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Full Length Research Paper

ENVIRONMENTALLY FRIENDLY SYSTEMS: EARTH HEAT PUMP SYSTEM WITH VERTICAL PIPES FOR HEAT EXTRACTION FOR DOMESTIC HEATING AND COOLING

Abdeen Mustafa Omer

Energy Research Institute, (ERI), Nottingham, UK
Email: abdeenomer2@yahoo.co.uk

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Aims/Purpose: The purpose of this study, however, is to contribute to the reduction of energy consumption in buildings, identify GSHPs as an environmental friendly technology able to provide efficient utilisation of energy in the buildings sector, promote using GSHPs applications as an optimum means of heating and cooling, and to present typical applications and recent advances of DX GSHPs. Study design: The main concept of this technology is that it utilises the lower temperature of the ground (approximately <32°C), which remains relatively stable throughout the year, to provide space heating, cooling and domestic hot water inside the building area. The main goal of this study is to stimulate the uptake of the GSHPs. Recent attempts to stimulate alternative energy sources for heating and cooling of buildings has emphasised the utilisation of the ambient energy from ground source and other renewable energy sources. Place and Duration of Study: Energy Research Institute (ERI), between November 2011 and March 20112. Methodology/Approach: This paper highlights the potential energy saving that could be achieved through use of ground energy source. It also focuses on the optimisation and improvement of the operation conditions of the heat cycles and performances of the direct expansion (DX) GSHP. Results/Findings: It is concluded that the direct expansion of GSHP are extendable to more comprehensive applications combined with the ground heat exchanger in foundation piles and the seasonal thermal energy storage from solar thermal collectors. Originality/Value: The study highlighted the potential energy saving that could be achieved through the use of ground energy sources. It also focuses on the optimisation and improvement of the operation conditions of the heat cycle and performance of the DX GSHP. It is concluded that the direct expansion of GSHP, combined with the ground heat exchanger in foundation piles and the seasonal thermal energy storage from solar thermal collectors, is extendable to more comprehensive applications.

Keywords: Direct expansion GSHPs, ground source, development and evaluation of the system.

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, NO_x 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 (Riffat, Boukhanouf, and Srivastava, 2002). 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 (ASHRAE, 1995): 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, 1995) and include high-temperature (>150^{o}C) for electric power production, intermediate temperature (<150^{o}C) for direct-use applications and GSHP applications (generally (<32^{o}C). 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 (Kavanaugh, and Rafferty, 1997). 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 (Austin, Yavuzturk, and Spitler, 2000).

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.

The most important first step in the design of a GSHP installation is the calculation of the building's heat load, 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 installation cost for little operational saving and will mean that the period of operation under part load is increased. Frequent cycling, on the other hand, 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.

Heat pumps work on a similar principle to domestic refrigerators, extracting heat from one source and transferring it to another. A key ingredient in the heat pump is the refrigerant in its coils, usually a substance called Freon, which vaporises into a gas at a boiling point far lower than the 100ºC that water requires to boil. When the refrigerant boils, it changes from a liquid to a gas, absorbing heat from its surroundings. As the refrigerant changes back into liquid form it gives up its heat to the surrounding atmosphere. An expansion valve and an electric compressor control this process of transformation from liquid to gas and back again.

RESULTS AND DISCUSSIONS

Figures 2 shows summary result of the data collected, at specific periods of the tests. Temperature T_1, T_2, T_3, T_4, T_5 and T_6 shown in Figure 2 indicates Heat exchanger temperature out let, compressor temperature, condenser temperature, vapour temperature, indoor temperature, and pit temperature respectively.

