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DESIGN OF AN APPARATUS TO MEASURE THE UNSTEADY TEMPERATURE DISTRIBUTION AROUND STRAIGHT AND U-SHAPED HEATED CYLINDERS BURIED VERTICALLY IN AN INFINITE MEDIUM (APPLICATION TO GROUND SOURCE HEAT PUMPS)

Jabbari M.Y., Novak D.M., Schilling C.H.
Department of Mechanical Engineering
Saginaw Valley State University
University Center, MI
United States of America
E-mail: jabbari@svsu.edu, dmnovak@svsu.edu

ABSTRACT

A major task of designing a ground source heat pump system (GSHP) is sizing of its ground heat exchanger (GHE; usually a run of straight or coiled or U-shaped pipe buried in the ground vertically or horizontally). The sizing of a GHE and prediction of its performance is complicated by many factors such as: the transient nature of the heat exchange; the accumulative effect and the history of heat exchange; the depth dependency of the ground's undisturbed temperature and thermal properties, and the presence of ground water. This paper presents the design of a laboratory apparatus to study GHE responses under controlled and specified conditions; as well as to introduce fundamental aspects of GHE to engineering students.

INTRODUCTION

In recent years, ground source heat pumps (GSHP's) have become a viable alternative-sustainable source of energy for heating-cooling of buildings. GSHP systems take advantage of the relatively constant temperature of the earth and can significantly reduce the cost of heating or cooling needs of buildings in areas where heating or cooling loads are high. Additionally, GSHP's are environmentally attractive because they are not a significant source of pollution.

GSHP technology is fairly new; there are still many uncertainties surrounding its design to capacity. Many of these uncertainties concern the design of the ground heat exchanger. For example, if there are not enough pipes buried in the ground, then the required rate of heat transfer will not take place and the system will not meet the building's demand. On the other hand, if the loop is too large, then it simply wastes money and makes the system too expensive to be economically attractive. Also of interest, and closely related to pipe length, are the questions of, at what rate, for how long, and how much (accumulative over time) can heat be transferred into the ground without impeding its heat-source (or heat-sink) capacity. Moreover, the ground heat capacity (GHC) is affected by how far from the pipe the ground temperature will be perturbed under the hourly, daily, and seasonally-varying load of the heat pump; and how quickly the temperature perturbation recovers. In addition, the GHC is also affected by the proximity of neighbouring tubes (or U-tubes). All these questions, and more, need to be answered in order to reliably predict operational capacity of GSHP systems under various conditions. The proposed laboratory apparatus is to provide data, collected under specified and controlled conditions, and to validate numerical and theoretical modelling of GHE as it introduces engineering students to GHE, enabling them to learn fundamental aspects of designing more efficient GSHP systems.

LITERATURE REVIEW

The ASHRAE handbook [1] provides an extensive discussion of applications and system design considerations of GSHP. The coverage is general and while it includes very useful knowledge, it provides limited information on the topic of heat exchange between soil and ground loops.

Conduction of heat from a buried pipe through an infinite medium is analytically characterized [2,3]. In these analyses the pipe is modelled as a line source (or a cylindrical source) of constant and uniform strength (temperature or heat flow per unit length). The solution obtained is relatively simple but, as expected, cannot fully account for the variation in design parameters encountered in application. In addition, the solutions are not applicable to situations where two pipes of varying strength (heat exchange between them) are buried in close proximity to each other. Consequently, numerous studies have been performed to answer related questions. For example, Brown and Wilson reported performance of loops laid horizontally in a large scale natural environment [4]. Using an analytical and experimental approach, the study finds general agreement between theory and in situ measurements. However, the large land area required for this type of installation limits its practical application in densely populated areas.

A historical account of research activities (up to 1987) employing the ground as a heat source is also available [5]. The author identifies several areas of importance for future research, most of which relate to the lack of sufficient knowledge regarding design and performance of ground heat exchangers. One specific area mentioned is the lack of detailed mathematical models to evaluate the heat absorbing (or rejecting) performance of the ground as it is heated (or cooled) periodically (over short or long time spans) and subjected to varying heat loads. Obtaining a closed form solution to the governing differential equation that includes the effect of various parameters is next to impossible. Thus, researchers have turned to numerical solution of the problem by developing computational packages and testing them against data collected from in situ installations.

For example, Morrison reported the development of GS2000™ software, which simulates different geometrical arrangements of loops [6]. In this software, the heat pump's entering water temperature is used as the measure of performance and is shown to be in fair to good agreement between prediction and measurement when the analysis is based on monthly ground loads. Using peak load analysis, however, the package predicts lower entering water temperatures during the heating season and higher temperatures during summer. A concern with this peak load approach is it can lead to design of an oversized heat exchanger.

