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Development and Evaluation of a Direct Expansion Heat Pump System

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ABSTRACT

The move towards a low-carbon world, driven partly by climate science and partly by the business opportunities it offers, will need the promotion of environmentally friendly alternatives if an acceptable stabilisation level of atmospheric carbon dioxide is to be achieved. This requires the harnessing and use of natural resources that produce no air pollution or GHGs and provides comfortable coexistence of humans, livestock, and plants. GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of GHGs. The main objective of the research is to stimulate the uptake of the GSHPs. This paper describes the details of a prototype direct expansion GSHP test rig and details of the construction and installation of the heat pump, heat exchanger, heat injection fan and water supply system. It also presents a discussion of the experimental tests currently being carried out.

Keywords: Direct expansion GSHPs; construction; development and evaluation of the system.

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INTRODUCTION

Globally buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling and air conditioning. An increase in awareness of the environmental impact of CO_2, NOx and CFCs emissions triggered a renewed interest in environmentally friendly cooling and heating technologies. Under the 1997 Montreal Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone. It was therefore considered desirable to reduce energy consumption in order to decrease the rate of depletion of world energy reserves as well as the pollution to the environment.

One way of reducing building energy consumption is to design buildings, which are more efficient in their use of energy for heating, lighting, cooling and ventilation. Passive measures, particularly natural or hybrid ventilation rather than air-conditioning, can dramatically reduce primary energy consumption [1]. Therefore, promoting innovative renewable energy applications including the ground source energy may contribute to preservation of the ecosystem by reducing emissions at local and global levels. This will also contribute to the amelioration of environmental conditions by replacing conventional fuels with renewable energies that produce no air pollution or GHGs. An approach is needed to integrate renewable energies in a way to achieve high building performance standards. However, because renewable energy sources are stochastic and geographically diffuse, their ability to match demand is determined by the adoption of one of the following two approaches [2]: the utilisation of a capture area greater than that occupied by the community to be supplied, or the reduction of the community's energy demands to a level commensurate with the locally available renewable resources. Ground source heat pump (GSHP) systems (also referred to as geothermal heat pump systems, earth-energy systems and GeoExchange systems) have received considerable attention in recent decades as an alternative energy source for residential and commercial space heating and cooling applications. The GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE [2] and include high-temperature (>150oC) for electric power production, intermediate temperature (<150oC) for direct-use applications and GSHP applications (generally (<32oC). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures.

The term "ground source heat pump" has become an inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or heat sink. GSHPs utilise the thermal energy stored in the earth through either a vertical or horizontal closed loop heat exchangers buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of GSHP systems. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore the system cost [3]. Other factors that are important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the United Kingdom space heating and cooling market [4].

The main objective of this research is to stimulate the uptake of the GSHPs. Direct expansion GSHPs are well suited to space heating and cooling and can produce significant reduction in carbon emissions. To design a GSHP system, the tools that are currently available require the use of key site-specific parameters such as temperature gradient and the thermal and geotechnical properties of the local area. Three main techniques are used to exploit the heat available are geothermal aquifers, hot dry rocks and GSHPs. Geothermal energy is the natural heat that exists within the earth and that can be absorbed by fluids occurring within, or introduced into, the crystal rocks. Although, geographically this energy has local concentrations, its distribution globally is widespread [4]. On average the amount of heat that is theoretically available between the earth's surface and a depth of 5 km is around 140 x 1024 joules [4]. Of this, only a fraction (5 x 1021 joules) can be regarded as having economic prospects within the next five decades and only about 500 x 1018 joules is likely to be exploited by the year 2020 [4].

The direct expansion (DX) GSHP installed for this study was designed taking into account the local meteorological and geological conditions. The site was at the School of the Built Environment, University of Nottingham, where the demonstration and performance monitoring efforts were undertaken. The heat pump has been fitted and monitored for one-year period. The study involved development of a design and simulation tool for modelling the performance of the cooling system, which acts a supplemental heat rejecting system using a closed-loop GSHP system.

LABORATORY MEASUREMENTS

This section describes the details of the prototype GSHP test rig, details of the construction and installation of the heat pump, heat exchanger, heat injection fan and water supply system. It also, presents a discussion of the experimental tests being carried out.

Main Experimental Test Rig

The schematic of the test rig that was used to support the two ground-loop heat exchangers is shown in Figure 1. It consisted of two main loops: heat source loop and evaporation heat pump. Three boreholes were drilled each 30 meters deep to provide sufficient energy. The closed-loop systems were laid and installed in a vertical well. The ground-loop heat exchaners were connected to the heat pump.

