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Thermal performance of a solar assisted horizontal ground heat exchanger

Yasameen Al-Ameen[*], Anton Ianakiev, Robert Evans

School of Architecture, Design and the Built Environment, Nottingham Trent University, Nottingham, UK

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ABSTRACT

This paper presents an experimental study of a solar assisted horizontal ground heat exchanger system (HGHEs) operating as a daily heat storage unit. Initially, several soils were assessed as sensible heat storage mediums, with sand and gravel selected as the most appropriate. Then, a HGHEs was designed and connected to a 15 m^2 test room with a heating load of 1 kW at Nottingham Trent University. Heating cables, simulating solar input, were used to heat the soil in the HGHEs to 70 °C, then a heat transfer fluid (HTF), was circulated through a closed loop heat exchanger to extract the stored heat. The parameters of soil backfill and HTF mass flow rate were investigated in the HGHEs. Several output flowrates ranging between 0.1 and 0.6 L/min were tested, producing discharge times varying between a few hours to a few days. The HTF mass flowrate was found to be the most significant parameter, affecting the HGHEs thermal capacity and heat exchange rates. The sand filled HGHE produced approximately 50% more hot water ($T > 35$ °C) during a longer duration achieving an efficiency of 78% compared to the gravel filled HGHE with a lower system efficiency of 58%. Insulating the HGHE system was found to reduce heat losses and avoid temperature fluctuations in the HGHEs. Overall, the results show the hot water quantity, temperature range and duration produced from the system were in line with low temperature district heating guidelines and can be applied to some household heating applications incorporating low flows and low temperatures.

1. Introduction

1.1. Background

Over recent years, there has been a shift from conventional resources towards energy efficient renewable sources of energy for building heating purposes [1]. The use of solar energy is of considerable interest because it leads to diminution of fossil fuels consumption and is a non-polluting source of energy [2]. Several types of solar energy systems are integrated with heat collection storage systems and have been developed for heating/cooling purposes in residential and commercial buildings. The main heat storage media are water, latent heat materials and ground materials. The ground is a stable heat exchange medium and is essentially unlimited and always available [1,3]. Ground heat exchanger systems (GHEs) have gained recognition for improved and easy exploitation of thermal energy from the ground [4]. Claims made by Garg [5] are that GHEs can 1) collect heat more efficiently, 2) store more heat at a lower cost, 3) be cheaper to build, and 4) deliver a higher solar fraction with the same collector area compared to a water tank HGHE system maintaining a higher level of performance even in colder climates [3,5].

GHEs installed for heating and cooling purposes in buildings have been extensively studied by various authors [6,7]. Closed ground-loop GHEs can either be installed in vertical (VGHEs) or horizontal (HGHEs) arrangement, and a comparison of HGHEs and VGHEs performance was studied by Lee et al. [8]. In this study, the focus was a solar assisted HGHEs with operating temperatures ranging between 35 and 70 °C [9]. HGHEs consists of heat exchange pipes, the pipes can come in a variety of configurations including straight, coil, slinky or loops that are buried in shallow ground trenches of up to 1–2 m depths. A HTF (water or anti-freeze solution) is circulated through the system to extract the stored heat upon requirement and return the cooled HTF to the ground storage where it gathers further energy, in a continuous cycle. HGHEs are surrounded by soil, and hence the performance of the system is highly dependent on ground heat-transfer characteristics [10].

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[*] Corresponding author.
E-mail address: Yasameen.alameen@ntu.ac.uk (Y. Al-Ameen).

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Ground thermophysical properties including soil texture, grain size distribution, bulk density, water content and thermal conductivity are correlated and highly influences the heat transfer between the circulating HTF in the GHEs and the surrounding soil, affecting the performance of the system [7,11–13]. HGHEs are preferred over VGHEs for residential installations because of their lower initial installation costs [14]. Although HGHEs offer a cost-effective and environmentally friendly alternative compared to other methods, large shallow land areas are required for pipe installations and the system is affected by temperature fluctuations caused by the system's proximity to the ground surface. Most GHEs are equipped with a ground source heat pump (GSHP) to assist the store charge and discharge process and to avoid the extreme high or low temperature conditions that compromise the energy performance of the systems [15]. Sarbu & Sebarchievici [16]; provided a detailed literature regarding of GSHP systems, and their recent advances. Lund et al. [17] reported that GSHPs have the largest energy use and installed capacity, according to 2005 data, accounting for 54.4% and 32.0% of the worldwide capacity and use.

Various experimental, numerical, economic and performance prediction studies related to GHEs have been reported in literature. The studies can be categorised into three broad groups: (i) Solar collectors coupled with a GSHP system [10,18–21] (ii) Ground heat exchanger systems coupled with a GSHP [1,6,7,10–12,14,22–26] (iii) Solar collectors coupled with a GHEs and a GSHP for heating purposes [1,2,23,27–30]. Bose & Smith [31] developed the first solar GHE, coupled with a GSHP at Oklahoma State University. GHEs coupled with a flat plate collector and GSHP were further developed by Ozgener et al. [32]; Yong & Sumathy [33] and Kupiec et al. [34].

