ARTICLE IN PRESS

Applied Thermal Engineering ■■ (2016) ■■–■■

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Study on ground temperature response of multilayer stratums under operation of ground-source heat pump

Shiyu Zhou [a], Wenzhi Cui [a,*], Jiaxiang Tao [b], Qingyuan Peng [b]

[a] *College of Power Engineering, Chongqing University, No. 174 Shazhengjie, 400030 Chongqing, China*
[b] *Nanjiang Hydrogeological & Engineering Geology Brigade, No. 554 Hongjin Street, 401121 Chongqing, China*

HIGHLIGHTS

- The ground temperature variation caused by the operation of a practical GSHP system is monitored.
- A numerical model is constructed according to the monitoring borehole and a TRT process is simulated.
- The temperature variation is different along the vertical direction due to the different thermal properties of the stratums.
- The relationship between temperature distribution and thermal properties along the depth direction is inferred.
- The fact that the heat flux along the borehole is proportional to thermal conductivities is demonstrated.

ARTICLE INFO

Article history:
Received 15 November 2015
Accepted 29 February 2016
Available online

Keywords:
Ground temperature
Multilayer
Stratum
Ground source heat pump
Thermal property

ABSTRACT

The operation of the ground source heat pump (GSHP) system in cooling dominated areas will cause heat accumulation under the ground, which results in the increase of the ground temperature. In the previous studies, the change of ground temperature was usually deemed as an average variation. This assumption may be right in the homogenous and isotropic soil. In multilayer ground geology, however, the temperature variation caused by the GSHP system operation is quite different along the vertical direction, which was illustrated in this paper based on the ground temperature monitoring data from a practical GSHP system. A numerical model was constructed according to the monitoring borehole that was located at the ground heat exchanger (GHE) field, and a long term heat injection process was simulated. It has been found that the temperature variation along the vertical direction at a distance from the borehole was in accordance with the monitored temperature variation. The fact that the heat exchange rate is proportional to the value of thermal conductivities was demonstrated with the distribution of the temperature difference between the circulating fluid and borehole wall.

1. Introduction

Ground source heat pump (GSHP) system has been accepted almost all over the world for its energy conservation and environmental friendliness. However, there are still some limitations in its application. One of them is the thermal imbalance in the ground heat exchanger (GHE) field. For example, Chongqing, the city is located in the hot-summer and cold-winter zone in China, where the cooling load is much higher than the heating load for most of the buildings in this area during a whole year. When GSHP is applied in this area, the accumulative heat that injected into the ground is much higher than that extracted from the ground. Consequently, the ground temperature gradually increases, which deteriorates the cooling performance of the GSHP in terms of capacity and energy efficiency [1,2].

The ground temperature variation induced by the operation of GSHP system has been studied in several papers. Shang et al. [3] predicted the geo-temperature distribution in operation and recovery period of a GSHP system. They discovered that the soil properties had great effect on the soil temperature recovery while the environmental factors had small effect. Esen et al. [4] simulated temperature distribution development in the boreholes of GSHP system operating in both cooling and heating modes with a 2D finite element model. Xi and Wang [5] analyzed the effects to the temperature field and the stress field caused by the GHE used in GSHP system. They also analyzed the relationship between the thermal affecting radius and the soil thermal conductivity. Gao et al. [6] found that the ground temperature variation was related to the system intermittent period and that the intermittence prolonged the heat transfer without reaching an utmost temperature (operation

---

* Corresponding author. Tel.: +86 23 65111867; fax: +86 23 65111867.
E-mail address: wzcui@cqu.edu.cn (W. Cui).

http://dx.doi.org/10.1016/j.applthermaleng.2016.02.130
1359-4311/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Shiyu Zhou, Wenzhi Cui, Jiaxiang Tao, Qingyuan Peng, Study on ground temperature response of multilayer stratums under operation of ground-source heat pump, Applied Thermal Engineering (2016), doi: 10.1016/j.applthermaleng.2016.02.130

limitation). Li et al. [7] simulated temperature distribution and variation trend of a tube cluster of the GHE for the long term performance with a 3D model that was constructed with FLUENT software. Fidorow and Szulgowska-Zgrzywa [8] presented the results of observations made during a whole year monitoring of the temperature of the 78 m deep boreholes that served as lower heat source for GSHP system. Besides, they also studied the ground temperature response induced by thermal response test (TRT). Raymond et al. [9] simulated the borehole temperature evolution during TRT process, allowing for the correlation of the subsurface thermal conductivity with stratigraphy. They found that the temperature inside the borehole homogenized rapidly after heat injection stopped.