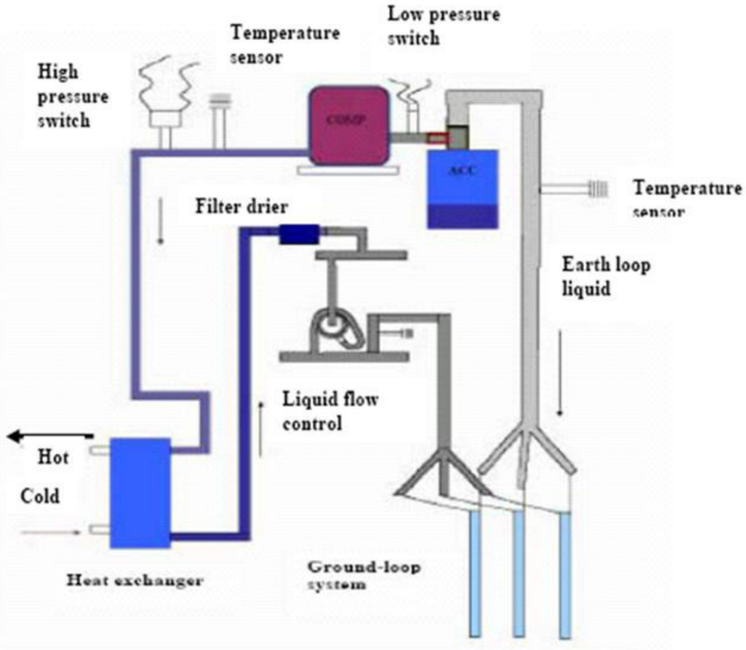

Figure 1. The whole heat pump system installation

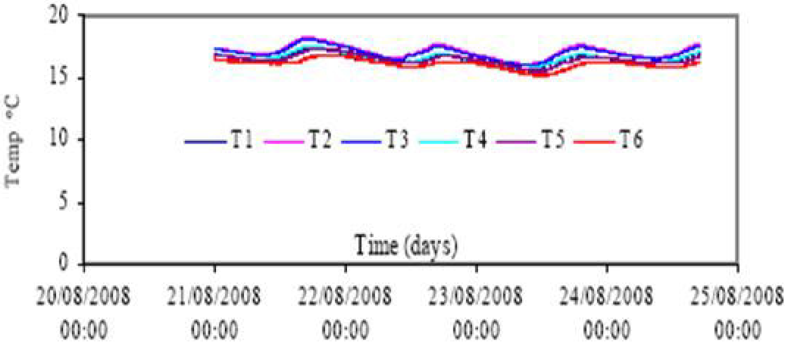

Figure 2. Variation of temperatures per 6 days for the GSHP system

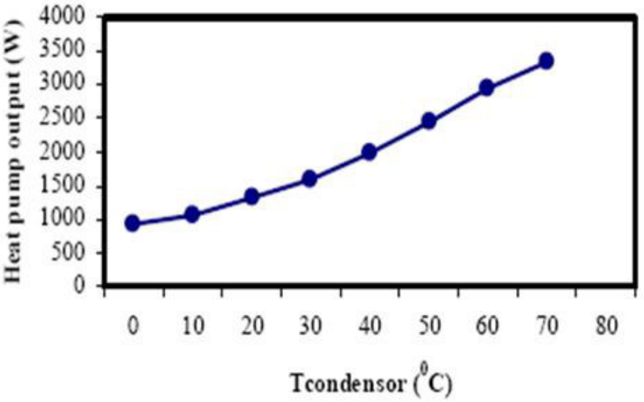

Figure 3. Variation of heat pump output with condenser temperature

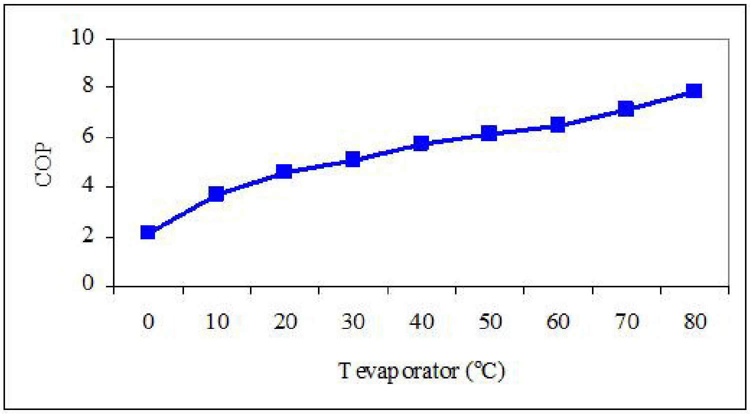

Figure 4. Heat pump performance vs evaporation temperature (°C)