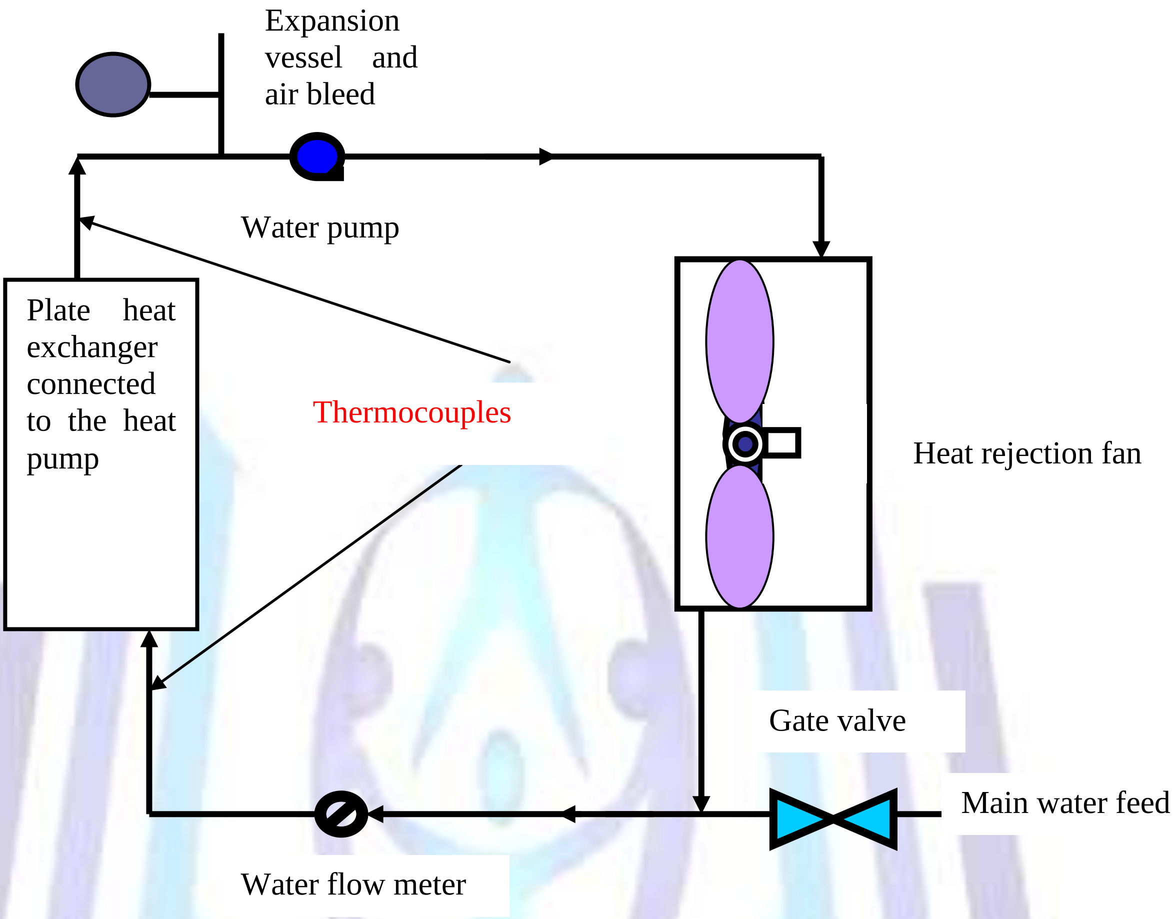

Figure 1 Sketch of installing heat pump

The experimental work undertaken was separated into three parts. The first part dealt with drilling three boreholes each 30 meter deep, digging out the pit and connection of the manifolds and preparation of coils. Holes were grouted with bentonite and sand. The pipes were laid and tested with nitrogen. Then, the pit was backfilled and the heat pump was installed. The second part was concerned with the setting up of the main experimental rig: construction and installation of the heat injection fan, water pump, expansion valve, flow meter, electricity supply, heat exchanger and heat pump. The third part was an installation of refrigerator and measurements.

Direct Expansion Heat Pump Installation

The aim of this project is to present and develop a GSHP system to provide heating and cooling for buildings (Figure 2). The heat source loop consisted of two earth loops: one for vapour and one for liquid. A refrigeration application is only concerned with the low temperature effect produced at the evaporator; while a heat pump is also concerned with the heating effect produced at the condenser.

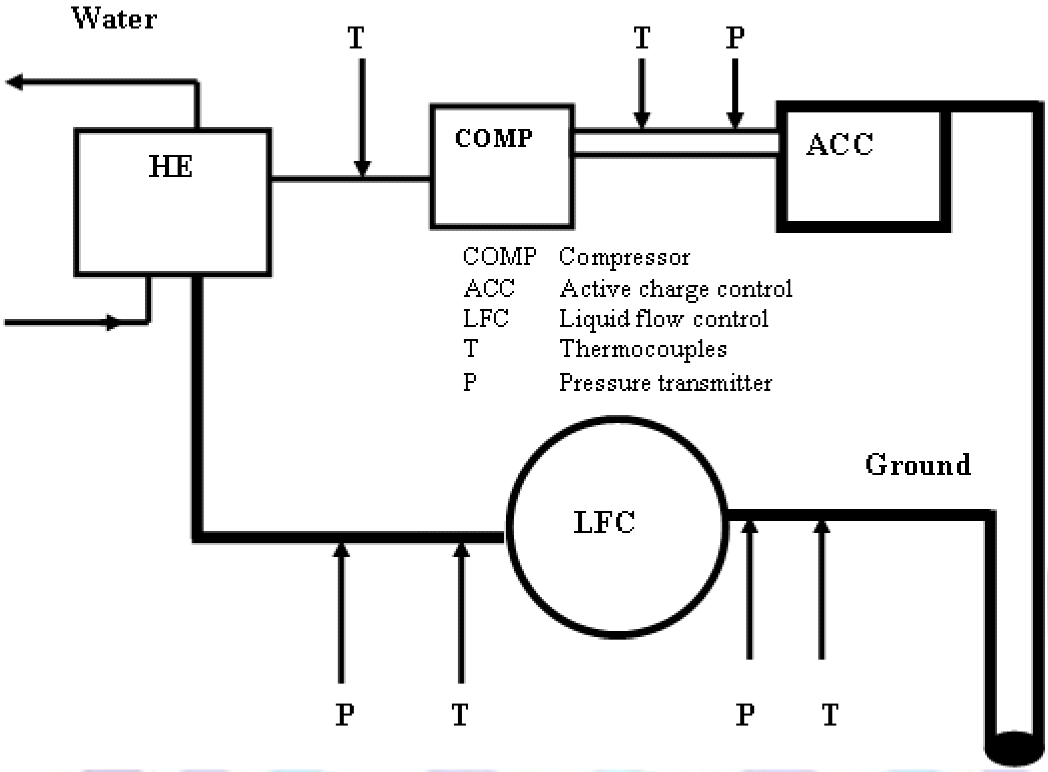

Figure 2 shows the connections of ground loops to heat pump and heat exchanger

The ground source heat pump – direct expansion was installed near the Energy Learning Centre, at the School of the Built Environment, University of Nottingham (Figures 3-4). With the help of the Jackson Refrigeration (Refrigeration and Air Conditioning engineers) the following were carried out:

- Connection of the ground loops to the heat pump
- Connection of the heat pump to the heat exchanger
- Vacuum on the system
- Charging the refrigeration loop with R407C refrigerant

Water Supply System

The water supply system consisted of water pump, boiler, water tank, flow metre and expansion valve. A thermostatically controlled water heater supplied warm water, which was circulated between the warm water supply tank and warm water storage tank using a pump to keep the surface temperature of the trenches at a desired level.

The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses to mine for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies. The theme undertakes an evaluation of heat absorption properties in the soil and carries out a performance test for a DX heat pump and a simulated operation test for the system. In fact, these policies are necessary for identifying operational performance suitable for heating and cooling, in order to obtain technical data on the heat pump system for its dissemination and maintain the system in an effort of electrification. In these circumstances, the study estimated the heat properties of the soil in the city of Nottingham and measured thermal conductivity for the soil at some points in this city, aimed at identifying applicable areas for ground source heat pump system.

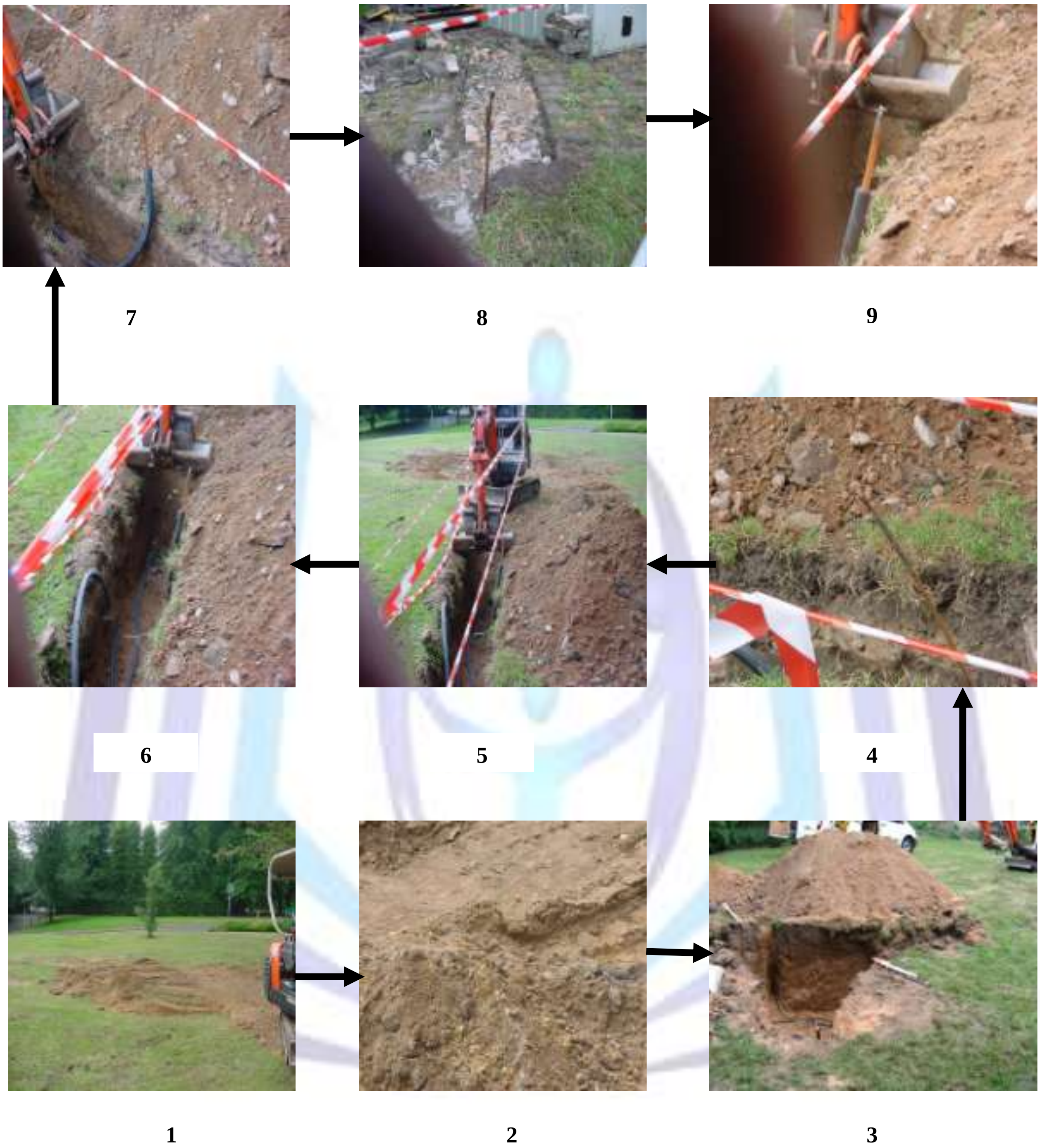

Figure 3 Showing the drilling (1-2) digging of the pit (3), connection of the manifolds (4), grouting, preparation of the coils (5-6) and the source loop, which consists of two earth loops: one for vapour and one for liquid (7-9)

Figure 4 Showing preparation of coils (1-2), installation of heat pump (3-6) and connection of water supply system (water pump, flow metre, expansion valve and the boiler) (7-9)

SOIL THERMAL PROPERTIES

One of the fundamental tasks in the design of a reliable ground source heat pump system is properly sizing the ground source heat exchanger length (i.e., depth of boreholes). Recent research efforts have produced several methods and commercially available design software tools for this purpose [5-7]. These design tools are based on principles of heat conduction and rely on some estimate of the ground thermal conductivity and volumetric specific heat. These parameters are perhaps the most critical to the system design, yet adequately determining them is often the most difficult task in the design phase.