In the above papers, scholars usually simplified the underground as homogeneous soil. The stratum profile was seldom taken into consideration, so that the underground temperature distribution in depth direction was not mentioned. Sutton et al. [10] developed a multilayer bore-field design algorithm that accounted for different thermal properties in each stratum within the geological regime. Lee [11,12] developed a modified model for a GHE borefield of a GSHP system based on 3D finite difference scheme which could cater for multiple ground layers in the soil. Deng and Fedler [13] investigated heat transfer in multilayered soil with GSHP system experimentally and numerically. They found that the heat transfer rates were discontinuous between soil layers. Du and Zhang [14] established a mathematical model of heat and moisture transfer between GHE and surrounding soil, in which the layers of soil in vertical direction were set according to the geological structure of an actual drill. With that model, they simulated the soil temperature fields in a continually running period for a GSHP system. Florides et al. [15] developed a new GHE model and applied it to a multiple layer ground regime with different properties. With the model, the effect of the layer sequence on the outlet temperature was examined. Doleck et al. [16] described the long-term, cumulative thermal response of the ground around a vertical GHE operating in both heating and cooling modes. They found that the temperature profile along the borehole was not constant and varied significantly when the lithology changed. Raymond and Lamarche [17] used the computer program MLU to analyze the TRTs in multilayer boreholes. They discovered that even though the heat injection was constant during simulations, the heat transfer rates at depth significantly changed over time, especially in the case of subsurface thermal conductivity varied greatly.

It can be known from the above survey that quite a few studies have been done on the ground temperature field affected by the operation of a GSHP system. Some studies [3,4,7,9] focused on the temperature filed of the horizontal cross section of the bore-filed rather than the vertical direction. Therefore, the multilayer stratums in the vertical direction could not be considered. Some studies [6,8,15,17] took the stratum profile into account; however, their works were basically based on the short-term operation of GSHP system or a TRT processes. There are few studies have been covered that based on the long-term operation of a practical GSHP system. Some scholars did this work only by simulation software without the GSHP system running data [5,12,14,16], while some other works still at the stage of theoretical or experimental analysis, in which the actual distribution of stratums was usually simplified as several ideal layers [10,11,13].

In actual cases, the stratum in the GHE borehole varies along the vertical direction, especially in the bedrock geology districts. There exist differences between thermal properties of various stratums, even if the same type of stratum may have different thermal conductivities due to their different porosities or moisture content. In this paper, a GSHP system located in the bedrock geology district was studied; the temperatures along the vertical direction in an unused borehole (in which there is no fluid circulating for heat exchange) have been monitored under a long-term GSHP system running. The monitoring borehole was surrounded by the running GHE boreholes, so that its temperature variations could represent that of the GHE field. According to the analysis of the temperature data and thermal properties distribution in the borehole, the ground temperature response of multilayer stratums under the operation of GSHP system was demonstrated and analyzed with a numerical model.

2. The GSHP system

The studied GSHP system is located at Chongqing of China. The object served by the air conditioning system is an office building, whose air conditioning area is 6368 m^2. The designed cooling load and heating load of the system are 605 kW and 298 kW, respectively. The GSHP system runs from 9:00 am to 5:00 pm every day except for the weekends in the cooling and heating seasons, which are usually from May 15th to September 15th and December 1st to February 15th, respectively. For the purpose of relieving the heat imbalance problem, the domestic hot water supply for the residences above the office building was also designed and incorporated in the system. However, it has not been operated so far for some reason, which means that the heat imbalance problem still exists. The GHE system is comprised of 90 boreholes, in which double-U pipe GHEs are applied. The distance between two adjacent boreholes is 6 m. A temperature monitoring borehole was established to acquire the underground temperature variations in the borehole field. The temperature monitoring borehole was not connected into the GSHP system, which means there is no circulating fluid in its pipes when GSHP system runs. The monitoring borehole is surrounded by other running GHE boreholes, as shown in Fig. 1, hence the temperature monitoring results of the monitoring borehole can be considered as the underground temperature of the GHE field.

3. Geological properties and monitoring system

The temperature monitoring borehole was drilled in 2009 for the purpose of geological survey. After that, the temperature monitoring system was set up in this borehole. Figure 2 shows the lithology profile of the borehole resulted from the geological survey. The figure shows that the geological structure of the borehole is mainly composed of mudstone and sandstone stratums except for some clay soils in the shallow ground. Table 1 lists the detailed geological information of the borehole field.

Thermal property test was performed on the monitoring borehole when it was drilled. The rock core samples drilled out were preserved in sealed PVC cases to avoid changes of the moisture content in them. The thermal properties of the core samples were then measured with the guarded hot plate apparatus to obtain those estimate values. The obtained values of those core samples at different depths are also included in Table 2.

The underground temperatures at different depths were measured with 25 resistance temperature detectors (RTDs), which were calibrated with an accuracy of 0.1 °C. The RTDs were installed on the legs of the U-pipe at specified positions as shown in Fig. 3, i.e., from the ground surface to 15 m depth; the RTDs were installed with one meter spacing and 10 meters spacing in the range from 20 to 100 m. All the temperature data were recorded using QSY200 automatic underground temperature acquisition module, which was manufactured by a domestic company. The data acquisition module collected the ground temperature automatically and sent them via wireless network to the data receiving and processing center in our lab. This module was powered by both solar PV cells and grid electricity.

Please cite this article in press as: Shiyu Zhou, Wenzhi Cui, Jiaxiang Tao, Qingyuan Peng, Study on ground temperature response of multilayer stratums under operation of ground-source heat pump, Applied Thermal Engineering (2016), doi: 10.1016/j.applthermaleng.2016.02.130