Energy 35 (2010) 4932–4940

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

An investigation of the heat pump performance and ground temperature of a piled foundation heat exchanger system for a residential building

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A R T I C L E I N F O

Article history:
Received 27 March 2010
Received in revised form
6 August 2010
Accepted 19 August 2010
Available online 25 September 2010

Keywords:
Energy pile
Ground source heat pump
Pile foundation heat exchanger
Residential heat pump
Ground temperature

A B S T R A C T

Novel methods are sought to provide greater efficiency of the installation of ground heat exchangers for GSHPs (ground source heat pumps) in domestic buildings. An economically viable option is to utilise concrete foundation piles as ground heat exchangers. The objective of this study is to investigate the operation of utilising a piled foundation structure as a ground heat exchanger. A test plot of 72 m^2 (ground floor area) was produced with 21 × 10 m deep concrete piles, with a single U tube pipe in each. Ground heat was extracted by a heat pump with the heat loading being varied in line with the date and the average air temperature. Over the 2007/2008 heating season this study had investigated the temperature changes in the foundation piles and the surrounding ground in addition to the heat pump operational performance. The temperature changes observed in the region of the test plot were compared with variations naturally experienced in the ground due to the seasonal climatic influence. The SPF (seasonal performance factor) of the heat pump was 3.62 and the ground temperature at a distance of 5 m from the test plot was seen to be undisturbed by the heat extraction and followed the predicted seasonal variation.

1. Introduction

The GSHP (ground source heat pump) is one of the efficient and sustainable methods to provide space heating and hot water for various kinds of buildings. The GSHP, works by means of the vapour compression cycle, which cools a circulating fluid (glycol–water mixture) that flows through a system of closed loops. These loops are buried within the ground either horizontally, if land space permits, or vertically by means of boreholes. The direction of heat flow is from the ground to the cooler fluid and this heat is 'upgraded' to a higher temperature through the vapour compression cycle for delivery to the building. In the UK borehole systems are commonly used due to land constraints and a borehole of 100 m depth is typical for a small system, which delivers a heat output of 5–6 kW. The cost of this ground loop installation in many cases, particularly in the domestic sector is prohibitive and as such this is seen as a significant barrier to entry in the sale and supply of GSHPs in the UK. Novel methods are sought to produce ground heat exchangers, which can be more efficiently installed into the ground. One method is to utilise foundation structures which are in direct ground contact, where loops are able to be embedded within the concrete. In many cases the construction of a building requires deep foundation supports, such as concrete piles and the additional utilisation of these members for ground heat extraction provides a good economic rationale. It is also possible to utilise a number of other ground structures such as floor slabs and diaphragm walls. Brandl [1] provides a detailed review of the so-called 'thermoactive structures' and also presents an introduction to the theory behind the extraction of ground heat via this process.

A great deal of research has been conducted to investigate the behaviour of heat movement in the ground and in particular reference to vertical borehole systems. Such borehole fields are typically 100 m deep and have separations between 5 and 8 m. Early work in the 1940s was performed by Ingersoll and Plass [2], who delivered the line source model from investigations of heat movement associated with heat extraction pipes in the ground. In 1947, Carslaw and Jaeger [3] presented their work involving heat conduction through the ground from a buried electrical cable and this provided the basis of the so-called 'cylindrical heat source model'. In 1987 Eskilson [4] developed a hybrid model combining

Abbreviations: COP, Coefficient of performance; DHW, Domestic hot water; EED, Earth energy designer; EGT, Entering glycol temperature (°C); GET, Glycol equilibrium temperature (°C); LWT, Leaving water temperature (from the heat pump) (°C); SPF, Seasonal performance factor.

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0360-5442/$ – see front matter
doi:10.1016/j.energy.2010.08.032

analytical and numerical solution techniques for determining the temperature distribution around a borehole, which simulated the long term thermal effects of the ground. The temperature responses from a number of boreholes could then be superimposed in space and a number of non-dimensional response factors were identified as '*g*-functions' for different borehole field geometries. Bennet and co-workers [5,6] reported the multipole method for determination of the exact analytical solution of the steady state case of the two-dimensional heat transfer between cylindrical pipes in a composite cylindrical region. This method could then calculate the steady state borehole thermal resistance. These studies and the work of others went on to produce borehole field simulation software such as EED (Earth Energy Designer) [7] and GLHEPRO [8]. The use of such simulation software has been shown to have good agreement with practical data in many vertical borehole installations and is now a widely used standard practice for a large number of borehole fields. The limitation of such software is that the geometries of the borehole fields, which can be simulated, are predetermined and have to be chosen within the program, whilst the layout of foundation piles can be highly varied in comparison. Additionally the calculations assume a constant ground temperature, which is justified for deep boreholes. The pile for a domestic building is typically up to 10 m deep and as such the ground temperature cannot be assumed to be constant due to it being influenced by the seasonally changing air temperature. Also there is the assumption that the heat is transported radially to and from the borehole; however for shorter depths the top and bottom have a more significant influence. Hence, such software packages may have much less applicability to the system of domestic dwelling energy piles.