The soil thermal measurements were carried out using KD2 Pro thermal properties analyser. The KD2 Pro is a handheld device used to measure thermal properties. The KD2 Pro is a battery-operated, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. It consists of a handheld controller and sensors inserted into the medium to be measured. The single-needle sensors measure thermal conductivity and resistivity, while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity. The thermal properties of common ground types are given in Table 1. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity.

Table 1 Typical thermal properties of soil [5-7]

Material	Conductivity ($Wm^{-1}K^{-1}$)	Specific heat ($kJkg^{-1}K^{-1}$)	Density (kgm^{-3})	Diffusivity (m^2d^{-1})
Granite	2.1-4.5	0.84	2640	0.078-0.18
Limestone	1.4-5.2	0.88	2480	0.056-0.20
Marble	2.1-5.5	0.80	2560	0.084-0.23
Sandstone				
Dry	1.4-5.2	0.71	2240	0.074-0.28
Wet	2.1-5.2			0.11-0.28
Clay				
Damp	1.4-1.7	1.3-1.7		0.046-0.056
Wet	1.7-2.4	1.7-1.9	1440-1920	0.056-0.074
Sand				
Damp		1.3-1.7		0.037-0.046
Wet*	2.1-2.6	1.7-1.9	1440-1920	0.065-0.084

* Water movement will substantially improve thermal properties

The study undertakes an evaluation of heat absorption properties in the soil and carries out a performance test for a unit heat pump and a simulated operation test for the system. In fact, these are necessary for identifying operational performance suitable for heating and cooling, in order to obtain technical data on the heat pump system. In these circumstances, the study estimated the heat properties of the soil in the city of Nottingham and measured thermal conductivity for the soil at some points in this city, aimed at identifying applicable areas for ground source heat pump system. The soil thermal conductivity, diffusivity and resistivity were measured for underground temperature. Thermo response test when a certain amount of heat was conducted into heat absorption soil. According to the measurement result, the soil thermal conductivity was observed slightly higher than the thermal conductivity estimated by the geologic columnar section. The future plan is to predict system operational performance at each observation point, based on the relationship between estimated soil thermal property and measured soil thermal conductivity. Figures 5-7 show the examples of measured and predicted soil temperatures. It is seen from the figures that temperature drops much faster for granite and slower for the coarse graveled soil either in the soil. This is mainly due to the fact coarse graveled material has a higher thermal storage capacity or lower thermal diffusivity than granite. Therefore, the high thermal energy stored found in the coarse graveled can provide longer heat extraction. Figure 8 shows summary of the soil thermal properties. It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. If bedrock is within 1.5 m of the surface or there are large boulders, it may not be possible to install a horizontal ground loop. For a vertical borehole the depth of soil will influence the cost as, in general, it is more expensive and time consuming to drill through overburden than rock as the borehole has to be cased.

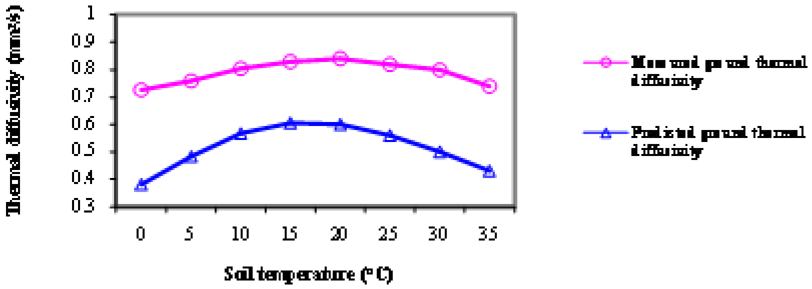

Figure 5 Measured and predicted data of soil thermal diffusivity

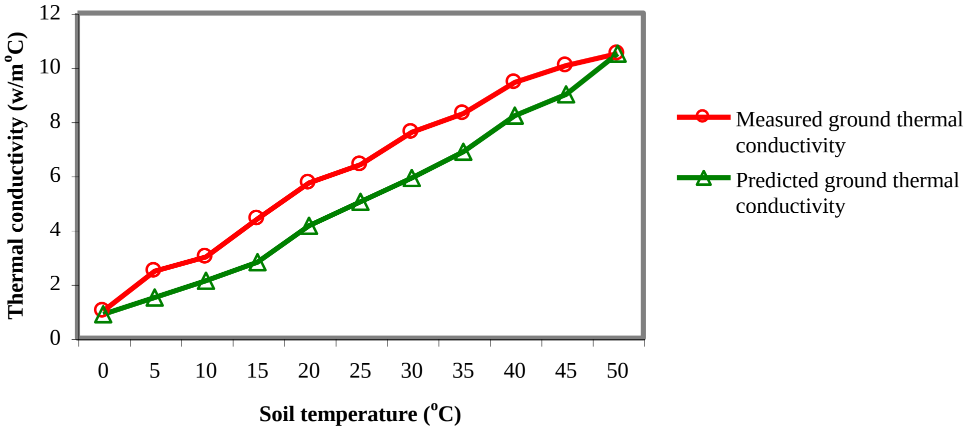

Figure 6 Measured and predicted data of soil thermal conductivity

The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10°C and 14°C depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compared to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75 m.

