The influence of the solar-ground heat pump system on the ground temperature in the boreholes and in their vicinity – study based on experimental data

Piotr Rynkowski^{1,*}

¹Białystok University of Technology, Faculty of Civil and Environmental Engineering,
15-351 Białystok, ul. Wiejska 45A, Poland

Abstract. The paper presents the results of observations of a brine-to-water a solar-assisted ground-source heat pump (SAGSHP) system located in building “INNO–EKO–TECH Innovative Research and Didactic Center for Alternative Energy Sources, Energy Efficient Construction and Environmental Protection” in the Białystok University of Technology, north-east Poland. As the heat source of the system are three vertical ground heat exchanger (VGHE), length 70, 85 and 100 m. Independently, there are three control probes to monitor the temperature in the vicinity of VGHEs. The experimental results indicate that soil temperature raises from 0.2°C for 5 m distance, up to 0.5°C for 5 m distance.

1 Introduction

A large number ground source heat pump (GSHP) systems are used in the world. The advantage of this kind of system is relatively stable temperature of the ground and high efficiency and environmental friendliness.

Poland has a heating-dominated climate. As a result, heating season is long and the GSHP system performance becomes less efficient. The borehole heat exchangers extract heat from the ground exclusively, when the heat pump works in the heating mode and the ground is not recharged. It can lead to a decrease the ground temperature over time.

Most typical heat transfer simulations models for VGHE have been described in detail in [1]. The various computer programs should be validated by measured field data. Discrepancies between the numerical models and the reality, mainly for complex phenomena in the ground can be significant. In this aspect, measurements of the temperature fields in the ground for different parts of the world are highly necessary.

The performance of a solar-assisted ground-source heat pump (SAGSHP) system is a new type of high efficiency, energy saving and environmental protection air-conditioning technology. A very comprehensive review on research and developments on solar assisted compression heat is reported in [2, 3]. In the first part of paper [2] the authors provides a detailed description on various system configurations, system modeling, performance, and

* Corresponding author: p.rynkowski@pb.edu.pl

its modifications for solar assisted compression heat pump systems. The second part [3] presents a comprehensive review on applications of solar assisted compression. According to [2] solar assisted compression heat pump system is the promising equipment used for heating applications.

As Liu et al. [4] marked that, despite the SAGSHP system's polarity and its high energy efficiency the COP (Coefficient of Performance) of the ground source heat pump system decreased gradually year after year caused by imbalance energy loads especially in heating-dominated climate zones. Solar thermal collectors can balance ground loads over a yearly cycle and can assist in maintaining more efficient heat pumps, with the results, soil temperature raised by 0.2°C. In addition, when solar thermal collectors are integrated, the total borehole length can be reduced, making the initial cost of installing the borehole more economic. The SAGSHP extracted heat from the ground by VGHE and it injected excess solar thermal energy into the ground was investigated in [5]. Six cold locations were analyzed in order to investigate solar assisted ground source heat pumps. According to the authors' results, when the solar thermal collectors were integrated and the total borehole length was unmodified, the seasonal energy efficiency was constant over time.

A systematic review on the past and present solar assisted heat pump systems for low temperature water heating applications was describe in [6]. Various configurations are compared in order to gain accurate and deep intuitive understanding of SAGSHP systems.

Yang et al. [7] experimental studies and numerical simulation on the performance of a solar-ground source heat pump system operated in different heating modes were presented. The results indicate that the excess solar energy collected during day can be stored in ground by the GHE to improve the operation performance of GSHP during night. In presented case, the proportions of heat source burdened by solar and geothermal energy are 43.3% and 50.2% respectively.

Fiodorów et al. [8] determined experimentally that during the heating season the heat source has cooled down by 0.3–1.1°C in comparison to the starting point. The temperature of non-regenerated borehole was lower by 0.4°C in the beginning of the next heating season in comparison to the former one. The temperature of borehole regenerated by solar collectors has risen by 0.2°C in comparison to the point before former heating season. In [8] the three years of work of the SAGSHP system was analysed. The VGHE were regenerated using passive and active methods. The data showed that in the tested system the borehole without the active regeneration cools down about 0.8°C per year. The authors explain the time needed for regeneration increases after each year of the system operation. Verma et al. [9] carried out experimental study investigation of SAGSHP system for continuous eight hours operation from morning to evening for Indian winter climatic conditions. With heat input from solar collector and ground heat exchanger the heat pump was able to absorb heat at temperature 5°C higher than the ambient temperature.

