves when source and sink temperatures are close together.

The GSHP system installed at the Marmont Renewable Energy Research Centre of the School of the Built Environment contains a water-to-air, electric-motor-driven, vapour compression, reverse cycle heat pump unit. The working fluid used in this heat pump is R-407C, which is a blend of three HFC refrigerants, namely R-32, R-125 and R-134A. R-407C is chlorine-free and therefore does not contribute to ozone depletion. It also has low global warming potential. The heat pump unit uses ground soil as a heat source/sink. It is coupled to the ground via three vertical closed loops (one U-tube and two concentric tubes).

2. EXPERIMENTAL WORK

The ground source heat pump system used in this project consists of three vertical closed loops, one U-tube and two concentric tubes (see Figure 3). These loops, which are normally called ground couplings or ground heat exchangers, are made from virtually indestructible fusion welded, high-density polyethylene pipes. The loops have a total ground-coupling length of 150 metres. They are filled with a mixture of water and antifreeze (mono propylene glycol) and connected in parallel to the heat pump unit. The mono propylene glycol antifreeze forms 20% of the solution by volume. A centrifugal pump circulates the glycol solution between the ground and the heat pump unit. In the heating mode, the glycol solution extracts heat from the ground which is then upgraded by the heat pump and released into the building. In the cooling mode, the system reverses its operation. The glycol solution draws heat from the building and rejects it into the ground. The heat pump unit incorporates an air fan which draws air from the building space, passes it through the heat pump to be heated or cooled according to the mode of operation and finally discharges it back to the building space. The fan has three speeds, representing air volume flow rates of 0.114, 0.149 and 0.179 m³/s.

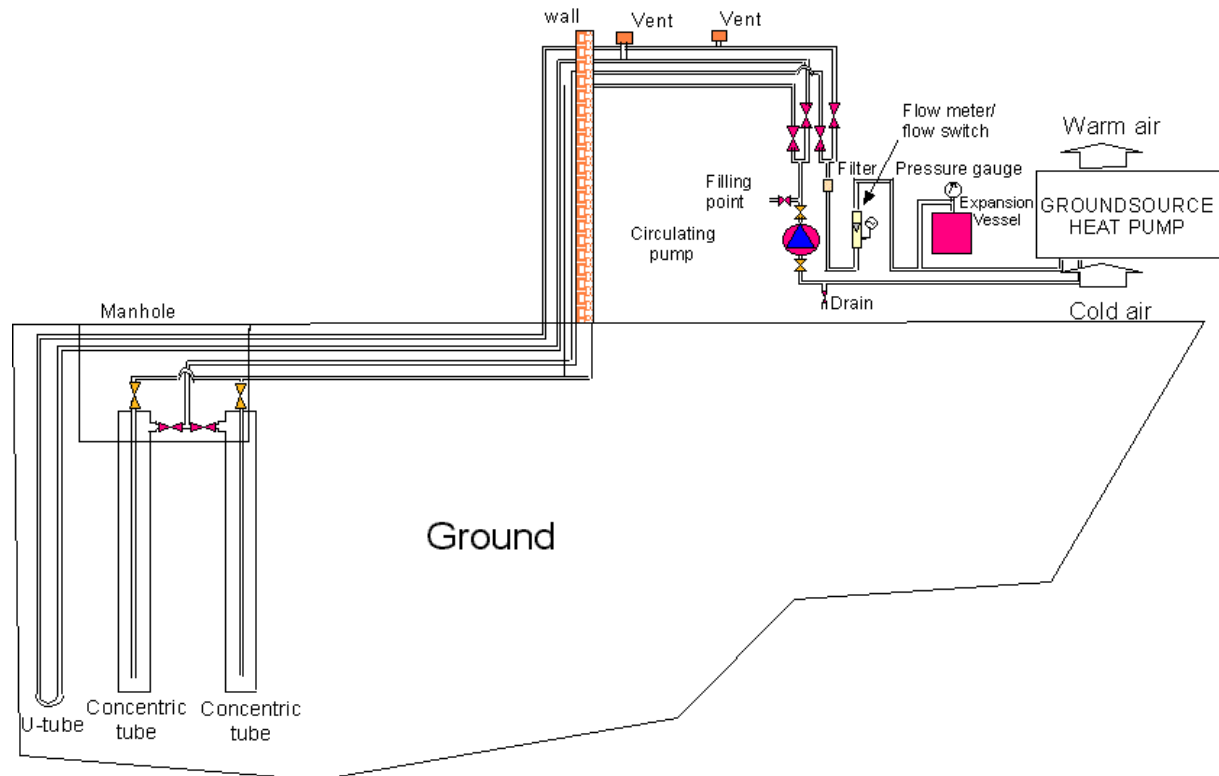


Figure 3 Schematic diagram for the ground heat pump system (Heating Mode). Note: Drawing not to scale

The thermal performance of the GSHP system was monitored for two different designs of ground couplings, i.e. U-tube and concentric tube, in order to investigate and compare their effect on the overall thermal performance of the system. Each ground coupling design was tested in both heating and cooling modes. For each mode three different volume flow rates of air were tested, giving a total number of 12 tests. For each test the following measurements were recorded:

- Air inlet/outlet temperature to/from the heat pump unit
- Air volume flow rate
- Glycol solution inlet/outlet temperature to/from the heat pump unit
- Glycol solution volume flow rate
- Quantity (mass) of water, condensed as a result of cooling air in the cooling mode
- Ground soil temperature at different depths
- Overall electrical power consumption of the system which includes the power consumption of the heat pump's compressor, air fan and water circulating pump.