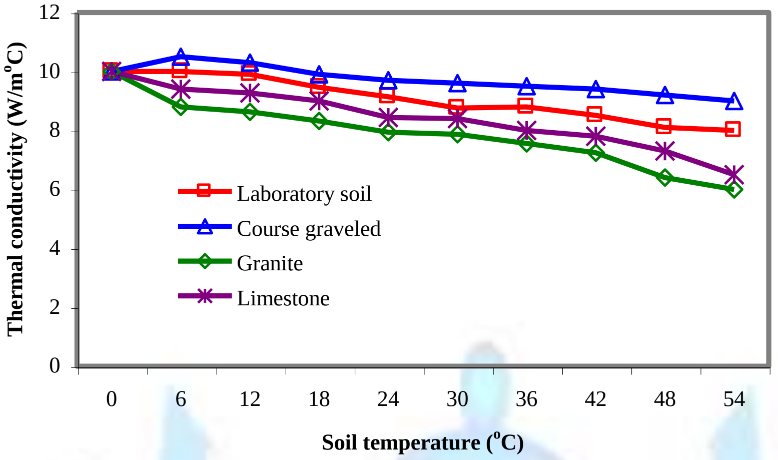

Figure 7 Comparison of measured data of soil thermal diffusivity

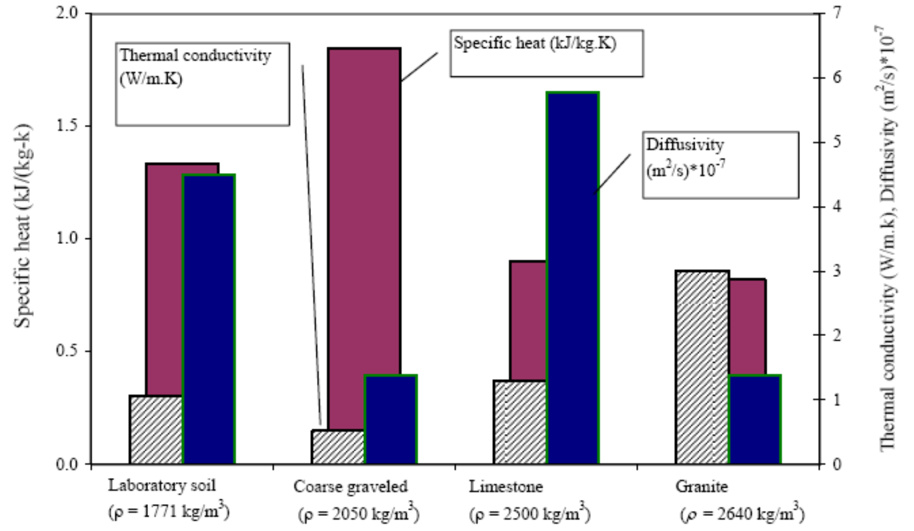

Figure 8 Comparison of soil thermal properties for different soils

GROUND TEMPERATURE

The temperature difference between the ground and the circulating fluid in the heat exchanger drives the heat transfer. So it is important to know the ground temperature. Figure 9 shows the profile of soil temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperatures at the surface. An empirical formula suggested by Eggen, 1990 [8] is:

$T_m = T_o + 0.02$ (1)

Where:

Tm is the mean ground temperature (°C)

To is the annual mean air temperature (°C)

H is the depth below the ground surface (m)

The temperature variation disappears at lower depth and below 10 m the temperature remains effectively constant at approximately the annual mean air temperature.

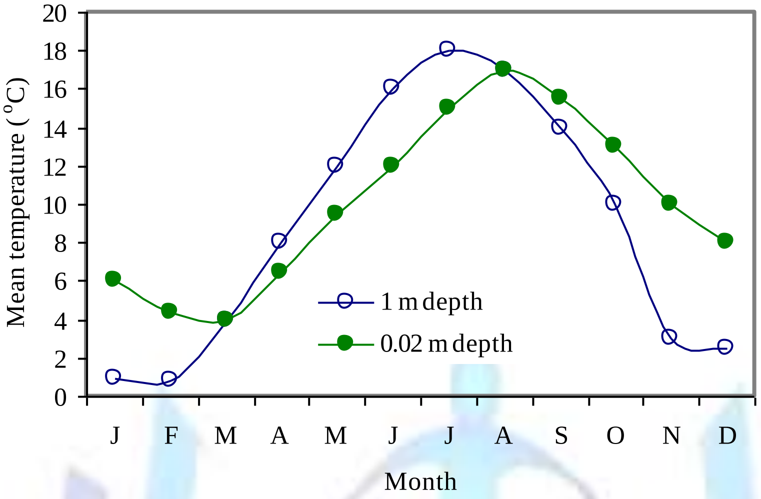

Figure 9 Seasonal variation of soil temperature at depths of 0.02 m and 1 m

It is important to maximise the efficiency of a heat pump when providing heating, not only to have a low heating distribution temperature but also to have as high a source temperature as possible. Overall efficiencies for the GSHPs are inherently higher than for air source heat pumps because ground temperatures are higher than the mean air temperature in winter and lower than the mean air temperature in summer. The ground temperature also remains relatively stable allowing the heat pump to operate close to its optimal design point whereas air temperatures vary both throughout the day and seasonally and are lowest at times of peak heating demand. For heat pumps using ambient air as the source, the evaporator coil is also likely to need defrosting at low temperatures. It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

DESIGN AND INSTALLATION

Installation of the heat pump system and especially the ground heat exchanger needs to be carefully programmed so that it does not interfere with or delay any other construction activities. The time for installation depends on soil conditions, length of pipe, equipment required and weather conditions. DX systems are most suitable for smaller domestic applications.