The performance of the heat pump is inversely proportional to the difference between the condensation temperature and the evaporation temperature (the temperature lift). These are stable operating conditions, but not true steady state conditions. At output temperatures greater than 40°C, the heat pump was providing heating to the domestic hot water. The variation is largely due to variations in the source temperatures (range 0.2°C to 4.3°C). These results indicate that the system performance meets the specified rating for the heat pump of 2.5 kW at an output temperature in the range of 45 (older systems) and 65°C (newer systems).

Heat pump performance

The performance of the heat pump depends on the performance of the ground loop and vice versa. Some of the factors that may affect performance of GSHP include:

- The underground pipes/boreholes may create undesirable hydraulic connections between different water bearing strata.
- Undesirable temperature changes in the aquifer that may result from the operation of a GSHP.
- Other issue that may need to be taken into consideration is the pollution of groundwater that might occur from leakage of additive chemicals used in the system.

Efficiencies of 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. In contrary in air source heat pumps, 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. 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 is 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 efficiency it is supplied with.

For electrically driven heat pumps the steady state performance at a given set of temperatures could be assessed in terms of the coefficient of performance (COP). It is defined as the ratio of the heat delivered by the heat pump and the electricity supplied to the compressor (Eggen, 1990):

$$COP = [\text{heat output } (kW_{th})] / [\text{electricity input } (kW_{el})] \quad (1)$$

Figure 3 shows the daily total space heating from the heat pump and the auxiliary heater for the two heating control systems.

Figure 4 shows the COP of heat pump as a function of the evaporation temperature. As can be seen, the theoretical measured 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. In practice, the achievable heat pump COP is lower than the ideal COP because of losses during the transportation of heat from the source to the evaporator and from the condenser to the room and the compressor. However, technological developments are steadily improving the performance of the heat pumps.

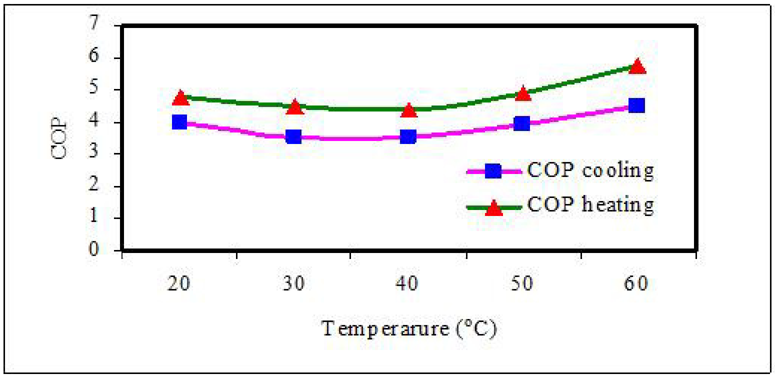

Figure 5. COP Vs condenser temperatures for different applications (°C)

Figures 5 shows COP of the ground source heat pump for different applications, and show that this increases slightly with condenser temperatures. As expected, the achievable COP is lower in cooling mode than in heating mode.

Over its first year of operation, the ground source heat pump system has provided 91.7% of the total heating requirement of the room and 55.3% of the domestic water-heating requirement, although only sized to meet half the design-heating load. The heat pump has operated reliably and its performance appears to be at least as good as its specification. The system has a measured annual performance factor of 3.16. The system is quiet and unobtrusive and achieved comfort levels.

