

Thermal Performance of Heat Exchangers for a Rainwater-Ground Source Heat Pump

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Abstract: This paper presents the results of experimental measurements of the performance of two types of heat exchanger-solid bars and heat pipes for a heat pump designed to make use of rainwater and ground as heat sources/sinks. A refrigerant was circulated through a closed loop of copper pipe to transfer heat between the heat pump and rainwater in a storage tank and the heat exchanger to transfer heat between the stored rainwater and surrounding soil. Tests were conducted under controlled laboratory conditions. Physical and thermal properties of soil such as water content, density, thermal diffusivity, specific heat and thermal conductivity were determined. Numerical simulations were also carried out for a rainwater storage tank installed under ground for a typical domestic application with different operating conditions of the heat pump.

Keywords: Ground-source heat pump; heat exchanger; rainwater storage

1. INTRODUCTION

Buildings account for approximately 40% of the total energy consumption in the developed countries. With the increasing concern over global warming due to CO₂ emissions from the use of fossil fuels, efforts are being made to develop energy efficient and environmentally friendly systems. Ground-source heat pumps (GSHPs), which make use of earth of ground water as the heat source or sink often through borehole heat exchangers, are suitable for heating and cooling of buildings and so could play a significant role in reducing CO₂ emissions. The main benefit of using GSHPs is that the temperature of the subsurface is not subject to large variations experienced by air, currently the most common thermal energy source for heat pumps, and so would allow construction of more efficient systems with superior performance. GSHPs do not need large cooling towers and their running costs are lower than conventional heating and air conditioning systems. There were about 800,000 GSHP installations worldwide by 2003, with an annual rate of increase of 10%^[1]. Most of the installations are found in the USA and Europe. In the UK, there are only a few hundred installations^[2]. One of the barriers to the wider use of GSHPs in the UK is the cost of drilling deep boreholes for the installation of ground heat exchanger loops. However, this obstacle could be overcome by making use of a rainwater collection system that employs underground storage tanks. The maximum excavation depth required for installing these tanks is only 2 to 3 m. This could be accomplished using ordinary excavators rather than specialised drilling machines required for deep boreholes.

Collection of rainwater for use in buildings has been practised since ancient times. Rainwater has a number of advantages over the mains water supply. For example, it is soft water and so eliminates the problems associated with hard water. Collection of rainwater also reduces loading on watercourses during rainfall and encourages conservative use of water. In a typical modern application, rainwater collected from the roof of a building is filtered and then stored in storage tanks^[3]. Water stored in this way could be a suitable energy source for heat pumps. The dual use of rainwater as a supplementary water supply and as a heat transfer medium would enhance the economic viability of GSHPs.

Over the last 20 years, investigations into GSHPs have been focussed on borehole heat exchangers resulting in well-established design and installation procedures. Research into the use of rainwater as a heat transfer medium for GSHPs has not previously been carried out. This research aims to develop a GSHP system utilising rainwater as a heat source/sink by employing a heat exchanger integrated into a water storage tank. Deployment of the system would reduce the need for heating/cooling of buildings as well as mains water supply and so reduce energy costs and CO₂ emissions.

2. LABORATORY TESTING OF A RAINWATER-GSHP PROTOTYPE SYSTEM

A rainwater-GSHP prototype system was designed and constructed for laboratory testing under controlled conditions. Fig. 1 shows the schematic diagram of the test rig. A thermostatically controlled water heater supplied hot water which was circulated between the hot water supply tank and hot water