The most important first step in the design of a GSHP installation is accurate calculation of the building’s heat loss, its related energy consumption profile and the domestic hot water requirements. This will allow accurate sizing of the heat pump system. This is particularly important because the capital cost of a GSHP system is generally higher than for alternative conventional systems and economies of scale are more limited. Oversizing will significantly increase the installed cost for little operational saving and will mean that the period of operation under part load is increased. Frequent cycling reduces equipment life and operating efficiency. Conversely if the system is undersized design conditions may not be met and the use of top-up heating, usually direct acting electric heating, will reduce the overall system efficiency. In order to determine the length of heat exchanger needed to piping material. The piping material used affects life; maintenance costs, pumping energy, capital cost and heat pump performance.

HEAT PUMP PERFORMANCE

The performance of the heat pump depends on the performance of the ground loop and vice versa. It is therefore essential to design them together. Closed-loop GSHP systems will not normally require permissions/authorisations from the environment agencies. However, the agency can provide comment on proposed schemes with a view to reducing the risk of groundwater pollution or derogation that might result. The main concerns are:

- Risk of the underground pipes/boreholes creating undesirable hydraulic connections between different water bearing strata.
- Undesirable temperature changes in the aquifer that may result from the operation of a GSHP.
- Pollution of groundwater that might occur from leakage of additive chemicals used in the system.

Efficiencies for the GSHPs can be high because the ground maintains a relatively stable temperature allowing the heat pump to operate close to its optimal design point. Efficiencies are inherently higher than for air source heat pumps because the air temperature varies both throughout the day and seasonally such that air temperatures, and therefore efficiencies, are lowest at times of peak heating demand.

A heat pump is a device for removing heat from one place - the ‘source’ - and transferring it at a higher temperature to another place. The heat pumps consist of a compressor, a pressure release valve, a circuit containing fluid (refrigerant), and a pump to drive the fluid around the circuit. When the fluid passes through the compressor it increases in temperature. This heat is then given off by the circuit while the pressure is maintained. When the fluid passes through the relief valve the rapid drop in pressure results in a cooling of the fluid. The fluid then absorbs heat from the surroundings before being re-compressed. In the case of domestic heating the pressurised circuit provides the heating within the dwelling. The depressurised component is external and, in the case of ground source heat pumps, is buried in the ground. Heat pump efficiencies improve as the temperature differential between ‘source’ and demand temperature decreases, and when the system can be ‘optimised’ for a particular situation. The relatively stable ground temperatures moderate the differential at times of peak heat demand and provide a good basis for optimisation.

The refrigerant circulated directly through the ground heat exchanger in a direct expansion (DX) system but most commonly GSHPs are indirect systems, where a water/antifreeze solution circulates through the ground loop and energy is transferred to or from the heat pump refrigerant circuit via a heat exchanger. This application will only consider closed loop systems. The provision of cooling, however, will result in increased energy consumption and the efficiently it is supplied. The GSHPs are particularly suitable for new build as the technology is most efficient when used to supply low temperature distribution systems such as underfloor heating. They can also be used for retrofit especially in conjunction with measures to reduce heat demand. They can be particularly cost effective in areas where mains gas is not available or for developments where there is an advantage in simplifying the infrastructure provided.

Heat pump technology can be used for heating only, or for cooling only, or be ‘reversible’ and used for heating and cooling depending on the demand. Reversible heat pumps generally have lower COPs than heating only heat pumps. They will, therefore, result in higher running costs and emissions. Several tools are available to measure heat pump performance. The heat delivered by the heat pump is theoretically the sum of the heat extracted from the heat source and the energy needed to deliver the cycle. Figure 10 shows the variations of temperature with the system operation hours. Several tools are available to measure heat pump performance. The heat delivered by the heat pump is theoretically the sum of the heat extracted from the heat source and the energy needed to derive the cycle. For electrically driven heat pumps the steady state performance at a given set of temperatures is referred to as the coefficient pf performance (COP). It is defined as the ration of the heat delivered by the heat pump and the electricity supplied to the compressor:

$$\text{COP} = \text{heat output } (\text{kW}_{\text{th}})/\text{electricity input } (\text{kW}_{\text{el}}) \qquad (2)$$

For an ideal heat pump the COP is determined solely by the condensation temperature and the temperature lift:

$$\text{COP} = \text{condensing temperature } (^{o}\text{C})/\text{temperature lift } (^{o}\text{C}) \qquad (3)$$

Figure 11 shows the COP of heat pump as a function of the evaporation temperature. Figure 12 shows the COP of heat pump as a function of the condensation temperature. As can be seen the theoretically efficiency is strongly dependent on the temperature lift. It is important not only to have as high a source temperature as possible but also to keep the sink temperature (i.e., heating distribution temperature) as low as possible. The achievable heat pump efficiency is lower than the ideal efficiency because of losses during the transportation of heat from the source to the evaporator and from the condenser to the room and the compressor. Technological developments are steadily improving the performance of the heat pumps.