Recent piling techniques have shown that piling domestic dwelling foundations can be economically competitive against traditional excavation and trench fill footings [9]. It is therefore considered that these piles can be utilised as ground heat exchangers, *alias energy piles*. Historically, the high heat loading requirements of domestic dwellings have meant that the estimated required ground loop length would have been much longer than any structurally required pile length. It is realised that with the continuing reduction in the heat load of domestic dwellings that the heat requirement now falls into a ground loop length, which is comparable to the total piled length.

There are a large number of papers, which provide experimental results for conventional borehole systems, indeed Bakirci [10] has recently reported on the performance of a GSHP in Turkey, which utilises two 53 m deep boreholes and a COP (coefficient of performance) of 2.6 was determined across the season. However, there are few practical examples concerning the evaluation of ground heat extracting pile foundation systems and more especially the thermal effects of the surrounding ground.

The majority of the case studies published with regards to energy piles relate to the non-domestic building, where the pile diameter and spacing tends to be much greater than that required for the domestic dwelling. One of the earliest studies concerning energy piles involved the use of a steel pile to a depth of 20 m. Morino and Oka [11] investigated the heat given up to the ground at different temperatures and various flow rates of circulating water. In 2006 an energy pile system for space heating had been reviewed for a small office and residential use building of 92.7 m^2 in Hokkaido, Japan [12]. The system was reported to have a mean COP of 3.2 over the year, but the study focused on the heat pump performance and did not look in any detail at the ground temperatures. More recently, Gao et al. [13] investigated both numerically and experimentally the use of energy piles for a district space heating and cooling system in Shanghai, China. However, the pile foundations investigated by Gao et al. [13] are 25 m in length, which is much longer than the majority of structural pile foundations used in the UK for residential buildings.

A number of unknowns remain with regards to the thermal behaviour of the ground and the performance of the heat pump in energy piles. The reason for this operational uncertainty is due to a number of factors including the fact that the piles have a much shorter separation compared to that of vertical boreholes. It is also known that the temperature of the surrounding ground local to the piles is seasonally influenced resulting in a temperature reduction across the winter season.

As more novel methods for the utilisation of ground structures are considered for the use of ground heat exchangers, there will also be a greater requirement for accurate building thermal modelling, heat pump monitoring and heat pump control. Greater emphasis is required on the collection of real data performance from installed heat pump systems in combination with the building thermal characteristics, such as seen by Ardehali [14]. More sophisticated heat pumps, with enhanced load control are also required, which will assist in the optimisation of heat pump efficiency as shown by Zhao et al. [15].

The objective of this study is to investigate the operation of utilising a foundation structure as a ground heat exchanger with the use of a GSHP for heating a domestic dwelling. The methodology adopted was to monitor the ground and pile temperatures, whilst extracting heat from the ground to fulfil the requirements of heating a modern low energy house. The pile system was specified for structural reasons only, other than each pile had a U tube within the pile centre for ground heat extraction. The test ran over the full 2007/2008 heating season and the overall heat energy output from the heat pump was 17.24 MWh. The usual heat pump parameters of electrical energy input, water and glycol flow rates and temperatures were also monitored to assess the heat pump performance. Ground temperature monitoring was performed at various depths around the piles and in an array within and away from the house foundation plot.

A previous paper, by Wood et al. [16] had reported on the preliminary findings of this research whereby experimental data was reported from temperature measurements taken within and around the test plot. The results provided some details in respect of ground temperature change in excess of that experienced at the far field location and overall seasonal performance of the heat pump. Literature survey showed that, prior to this work [16], no experimental information was available with regards to ground temperature changes within an energy pile plot, which provides some comprehension of the thermal effects upon the ground. However, within the paper [16] no account was taken for the validity of the far field being solely influenced by the seasonal air temperature. The present paper extends on the previous work [16] by investigating ground temperatures in greater detail through comparisons with data from theoretical models, based upon soil parameters and air temperature data. The thermal effects of flow reversal through a pile loop circuit and parameters impacting upon heat pump performance and efficiency are also investigated in this paper.

2. Experimental setup

The building plot had an area of 72 m^2 and a pile layout as seen by the numbered locations in Fig. 1. The total number of piles installed was 21, which would be necessary for the foundation requirement of a constructed dwelling. In the absence of a building on the site plot, white polyethylene covers were placed across the ground to reduce the effects of solar gain and rain water penetration of the soil. These covers have negligible mass and insulation properties and provided little other thermal effects on this system. Only the perimeter 16 piles were used for the purpose of heat