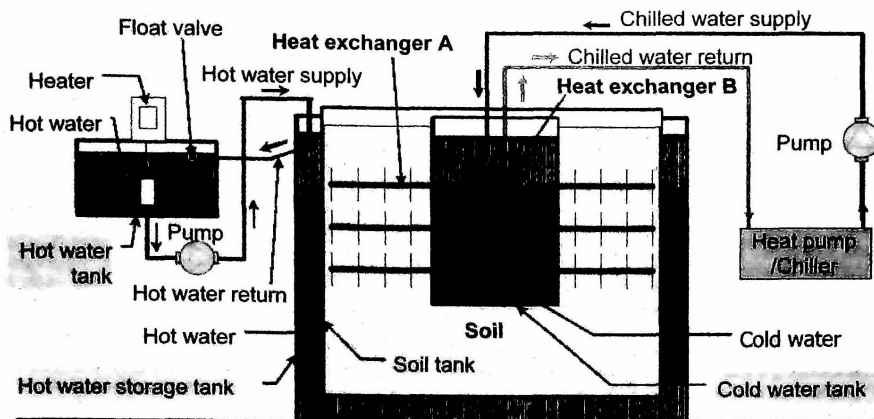


Fig.1 Schematic diagram of the test rig

storage tank using a pump to keep the temperature of the soil storage tank at a desired level. A heat exchanger (A) was used to transfer heat from soil in the soil tank to the cold water from which heat was further transferred to the heat pump or chiller through another heat exchanger (B) using a mixture of glycol and water.

The following two types of heat exchanger A were designed and tested:

- Solid bars (3 rows $\times$ 8 bars, each 63.5 mm in diameter and 400 mm long)(Fig. 2)
- Heat pipes (2 rows $\times$ 4 pipes, each 38.1 mm in diameter and 400 mm long)(Fig. 3)

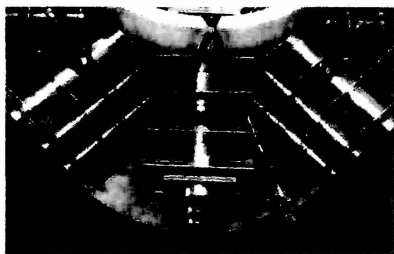


Fig. 2 Solid bar heat exchanger

Plate fins were used for heat exchanger A. The surface area of fins for part of the exchanger in the cold water tank was much smaller than that in the soil because of the limited space available. To compensate for this, a small pump was used to circulate the cold water within the tank to increase the heat transfer between the fins and cold water. This

also helped to maintain a more uniform water temperature in the cold water tank.

For heat exchanger B, a double spiral coil was used with a total heat transfer area of 1.02 m². In addition, two types of cooling device were used as a heat sink-heat pump and chiller. The chiller was able to supply the fluid circulating through heat exchanger B at controlled temperatures between 4°C and 13°C. The heat pump was originally connected to the looped ground source to provide heating/cooling of the laboratory building. It was adjustable for power output but not controllable for the temperature of the working fluid and so when it was used as the heat



Fig. 3 Heat pipe heat exchanger in soil and water tanks

sink the temperature in the cold water tank would drop below the freezing point. This was useful to determine, e.g., how long the system could be operated continuously but it was not feasible to obtain data for long period, say 24 hr, operation.

Soil temperatures at three vertical sections and 11 horizontal points along the heat flow path from hot to cold water storage tanks were measured using thermocouples. Thermocouples were also used to measure temperatures of hot and cold water and the fluid mixture in heat exchanger B. The flow rate of the fluid in heat exchanger B was measured using a rotameter. The cooling capacity was calculated from the measured inlet and outlet temperatures and the flow rate of the fluid in heat exchanger B. The density and water content of soil were measured using standard methods [4]. The measured density and water content for one batch of soil were 1771 kg/m³ and of 17.4%, respectively. Soil thermal properties were determined as described in the following section.

The following three sets of tests were carried out under different hot and cold water temperatures:

- Set 1: Soil without heat exchanger A
- Set 2: Soil with solid bar heat exchanger
- Set 3: Soil with heat pipe heat exchanger

For each set of tests, both the heat pump and chiller were used as the heat sink.