Hellstrom reviewed the use of vertical borehole heat exchangers in GSHP systems [7]. The author concluded that the thermal resistance between the carrier fluid and the borehole surface is dominant in systems with large magnitudes of heat exchange per unit length of the borehole; as encountered in ground heat storage applications. In contrast, lower magnitudes of heat exchange in a GSHP tend to be dominated by the transient nature of the thermal resistance of soil between the borehole surface and regions of soil where the temperature is not disturbed. The author also noted that, in the absence of ground water migration, the ground's radial heat conduction is dominant, leading to negligible effects of the ground surface temperature (depending on the borehole depth). In that same article, it is stated that, if the spacing between adjacent boreholes is large, the effects of neighbouring boreholes on one another are negligible but become noticeable over time. Moreover, the author concluded that heat exchange between fluids flowing in the two legs of a U-Tube in a borehole is important if the flow is laminar or the U-Tube is very long (200 m or more).

Spitler reported GLHEPRO software to design ground loop heat exchangers for commercial buildings [8]. The package is capable of sizing heat exchanger loops to meet a specific building's monthly heating/cooling loads, but it is not capable of automatically optimizing the same. The author recommends further efforts to be spent on developing and validating optimization software. Spitler and colleagues also reviewed recent progress in the research and development of GSHP systems, providing procedures to size vertical heat exchanger loops for commercial and institutional buildings while accounting for the effects of short-term load variations on long-term performance [9].

Hellstrom and Sanner compared performance histories of software used to model borehole heat exchangers [10]. The authors noted that even though the design outcome of the early programs varied considerably (about 30 % of the mean value of the required borehole length), later software improvements reduced that variation to about 11%. The difference, it is pointed out, is partly due to simplifying assumptions and partly due to the problem's complexity.

Inclusion of heat transfer between adjacent legs of U-tubes in a theoretical analysis of vertical borehole heat exchangers is reported [11]. The analysis also includes an explicit solution to a finite line source model of heat transfer in the ground adjacent to the borehole. Even though the model agrees satisfactorily with earlier studies, the authors recommend validation of the model against laboratory and in situ experimental measurements.

Another modification to the line-source model is presented in [12]. This analytical model also includes the effects of interference between adjacent boreholes on the long-term performance of GSPH systems. The authors find agreement between their analysis and earlier published works and conclude the model works as well for short-term analysis.

Bandos and co-workers reported analysis of a three dimensional finite line-source model [13]. Included in the analysis are geothermal temperature gradients and varying ground surface temperatures. The authors' method averages the borehole temperature over its length; which in turn overcomes a problem with earlier studies: over estimation of the borehole temperature. A number of studies have pointed out that the thermal properties of soil/rock surrounding the borehole as well as the thermal resistance between fluid in the U-tube and the wall of borehole have important effects on the design of ground loop heat exchangers [14,15,16,17,18]. The common practice is that these properties (or their effects) are measured on site using the so-called thermal response test (TRT). Results of several such measurements are compared, and a procedure is recommended to insure reliable measurement [16]. Monzo compared results of two newer methods of DTRT (distributed thermal response measurements) and studied the effects of different line-source models used in the analysis data [19].

Bernier reported that, although GSHP are proven to be economically and environmentally advantageous, it appears a sizable number of application engineers and real state owners are reluctant to use it, perhaps, because of uncertainty and perceived difficulty associated with system design [20]. It is our opinion that another reason for this lack of acceptance is that today's graduating engineer is not fully exposed to basic aspects of the performance of transient heat exchange in soil. To alleviate this notion, the experimental apparatus reported herein is intended to provide engineering students with a hands-on opportunity to experiment with various fundamental aspects of designing a GSHP system; and to provide experimental results over a wider, and better controlled, range of variables to supplement numerical works in the literature. The first part of this study has been to design a suitable apparatus capable of adaptation to various experimental conditions in the laboratory. This part is currently underway. With this paper, the authors' intent is to present the apparatus to a body of interested and expert colleagues in the hope of receiving critical review and suggestions to improve the design.

APPARATUS

A laboratory apparatus was designed and constructed for two purposes: (*i*) to help engineering students better understand the process of transient heat transfer from a pipe buried in the ground; and (*ii*) to collect thermal response data under controlled conditions, data that will in turn be used to validate numerical and theoretical modelling of GHE.

The apparatus consists of a hollow cylinder that is precision-fabricated from polyethylene and measures 49.5 cm inside diameter by 0.6 cm wall thickness. The cylinder is filled with silica sand of a known purity and particle size distribution. A cylindrical cartridge-style electric heater (1.6 cm diameter by 16.5 cm long) is located along the central axis of the cylinder. The apparatus is also fitted with a set of probe- and surface-thermocouples; and a computerized data acquisition system that records temperatures and power consumption by the heater.