3. EXPERIMENTAL RESULTS

The ground heat exchanger designs tested in this work were the U-tube and the concentric tube. A comparison between the thermal performances of these designs is shown in table 1 (for the heating mode) and in Table 2 (for the cooling mode). As can be seen from these tables, the concentric tube was more efficient than the U-tube both in heating and cooling modes. The average heating and cooling loads provided by the GSHP system using the U-tube heat exchanger were respectively 249 and 161 kWh/year per metre length of the ground coupling. In the case of the concentric tube, the average heating and cooling loads were 436 and 300 kW/year/m respectively. It should be noted that the load figures given here are based on the GSHP working all year round in the heating or cooling mode. These figures, however, should be adjusted according to the load factor of the heat pump in heating or cooling mode. The concentric tube was also more efficient than the U-tube in terms of collecting heat energy from the ground (heating mode) or depositing heat energy to the ground (cooling mode). While operating in the heating mode, the concentric tube collected 394 kWh/year/m of heat energy from the ground compared to 217 kWh/year/m for the U-tube. In the cooling mode, the concentric tube rejected 531 kWh/year/m of heat energy to the ground

compared to 293 kWh/year/m for the U-tube. Tables 1 and 2 also show that, regardless of the type of ground heat exchanger, the heat pump performed better in the heating mode than in the cooling mode.

Table 1 Effect of ground heat exchanger type on the thermal performance of a GSHP system (Heating mode)

	U-tube	Concentric tube
Load delivered to air, kWh/year/m*	249	436
Load absorbed from ground, kWh/year/m*	217	394

*Loads were calculated for one metre length of the ground heat exchanger with the heat pump working all year round

Table 2 Effect of ground heat exchanger type on the thermal performance of a GSHP system (Cooling mode)

	U-tube	Concentric tube
Load absorbed from air, kWh/year/m*	161	300
Load deposited to ground, kWh/year/m*	293	531

*Loads were calculated for one metre length of the ground heat exchanger with the heat pump working all year round

The system's COP increased with increasing air volume flow rate, both in heating and cooling modes. This is shown in Figure 4 for the system using the U-tube ground heat exchanger. In the heating mode, for example, The air within the space to be heated is drawn by a fan which is an integral part of the heat pump unit. The air passes across the condenser of the heat pump from which it picks up heat energy and then returns back to the space. The energy delivered by the heat pump to the circulated air (heating mode) can be calculated from the following equation,

$$Q = \rho V c_p \Delta T \quad (1)$$

where:

Q Rate of heat energy delivered or extracted from the fluid, kW
 ρ Density of fluid, kg/m³
V Volume flow rate of fluid, m³/s
 c_p Specific heat of fluid at constant pressure, kJ/kgK
 ΔT Temperature difference between fluid inlet/outlet to/from a heat exchanger, K

In the cooling mode, both sensible and latent heat energy extracted from the circulated air were calculated. Sensible heat energy was calculated from Equation (1) and latent heat energy was calculated by multiplying the mass of water condensed in a certain time by the latent heat of vaporisation of water.

The coefficient of performance of the system is calculated as follows,

$$COP = \frac{Q}{W} \quad (2)$$

where:

COP Coefficient of performance of the system
W Overall electrical power consumption of the system, kW

As the volume flow rate of the air (V) increases, the air temperature difference (ΔT) decreases, both in heating and cooling modes and the total power consumption (W) increases slightly. However, the decrease in ΔT and the increase in W are less important than the increase in V and, therefore, referring to Equations (1) and (2), the rate of heat energy delivered to the air (Q) increases and COP also increases with the increase in V.

Figure 4 also emphasises that the COP of the GSHP system is higher in the heating than in the cooling mode. This is a characteristic of heat pump cycles as $COP_{hp} = COP_{rf} + 1$ (Çengel, 1989), where COP_{hp} is the coefficient of performance when the cycle is used for heat pumping (e.g. space heating) and COP_{rf} when used for refrigeration (space cooling).

For a heat pump working in the heating mode, the rate of heat energy gained by air (Q_H) should be, theoretically, equal to the sum of the rate of heat energy extracted by water from the ground (Q_L) and the rate of the heat energy consumed by the system (W). In all tests, it was found that $Q_H < Q_L + W$. This may be attributed to heat losses to surroundings which result in a reduced COP of the system. These heat losses decreased with an increase in the air flow rate. For instance, the losses in the total heat input to the system, i.e. ($Q_L + W$) while using 2-concentric tubes, were 22%, 13% and 12% for air flow rates of 0.114, 0.149 and 0.179 m³/s respectively.