Additionally, the heat pump did not reduce the useful space in the laboratory, and there are no visible signs of the installation externally (no flue, vents, etc.). However, the performance of the heat pump system could also be improved further by eliminating unnecessary running of the integral distribution pump. It is estimated that reducing the running time of this pump, which currently runs virtually continuously, would increase the overall performance factor to 3.43. This would improve both the economics and the environmental performance of the system. More generally, there is still a potential for improvement in the performance of the heat pump, and seasonal efficiency for ground source heat pumps of 4.0 might be possible. It is also likely that unit cost will fall as production volumes increase.

Air conditioning systems are an example of an air-to-air heat pump. They are becoming increasingly prevalent, particularly because new cars are often fitted with air conditioning systems and people are beginning to ask for more controlled internal environments. However in the UK, the need for air conditioning is often a result of overheating because of unsatisfactory shading and poor natural ventilation. Every attempt should be made to design buildings, which do not require air conditioning, because of the additional energy load required.

Thermal Behaviour

From equation (2), it can be inferred that the wave amplitude decreases exponentially with depth (Freeze, and Cherry, 1981):

$$A_x = A_s e^{-x}\sqrt{\frac{\Pi}{365\alpha}} \quad (2)$$

Where:
A_x is the thermal wave amplitude at the depth x (°C)
In addition, the phase lag decreases linearly with the depth.

$$t\text{-}t_o = ½ \sqrt{\frac{365}{\alpha\Pi}}x \quad (3)$$

The equations (2 and 3) can be used to deduce that the ground temperature at any depth depends on the surface temperature of the soil (mean temperature and amplitude) and of the physical properties of the soil profile: conductivity (k), density (ρ) and specific heat (c), grouped in the apparent thermal diffusivity (α) considering a homogenous soil (Fetter, 1981):

$$\alpha = k/\rho c \quad (4)$$

Thus, the soil properties and depth determine the damping and the phase lag of the temperature wave. The greater the depth to which the pit is excavated and the lower the apparent thermal diffusivity of the soil, the greater the stability inside it and the less the external variations will be perceived. Figures 6-.9 are examples in which it can be seen how temperature varies with the depth and thermal diffusivity of an ideal surface temperature of 12°C, annual amplitude of 10°C and phase lag of 20 days.