Fig. 4 shows an example of measured soil temperatures at selected points along the heat flow path from the hot water tank to the cold water tank (T_1 for soil near hot water tank to T_6 for soil near cold water tank) and mean value (T_{mean}), with the solid bar heat exchanger and using the chiller as the heat sink. The mean soil temperature was taken to be the mass weighted average of the measured soil temperatures for all the points along the radius. The soil temperature(T) was normalised by the hot (T_h) and cold (T_c) water temperatures. The soil temperature ratios were not

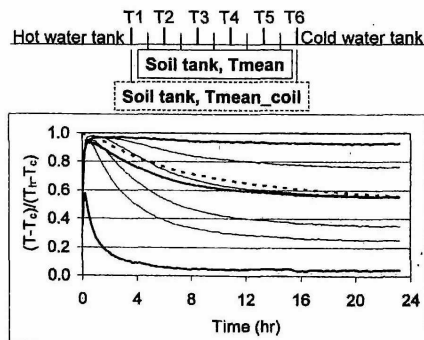


Fig. 4 Measured soil temperatures for test Set 2

equal or close to one at the start of the test because the cold water was at a similar temperature to the soil temperature. Unlike traditional transient heating/cooling tests such as the hot plate method for determining the thermal conductivity of materials where the heat source/sink at a controlled rate or temperature is

applied suddenly to recode the temperature history, the cold water for this investigation was part of the energy source. Therefore, the cold water temperature, like the soil temperature, decreased continuously during the entire test period as shown in Fig.5. The decrease in the temperature was most pronounced during the first hour of the test by then the temperature had been reduced by 50% from its initial to final temperatures. When the soil temperature was normalised by the temperature of the cooling fluid in heat exchanger B, which was constant from the chiller, instead of the cold water temperature, the temperature ratio (dashed line, denoted by $T_{mean-coil}$ in Fig.4) decreased continuously from one at the beginning.

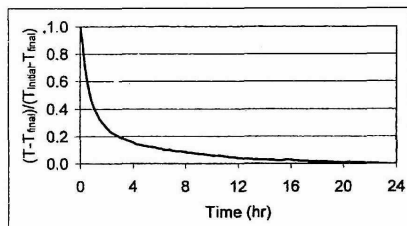


Fig. 5 Variation of cold water temperature

Fig. 6 shows a comparison of measured mass averaged soil temperatures using the chiller as the heat sink for the three sets of tests. Without a heat exchanger in the soil, heat transfer from hot water through soil to cold water was slow due to the limited contact area between soil and the cold water tank. For example, the normalised temperature drop was approximately 0.17 in six hours of operation. Deployment of the heat exchangers increased the heating/cooling rate and capacity of the system considerably. The temperature drop increased to 0.31 and 0.23 for the same cooling period with the solid bar and heat pipe heat exchangers, respectively. Thus, the

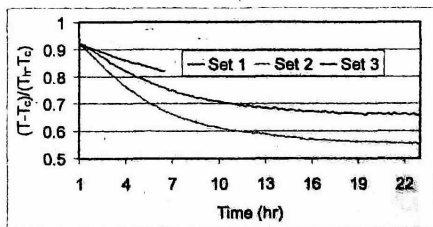


Fig. 6 Measured soil temperatures using the chiller as a heat sink

heat transfer rate was increased by over 80% and 35% using the solid bar and heat pipe heat exchangers, respectively. Heat pipes are generally superior to solid bars for heat transfer because of the latent heat transfer in the partially evacuated pipes. However, it was found

that the heat pipe heat exchanger was not as effective as the solid bar heat exchanger for this application. As indicated in Fig. 6, the heat transfer rate using the heat pipe heat exchanger lay roughly in the middle of the two other cases—one without heat exchanger A and the other with the solid bar heat exchanger. This was due to the much lower efficiency of fins for the heat pipes (varied from 25% to 54%) than that for solid bars (86%) because much larger fins were used for 2x4 heat pipes than those for 3x8 solid bars in order to compare the performance under the same total fin surface area and for the same amount of heat transfer through the heat pipes and solid bars. If the same number and size were used for heat pipes and solid bars, i.e., same fin efficiency and heat transfer area, the heat pipes would be expected to be more effective but would cost much more to produce. As the fin efficiency and/or the surface area of the heat exchanger in contact with soil would likely be the main limiting factor for GSHP installation to cover a large area, it can be concluded that a solid bar heat exchanger is more cost effective than a heat pipe heat exchanger.