The rate of heat energy collected by the glycol solution from the ground (Q_L) was calculated from Equation (1). The volume flow rate of the glycol solution was maintained at 0.159 litres/sec in all tests. This is the flow rate recommended by the manufacturer of the heat pump unit. In the heating mode, the rate of heat energy absorbed from the ground by the glycol solution increased with the increase in air volume flow rate. As mentioned above, with increased airflow, the rate of heat energy delivered to the air increases and the rate of heat energy consumed by the system increases slightly due to higher fan speed. Therefore, to maintain an energy balance, i.e. ($Q_H = Q_L + W$) and if the thermal losses from the system are ignored, Q_L will increase with the increase in airflow rate.

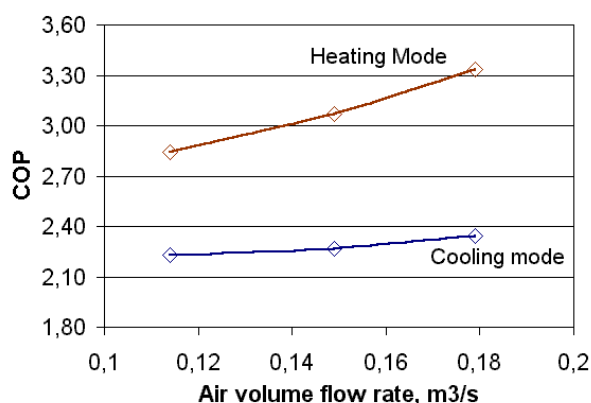


Figure 4 Variation of COP with air volume flow rate for a system using U-tube as a ground heat exchanger

Figure 5 shows the variation of the ground soil temperature with time at a depth of six metres. The average temperature of the soil at this depth is relatively stable at 12 °C all year round. However, the temperature of the soil in the vicinity of the ground coupling may differ slightly from this temperature. For instance, during testing the GSHP system with the concentric tube ground heat exchanger, it was found that the average temperature of the soil surrounding the ground coupling during the heating mode was 9.2 °C and during the cooling mode was 15 °C. In the heating mode, the glycol solution abstracts heat energy from the soil surrounding the tube, this heat is then upgraded by the heat pump to be used for space heating. This reduces the soil temperature. In the cooling mode, the heat pump absorbs heat energy from the space and delivers it to the glycol solution which in turn dumps it into the ground. Hence the temperature of the soil in this case increased.

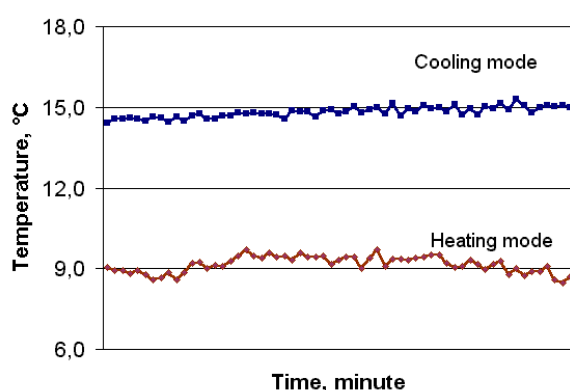


Figure 5 Variation of ground soil temperature with time at a depth of 5.5 metre for a system using one-concentric tube ground heat exchanger

4. CONCLUSIONS

It has been found that a GSHP system performs better with a concentric tube as a ground coupling than with a U-tube in terms of exchanging heat energy with the building, both in heating and cooling modes. The heat energy gained by air from the GSHP system (space heating) improved by 75% and the heat energy extracted from air by the system (space cooling) improved by 86% when a concentric tube was used instead of a same size U-tube. The concentric tube ground heat exchanger was also more efficient than a U-tube of the same size in terms of collecting heat energy from the ground (heating mode) or depositing heat energy to the ground (cooling mode). For example, the concentric tube collected 81% more of heat energy from the ground and rejects 81% more of heat energy to the ground than a U-tube of the same size.

The COP of the GSHP system increased with increased air volume flow rate, both in the heating and cooling mode. The rate of heat energy extracted from the ground by the glycol solution increased with increased air volume flow rate, both in heating and cooling modes.

Regardless of the type of ground coupling, the GSHP system always performed better in the heating mode than in the cooling mode. The COP of the GSHP system under investigation varied between 2.98 and 3.32 in the heating mode and between 2.05 and 2.32 in the cooling mode.

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NOMENCLATURE

COP Coefficient of performance of the system
COP_{hp} Coefficient of performance of the system in the heating mode
COP_{rf} Coefficient of performance of the system in the cooling mode
c_p Specific heat of fluid at constant pressure, kJ/kgK
Q Rate of heat energy delivered or extracted from the fluid, kW

Q_H Rate of heat energy absorbed from the heat pump's condenser, kW
Q_L Rate of heat energy delivered to the heat pump's evaporator, kW
V Volume flow rate of fluid, m³/s
W Overall electrical power consumption of the system, kW
ΔT Temperature difference between fluid inlet/outlet to/from a heat exchanger, K
ρ Density of fluid, kg/m³