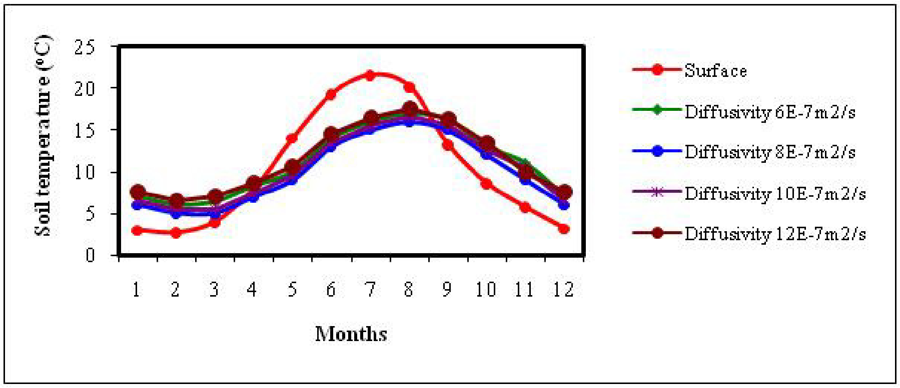

Figure 6. Temperature of ground at depth 1 m for different thermal diffusivity

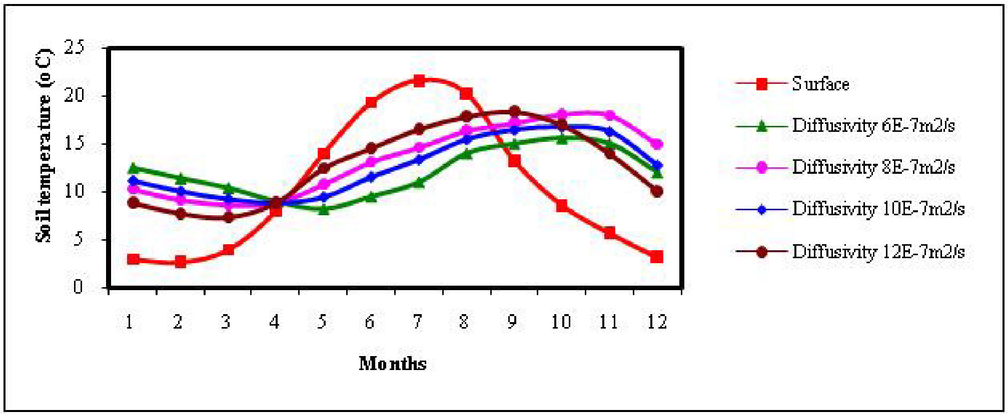

Figure 7. Temperature of ground at depth 3 m for different thermal diffusivity

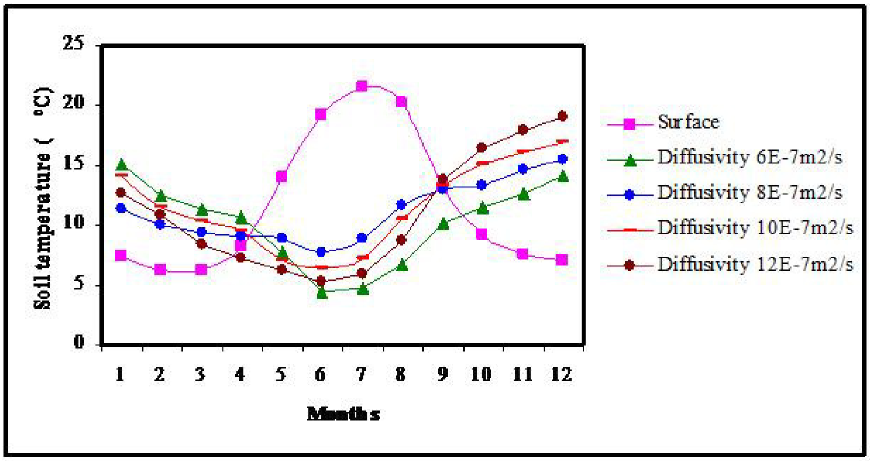

Figure 8. Temperature of ground at depth 5 m for different thermal diffusivity

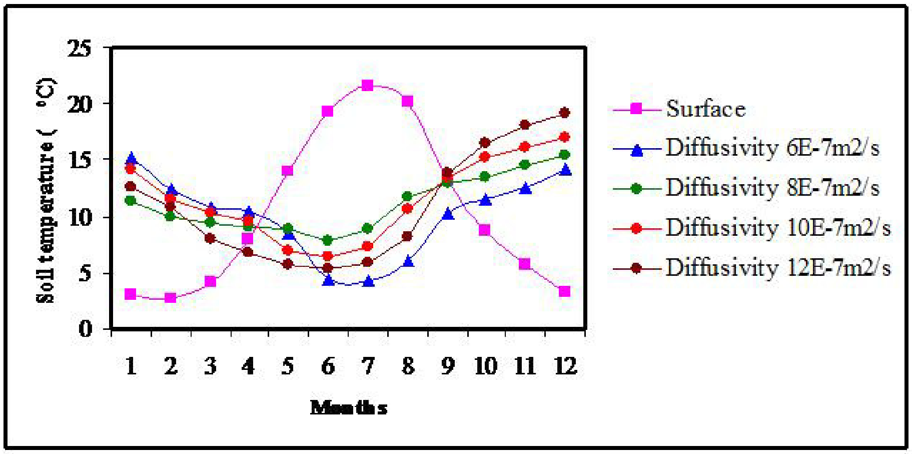

Figure 9. Temperature of ground at depth 7 m for different thermal diffusivity

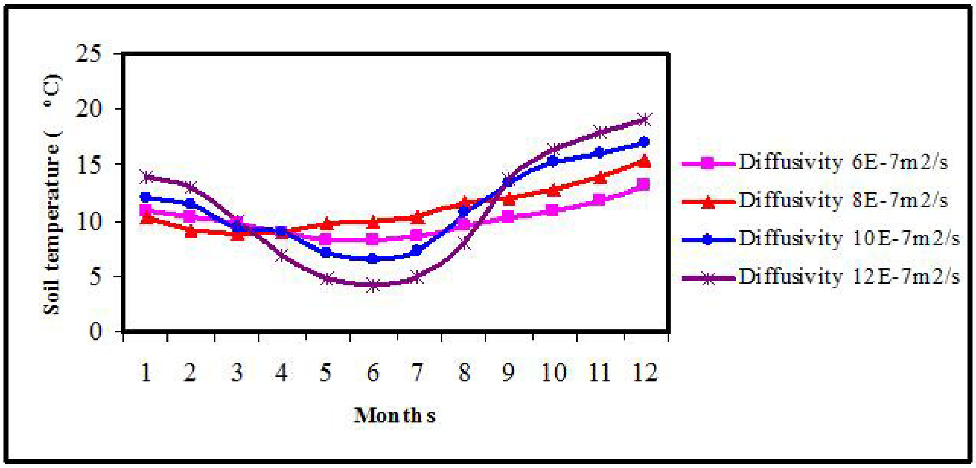

Figure 10.Temperature of ground at depth 9 m for different thermal diffusivity

There are a number of different methods to heat a building using geothermal energy:

- Groundwater GSHP, of which there are two variations, open loop and closed loop. An open loop groundwater GSHP supplies ground water directly to each heat pump and then returns the well water to the source. This system is normally not recommended because of fouling and corrosion concerns. The closed loop uses an isolation plate and frame heat exchanger between the ground water and the building water loop.
- Surface-water GSHP, which uses multiple heat exchangers made from spooled plastic pipe submerged in a body of surface water and connected to the building heat pumps.
- Ground heat exchanger GSHP, which relies on a ground-coupled heat exchanger installed either horizontally in trenches or as “U” tubes in vertical bores.

As well as damping the amplitude and phase lag of temperature wave, the oscillations also reduce with depth although this effect is not shown in equation 3. Figures 10-11 show experimental data of the ground temperature, where it can be seen how the daily variations recorded decrease as depth increases. The stability of earth temperatures with respect to daily cycles and the phase lag of the annual wave make the ground a useful heat source in winter and a means of cooling in summer.

$$T(x,t)=(T_m-k)\,A_s e^{-x}\sqrt{\frac{\Pi}{365\alpha}}\cos\left[\frac{2\Pi}{365}\left(t-t_o-\frac{x}{2}\sqrt{\frac{365}{\Pi\alpha}}\right)\right]$$

(5)