3. COMPUTER MODELLING OF RAINWATER-GSHP SYSTEMS

A finite difference method was used to solve a set of conduction and convection equations for the heat transfer between the hot water, cold water, heat exchanger (A) and surrounding soil (see Fig. 1). In addition, a commercial computational fluid dynamics (CFD) software FLUENT^[5] was used to predict the performance of the GSHP system involving fluid flow in the water tank, conduction heat transfer in soil and convective heat transfer between the interface of soil and water tank as well as soil and atmosphere. Modelling was carried out both under laboratory test conditions to determine the thermal properties of soil and under simulated rainwater tank installations for domestic use.

3.1 Determination of soil thermal properties

The thermal diffusivity, specific heat and thermal conductivity of soil were determined based on the predicted and measured soil temperature histories and physical properties. Predictions were performed for the transient temperature distribution without heat exchanger A in the soil tank using the measured surface temperatures as boundary conditions. The thermal diffusivity of soil was then determined through fitting the predicted temperature history to the measured temperatures along the heat flow path from the hot water tank to the cold water tank, Fig. 7. The 'measured' thermal diffusivity for the soil with a density of 1771 kg/m³ and water content of 17.4% was 0.45 mm²/s. Fig. 7 also shows that use of a higher value (0.81 mm²/s) for the thermal diffusivity based on data from CIBSE^[6] would over-predict the rate of heat transfer. The specific heat of soil was 1334 J/kgK, calculated from the solid and water components of the soil. The soil thermal conductivity was given by the product of the thermal diffusivity, density and specific heat.

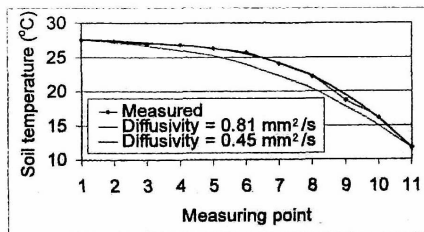


Fig. 7 Measured and predicted (with specified diffusivity) soil temperatures without heat exchanger A at 6th hour

3.2 Simulation of the rainwater storage tank and heat exchanger

Simulations were carried out for a cylindrical rainwater storage tank installed 1 m below the ground surface for different heat extraction/rejection rates and duration (continuous or intermittent operation) by the heat pump, different materials and configurations of the heat exchanger between the rainwater tank and surrounding earth. For example, assuming that a 2-storey house of 10 m long x 6 m wide x 3 m ceiling height required heating fresh air at one air change rate by a 15 K temperature increase, using a heat pump with a coefficient of performance of 3 would require a heat extraction rate from the ground of 1.2 kW. This is approximately the same as for a temperature drop of 5 K of rainwater stored in a 5 m³ tank in one day. In the examples illustrated below, the heat exchangers (both A and B) were simplified as flat plates (made of copper or aluminium) without fins. The ambient air was assumed at 5°C temperature and 3 m/s wind speed. Fig. 8 shows examples of predicted temperatures of soil and stored water with and without a heat exchanger to transfer heat between the two media using FLUENT. Results suggested that without heat exchanger A, operating the heat pump continuously would lead to the stored water at an initial temperature of 10°C completely frozen in three days. When a horizontal heat exchanger was used to transfer heat from soil to the stored water, the heat pump could be operated continuously for five days with the aluminium heat exchanger or 19 days with the copper heat exchanger before the water surrounding the evaporator coil of the heat pump began to freeze.

For intermittent operation, the stored rainwater could be used for heat transfer for longer periods. For example, for 12-hour-on (heating) and 12-hour-off operation, the system without heat exchanger A could be run for seven days compared with two days for continuous operation before the water in the tank would freeze. The operating period for the system integrated with an aluminium heat exchanger could be extended from five days continuously to 24 days intermittently. Using a copper heat exchanger, the system could be operated intermittently for practically