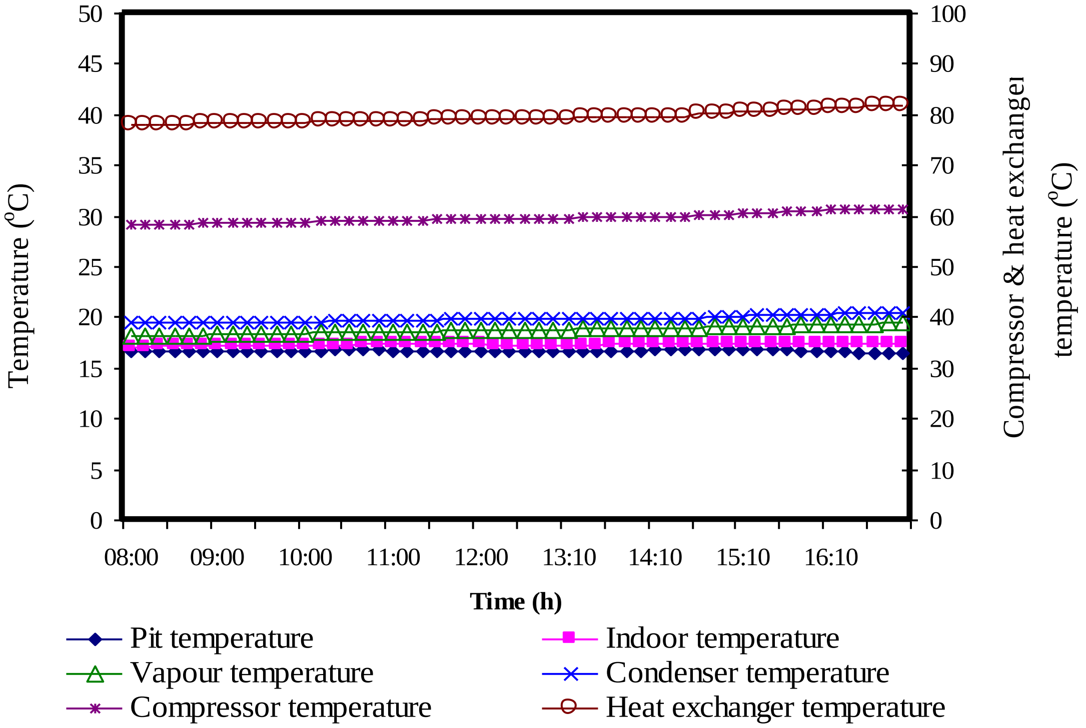

Figure 10 Variation of temperatures per day for the DX system

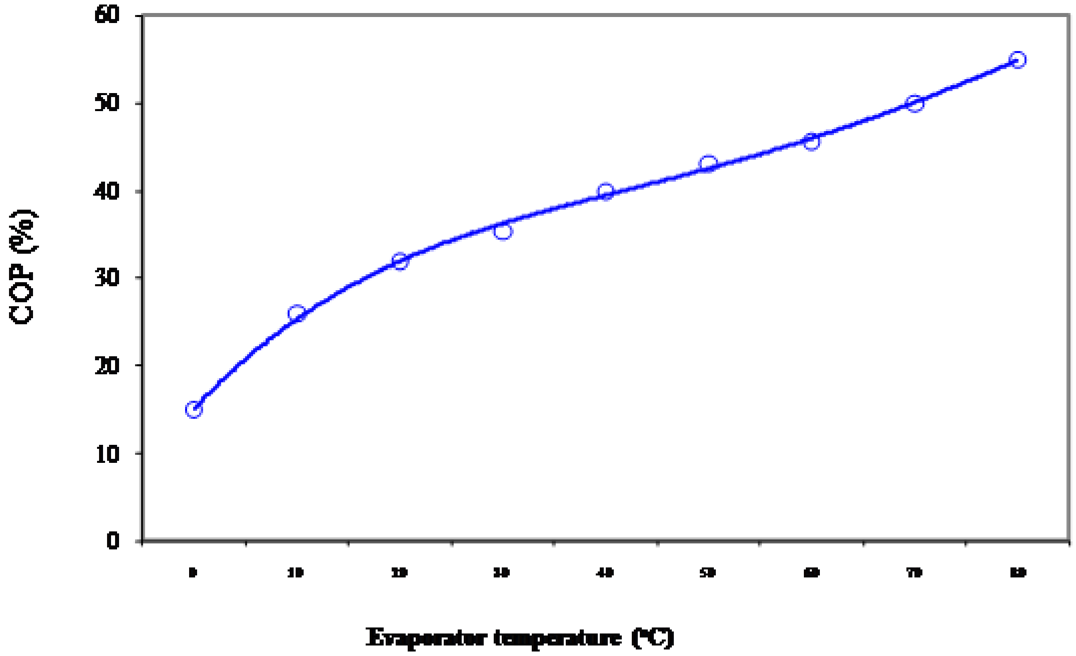

Figure 11 Heat pump performance vs evaporation temperature

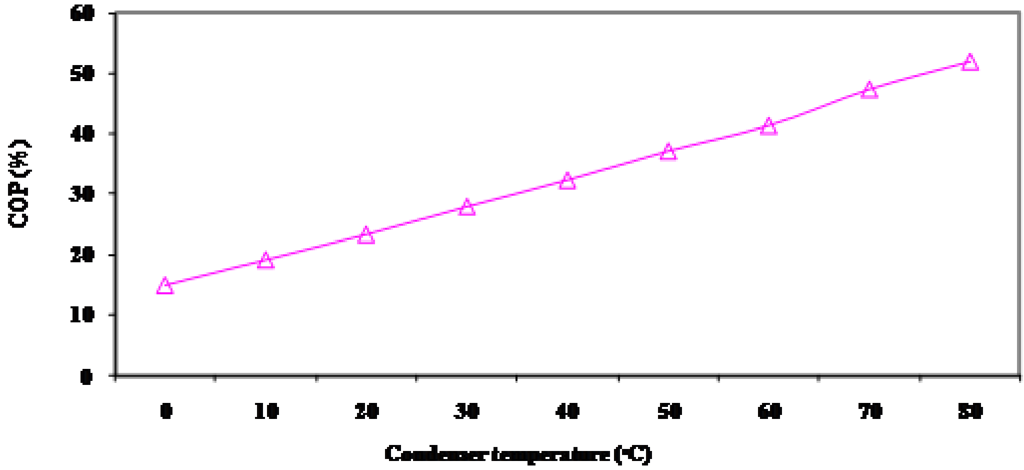

Figure 12 Heat pump performance vs condensation temperature

ECONOMICS

The discounted payback period (DPP) is a method of comparing alternative investments or for evaluating a single investment in payback analysis. Payback period is the time required for the total accumulated savings or benefits of a system to offset investment costs. Since the time value of money must be considered in payback computations, all the costs must be discounted to calculate the discounted payback period. Payback is achieved when the total accumulated present value (PV) savings are enough to offset the total PV costs of an alternative. The discounted payback period is simply the total elapsed time between the point when the savings begin to accrue and the point at which payback will occur. Figure 13 shows the discounted payback period of the combination of GSHP and gas heating system about 5.5 years for electric heater heating system and 25 years comparing gas-fired condensing boiler system.

However, in terms of the number of year of discounted payback period, the combined GSHP and gas heating system is less attractive compared with an electric heater heating system and gas-fired condensing boiler, with the payback period of 5.5 years and 25 years respectively.

Table 2 Costs of the ground source system compared with alternatives

System	Capital cost installed (£)	Energy consumed (kWh)	Annual running cost (£)
Ground source heat pump	**1800**	**7825**	**420**
All electric2 (efficiency 100%)		**18690**	**545-1100**
Regular oil-fired boiler (efficiency 70%)	**1280**	**26686**	**380**
Regular oil-fired boiler (efficiency 79%)		**23646**	**340**
Gas-fired condensing boiler (efficiency 85%)		**21976**	**365**