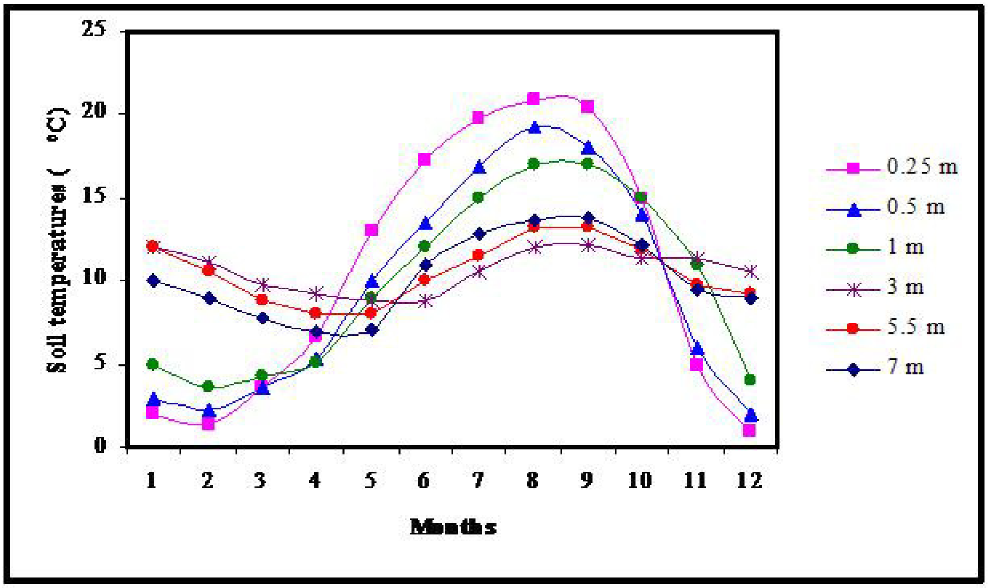

Figure 11. Experimental soil temperatures at various depths

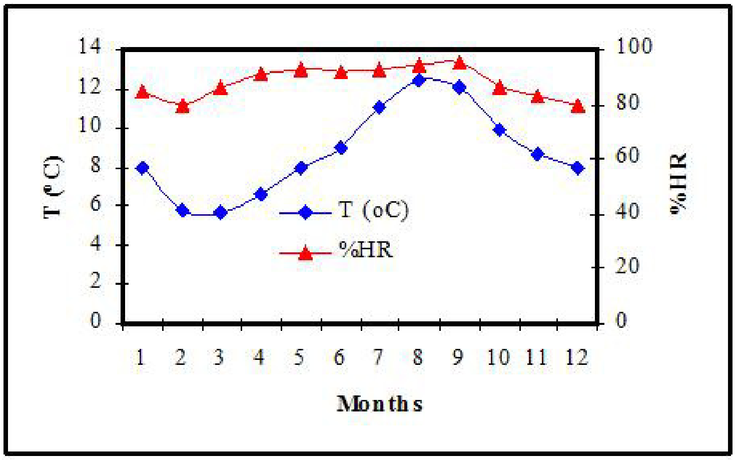

Figure 12. Experimental temperature and relative humidity values for the air inside the pit at an average depth of 3 m

The measured temperatures of the ground loops start at the winter – 14°C are the mixed output of all ground loops (situated at 1 m and 1.7 m and two levels in between) as shown in Figures 12. The surface temperature from 2 m onwards the recorded temperatures for the more recent set of measurements were slightly lower than those from the earlier, whilst the 1m measurement was higher. This suggests that the surface temperature may have an influence, probably through conduction within the copper pipe, on the temperature recorded at the first metre depth, but that this effect becomes negligible at lower depths.

There are lots of disturbing factors affecting measurements. Surface topography, vegetation and hydrological conditions affect also to the subsurface temperature. Below surface the temperature profile is being disturbed by changes in groundwater conditions. From the measurements it has been found out that daily variation of surface temperature can be seen in the depth of 2 meters and annual variation of surface temperature can be seen in the depth of 20 meters. Rapid temperature changes are therefore not conveyed very deep so the temperature reconstructions from boreholes do not show rapid temperature changes, but they show how the temperature has varied during decades and centuries.