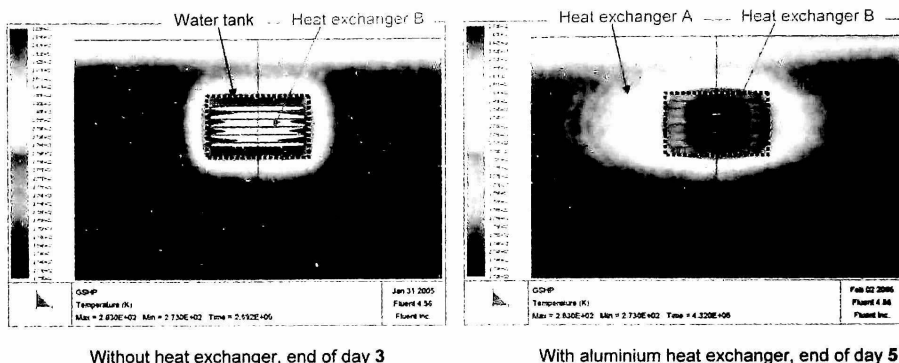


Fig. 8 Predicted water and soil temperatures, scale from 0°C (blue) to 10°C (red)
(White in the water tank < 0°C, i.e. ice)

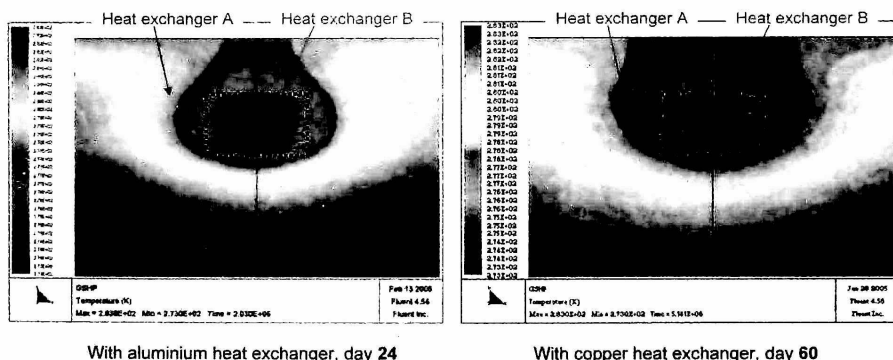


Fig. 9 Predicted water and soil temperatures for intermittent operation

an unlimited period under the same constant ambient conditions. Fig. 9 shows that the water temperature would still be about 2°C above the freezing point after 60 days intermittent operation of the system with the copper heat exchanger. This means that the heat exchanger would be capable of transferring heat from soil to water fast enough to provide the specified heating load. However, in practice, the ambient conditions would change during such a long period. The system operating performance can still be predicted if variations in the air temperature and wind velocity are known.

These simulations were performed for water in storage without inflow from the roof catchment. If the flow of fresh rainwater into the tank was taken into account, the system could be run for longer periods than predicted before the stored water froze,

depending on the rainfall pattern as well as rainwater temperature.

The duration of operating the GHSP system would also depend on various other parameters such as the size of the rainwater storage tank, heat extraction/rejection rate and surrounding earth properties. Using the computer models and modelling techniques developed from this research would allow the optimum design and operation of a GSHP system.

4. CONCLUSIONS

A unique facility has been developed to test the performance of individual components and the integrated system of a rainwater-GHSP involving a heat pump, water tank, soil and heat exchangers under controlled conditions.

Two types of heat exchanger-solid bars and heat pipes-have been designed and tested for the heat pump to transfer heat between stored rainwater and soil. The solid bar heat exchanger was found to be more effective due to the larger cross section and higher fin efficiency.

CFD has been used to determine the thermal diffusivity/conductivity of soil and predict the thermal performance of a rainwater-GSHP for a typical domestic application with different operating conditions. Results suggest that it is necessary to employ a heat exchanger to transfer heat between rainwater and surrounding soil in order to operate such a GSHP system at a design heating/cooling rate for a long period. Otherwise, the heating or cooling capacity of the system would decrease after a short period of operation if water temperatures have to be controlled between say 1°C to prevent ice building up and 20°C to prevent rapid growth of bacteria such as the *Legionella*. The numerical method can also be used for optimum design of rainwater storage tank and heat exchangers.

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