The choice of horizontal or vertical system depends on the land area available, local ground conditions and excavation costs. As costs for trenching and drilling are generally higher than piping costs it is important to maximise the heat extraction per unit length of trench/borehole. The piping material used affects life, maintenance costs, pumping energy, capital cost and heat pump performance. Both gas-fired and oil-fired systems are likely to have higher annual servicing costs than those for the heat pump system (Table 2). The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. This would improve both the economics and the environmental performance of the system. More generally, there is still potential for improvement in the performance of heat pumps and seasonal efficiencies for DX GSHPs. It is also likely that unit costs will fall as production volumes increase. GSHPs can provide an energy-efficient, cost-effective way to heat and cool building facilities.

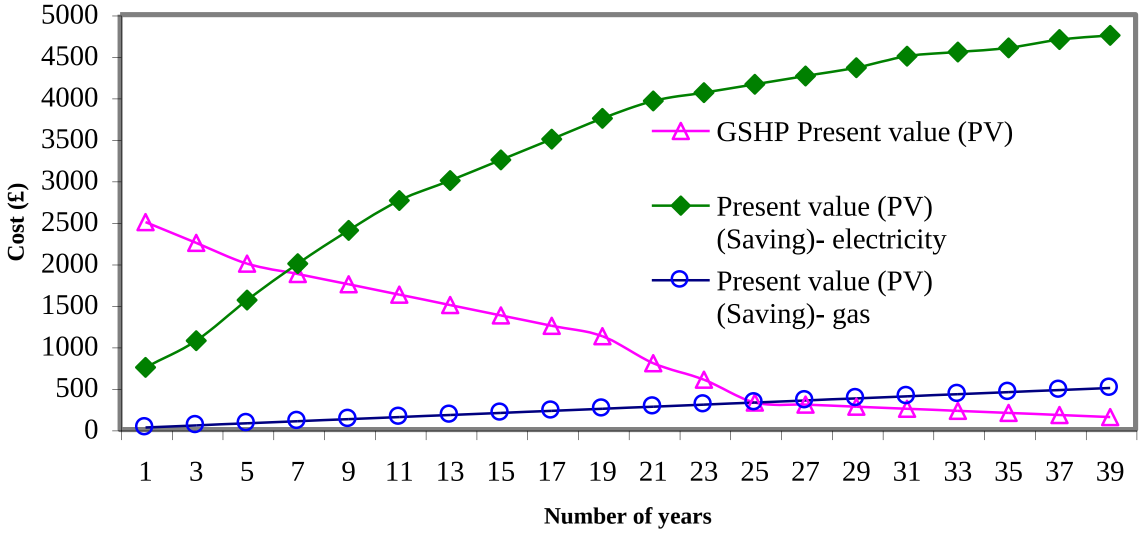

Figure 13 Comparison of present values of different energy sources

Conclusions

Direct expansion (DX) ground source heat pump (GSHP) system are known to perform very well throughout the year mainly because of the constant nature of the earth temperature. Despite of the apparent advantages of DX GSHPs, at present geothermal energy makes a very small, but locally important, to the world energy requirements. The main barriers that restrict a wider uptake of the technology appear to be the lack of awareness of the benefit of the technology and high capital cost. The shortage of manufacturers, suppliers and installers are also among the barriers. It is likely that this situation will continue unless these problems are tackled. Direct expansion (DX) ground source heat pump (GSHP) system suitable for provision of heating and cooling for buildings have been investigated. The research efforts have been directed towards finding of environmentally acceptable replacement refrigerants and optimisation of the heat pump system. Considerable improvement in system performance has been achieved as a result of this optimisation.

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