The cylinder is capped with two polyethylene disks at the top and the bottom. Each disc is 2.54 cm thick and 55.9 cm in diameter. Figure 1 shows a solid model of the upper disk, lower disk, and side wall fully assembled (without holding bolts). Not shown in Figure 1 are two sheets of rigid foam insulation, each cut into a circle of the same diameter as the upper and lower discs. One sheet of insulation is centrally located atop the upper disc and the other beneath the lower disc.

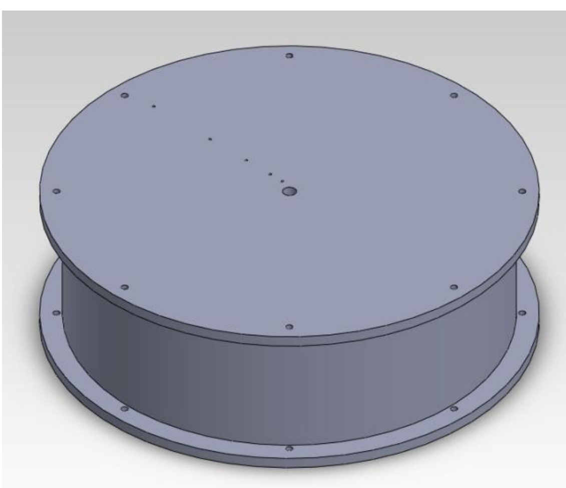

Figure 1. The assembled top disk, bottom disk, and hollow cylinder.

To simulate periodical heat transfer from an axially-located pipe, the cylindrical heater is used with a direct current power supply. The power supply has a digital readout for supplied voltage and amperage, and the heater's electrical resistance is known (46.5 Ω), so the power supplied, or the heat dissipated, can be easily set and maintained. This heater is long enough to sit in a groove machined in the bottom disc and extend into the top disc, providing support on the top and bottom. The approximately constant power dissipation along the length of the heater provides constant heat transfer per unit length as a boundary condition.

Each thermocouple in this system is used for a specific purpose. For example, two thermocouples are attached to the surface of the heater and are used to measure the heater's surface temperature. They are placed near the top and the bottom of the heater to ensure that the heater's symmetrical surface temperature relative to its midpoint prevails**.** This, additionally, validates that the apparatus has radial heat transfer in a slice of the medium on either side of the symmetry plane.

The apparatus is also equipped with five thermocouple probes to measure the temperature at five different radial distances from the heater along the plane of symmetry. These probes each have one thermocouple bead and are positioned so that the bead is in the plane of symmetry. They are positioned on the tangent line of the heater instead of directly on a radial line extending from the center of the plane outward. This is intended because heat transfer will only occur in the radial direction in this experiment (due to symmetry and insulation on the top and bottom). With this configuration, heat flow line interruption by one probe will not affect succeeding probes.

A thermocouple on the inner surface of the cylinder sidewall serves two purposes. First, it acts as a sixth radial thermocouple. Second, its reading can be compared with the reading from the surface thermocouple on the outer surface of the sidewall to determine if heat transfer through this wall is occurring. The tenth, and the final, thermocouple is used to measure ambient air temperature for model calculation purposes. Two data acquisition terminal boxes and analog-to-digital converter hardware are used along with specialized computer programming for data storage. Each terminal box has the capability of handling eight differential analog signals, so this system has the capability of adding six more thermocouples to the existing ten.

Silica sand with a high purity (over 99% by volume) and narrow particle size distribution is used to model the heat sink properties of the ground. This type of sand is used for several reasons. First, its particle-size uniformity helps prevent the settling of sand over time and will eliminate a packing-density gradient through the height of the container. Second, the same sand with the same properties is easily obtainable. Third, its purity makes its thermal conductivity determination more reliable. Finally, published data on the thermal conductivity of silica sand is available.

Preliminary tests of the apparatus in Figure 1 and its data acquisition system will begin soon. To validate operation of the system, first a single cylindrical cartridge heater (simulating a line and/or a cylindrical heat source with fixed heat output) will be employed. The data collected (subject to fixed and specified thermal properties of the medium) will be compared to analytical models [2,3] and numerical models that will be developed using commercially available software packages [such as CFD, Solid Works, etc.]. Subsequently, the cylindrical heater will be replaced with a U-shaped cartridge heater, where the heat output from each leg can be independently varied by the user. Examination of the effects of the distance between the legs of the U-shaped heater and varying thermal properties of the medium will follow. As an educational tool, the authors intend to design a set of parametric studies for engineering students to perform; studies that will illustrate the role of various performance parameters (e.g., electric power input) on the ground temperature transient response.

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