The ground source heat pump (GSHP) systems have been identified as one of the best sustainable energy technologies for space heating and cooling in residential and commercial buildings. The GSHPs for building heating and cooling are extendable to more comprehensive applications and can be combined with the ground heat

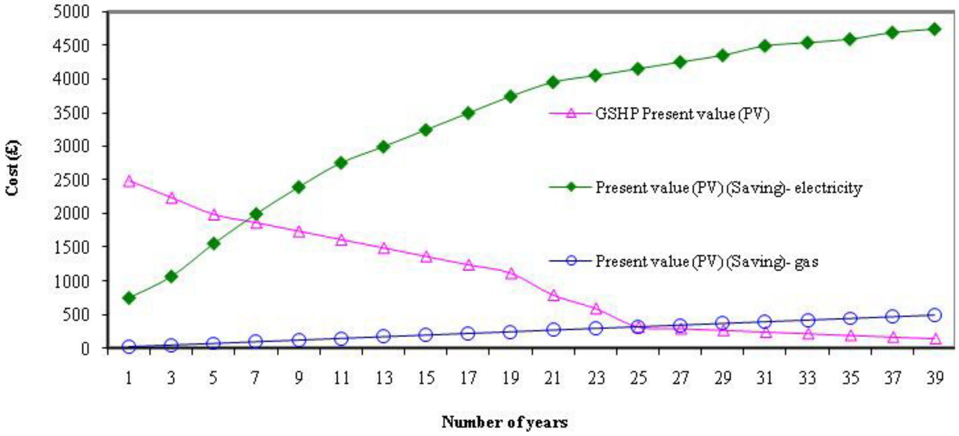

Figure 13. Comparison of present values of different energy sources

exchanger in foundation piles as well as seasonal thermal energy storage from solar thermal collectors. 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 and are not recommended as an energy-efficient heating option. The GSHP system can provide 91.7% of the total heating requirement of the building and 55.3% of the domestic water-heating requirement, although only sized to meet half the design-heating load. The heat pump can operate reliably and its performance appears to be at least as good as its specification. The system has a measured annual performance factor of 3.16. The heat pump system for domestic applications could be mounted in a cupboard under the stairs and does not reduce the useful space in the house, and there are no visible signs of the installation externally (no flue, vents, etc.).

The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. It is estimated that reducing the running time of this pump, which currently runs virtually continuously, would increase the overall performance factor to 3.43. 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 ground source heat pumps of 4.0 are being achieved. It is also likely that unit costs will fall as production volumes increase. By comparison, there is little scope to further improve the efficiency of gas- or oil-fired boilers. The need for alternative low-cost energy has given rise to the development of GSHP systems for space cooling and heating in residential and commercial buildings. GSHP systems work with the environment to provide clean, efficient and energy-saving heating and cooling the year round. GSHP systems use less energy than alternative heating and cooling systems, helping to conserve the natural resources. GSHP systems do not need large cooling towers and their running costs are lower than conventional heating and air-conditioning systems. As a result, GSHP systems have increasingly been used for building heating and cooling with an annual rate of increase of 10% in recent years.

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.

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. 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 (Isiorho, and Meyer, 1999).

CONCLUSIONS

The installation and operation of a geothermal system may be affected by various factors. These factors include, but are not limited to, the field size, the hydrology of the site the thermal conductivity and thermal diffusivity of the rock formation, the number of wells, the distribution pattern of the wells, the drilled depth of each well, and the building load profiles. 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.

The results of soil properties investigation have also demonstrated that the moisture content of the soil has a significant effect on its thermal properties. When water replaces the air between particles it reduces the contact resistance. Consequently, the thermal conductivity varied from 0.25 W/m/K for dry soil to 2.5 W/m/K for wet soil. However, the thermal conductivity was relatively constant above a specific moisture threshold. In fact, where the water table is high and cooling loads are moderate, the moisture content is unlikely to drop below the critical level. In Nottingham, where the present study was conducted, soils are likely to be damp for much of the time. Hence, thermal instability is unlikely to be a problem. Nevertheless, when heat is extracted, there will be a migration of moisture by diffusion towards the heat exchanger and hence the thermal conductivity will increase.

Long measurements have shown that, the net energy exchange in the soil after one year of operation was only 3% of the total cold energy charged. This shows that there was no acute soil temperature change after the whole year operation of the GSHP system. Therefore, the system is feasible technically and the operation mode is reasonable.

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