Extensive research has been undertaken into HGHEs by various researchers throughout the years, most of which were focused on monitoring HGHEs coupled with a GSHP where the heat pump output and the coefficient of performance (CoP) ratio was calculated to maintain daily indoor temperature. Other studies attempt to enhance the thermal performance of experimental HGHEs by improving the heat transfer between the surrounding soil and the heat exchanging pipes. The methods used to achieve this is by varying the heat exchange pipe properties, type and orientation. Esen & Yuksel [4] experimentally investigated greenhouse heating by biogas, solar and ground energy in Turkey's climate conditions and concluded that the slinky-type HGHEs occupies less space in the ground and can be successfully used for greenhouse heating purposes. Kim et al. [12] investigated the performance of HGHE via experiments and numerical analyses in a steel box filled with dried Joomunjin sand, comparing coil-type and slinky-type heat exchange pipes performance in HGHEs and found slinky-type to have better performance. Gonzalez et al. [35] conducted a study on the interactions between the soil, HGHE and the above ground environment in the UK and the results show that the slinky influences the surrounding soil by significantly decreasing soil temperatures. Koyun et al. [36] studied the effects of burying aluminum finned pipes in the soil over the traditional plastic polypropylene (PPRC) pipe and concluded that aluminum finned pipe has higher heat transfer values and is therefore more useful in GHEs. İnallı & Esen [29] carried out experimental measurements of a HGHEs connected to a GSHP to validate the effects of the parameters including the buried depth of soil, the coupled heat exchanger, mass flow rate of the water-antifreeze solution and sewer water on the performance of the system to be used for space heating applications. Results show the CoP of the HGHEs in the different trenches, at 1 and 2 m depths, were different. [26] [37]; experimentally and numerically studied the thermal performance of a HGHEs ground-coupled GSHP in a UK climate and concluded that heat extraction from the HGHEs increased with ambient temperature and soil thermal conductivity, however it decreased with increasing refrigerant temperature. Kim et al. [12] also found that GHEs type and soil thermal conductivity are the main factors determining the heat exchange rate of a GHE, whereas the pipe diameter did not have any effect on the GHE performance. Congedo et al. [38] carried out computer simulations on several HGHEs configurations considering soil thermal conductivity, installation depth, fluid velocity and concluded that the optimal soil type to use around the heat exchanging pipes was that with the highest thermal conductivity. Also, the HGHEs installation depth did not play an important role on the system performance.

1.2. Study objectives

As evident from Section 1.1, a considerable amount of recent research has been devoted to pipe design characteristics and the addition of GSHP to HGHEs, with much less focus on the ground media used for storage and the air temperature fluctuations caused by the proximity of HGHEs to the ground surface. Moreover, there are limited studies in literature concerning improving the performance of solar PV panels and solar heat collectors assisted HGHEs. Therefore, the objectives of this study are twofold:

- The first objective was to present a comparative study of heat transfer in seven ground media.
- The second objective, was to investigate how excess electricity produced from solar PV panels can be more efficiently stored in an insulated HGHEs to heat a 15 m^2 test room with a heating load of 1 kW during the typical winter conditions in Nottingham, UK (Temperature of -6 °C) without the use of a GSHP. For this purpose, an experimental HGHEs was set-up using two soil types as backfill media including sand (LB) and gravel (GR) and tested under various HTF mass flow rates to evaluate the performance of the system in heating mode (charging) and extracting mode (discharging).

The novelty points of this study are: (1) The system simulates storing excess electricity generated from solar PV panels in the form of heat and/or storing heat obtained directly from a solar heat collectors, (2) Testing and comparing two soil backfill media in a HGHEs under the same working conditions including: the same solar radiation, ambient air temperature, collector materials, insulating materials and HGHE dimensions, (3) The HGHEs is insulated to avoid heat loss to the surroundings and reduce air temperature fluctuations caused by the proximity of HGHEs to the ground surface, and (4) The HGHEs does not use a GSHP to assist in the heating process. These points will assist designers in designing HGHEs.

2. Experimental work

The experimental work was divided into four activities as follows:

- Establishing soil thermophysical properties (Activity 2.1)
- Conducting thermal testing of soils (Activity 2.2)
- The experimental HGHE system set-up (Activity 2.3)
- The soil backfilled HGHE (Activity 2.4)

Seven soils were utilised in this experimental study, these include: Gravel (GR), Leighton buzzard sand (LB), Washed sand (WS), Building sand (BS), Mercia mudstone clay (MM), Gault clay (GA) and Lias clay (LI) as shown in Fig. 1. From a designer's point of view, the selected soils represent widely available and abundant soil types in the United Kingdom which are cheap, sustainable and can be purchased from local building merchants.