The numerical simulation of a solar assisted ground coupled heat pump system which can provide both space heating and domestic hot water was presented by Chen and Yang [10]. Li et al. [11] a combined solar thermal heat pump system with seasonal energy storage proposed for both space heating and domestic hot water in cold climate area. Comparing with the base system COP increased by 1.4 times. Simulation and performance analysis presented Jonas et al. [12]. Cimmino et al. [13] using a simulation model in series arrangement showed that solar heat injection into the ground decreases the required borehole length by a greater amount for a field of shallow boreholes than for a one deep borehole configuration.

The idea to couple a solar collector to the VGHE was first proposed by Penrod in 1956 [14]. Chiasson and Yavuzturk [15] presented a system simulation approach to assess the feasibility of SAGSHP system in heating-dominated buildings. Yuehong et al. [16] presented the solar-ground source heat pump system with a vertical double-spiral coil

ground heat-exchanger. The experimental results showed the coefficient of performance (COP) increased 21% over the single-pipe horizontal GHE. The performance characteristics of SAGSHP greenhouse heating system with GHE using exergy analysis method were investigated in [17]. Allaerts et al. [18] compared a hybrid ground-source heat pump system with dual borefield and active air-source regeneration to a standard single borefield ground-source heat pump system. Their results showed size-reduction of 47% in the hybrid configuration compared to a single borefield.

A detailed literature survey indicates that many research works have been reported on the performance study of SAGSHP during long time space heating application. The performance of underground thermal storage of the SAGSHP depends strongly on the intensity of the solar radiation and the matching between the water tank volume and the area of solar collectors. The use of the solar thermal energy for heat storage is recommended by using VGHE as low source of energy for compressor heat pump.

2 Description of experimental set-up

The installation of the SAGSHP is located in north-eastern Poland. Fig. 1. depicts the solar-assisted ground source heat pump diagram and experimental set-up established at Department of HVAC Engineering of Bialystok University of Technology, north-east Poland (latitude 53°11"N, longitude 23°15"E). The SAGSHP system is a heat source for the floor heating, for four rooms in the building.

Fig. 1. Schematic diagram of solar-assisted ground-source heat pump system.

The SAGSHP works as two independent sub-systems. One is thermal storage system; the second is GSHP heating system. Thermal storage system works only during the summer season and the heat pump heating system works only during the heating season. The system set-up consist of heat pump, two types of solar collectors, flat type and heat-pipe type, water tank, intermediate heat exchanger and three VGHE, with three independent test probes (Fig. 2). The ground temperature measurement system can measure and record the soil temperature in different depths every 5 minute, in VGHE and in the test probes. The data acquisition system consists of the temperature measurement system, the flow rate measurement equipment and the power consumption measurement system. The basic data about the specification of SAGSHP setup components are given in Table 1.

The length of VGHEs are respectively 75 m (GHE 1), 100 m (GHE 2) and 85 m (GHE 3). For verifications the ground temperature profile 27 temperature sensors were installed in each boreholes. The sensors are located at 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 80, 90 and 100 m depth. Each of the VGHE and

additional control probes have the temperature sensors up to 100 m. In the experimental system one single U-tube were buried in the vertical boreholes with 100 m depth each. The borehole diameter is 150 mm and the spacing between them as on Fig. 2. High density polyethylene (HDPE) tubes with 40 mm outside diameter and 32 mm inside diameter are used to construct the VGHE. Between the VGHEs and surrounding ground, the annular space between the VGHE and borehole wall is grouted by mixtures with drilling mud and sand.

Table 1. Specification of SAGSHP setup components.

Items	Technical specification		
Collector type	flat type	heat-pipe type	
– absorber area	2 x 2.32 m ²	2 x 3.03 m ²	
– number of tubes	-	2 x 24	
– optical efficiency	86.3%	81.3%	
heat pump performance data for	B0W35 ΔT 5 K	B0W35 ΔT 10 K	B0W55 ΔT 5 K
– heating output	7.8 kW	8.0 kW	7.8 kW
– power consumption	1.7 kW	1.6 kW	2.5 kW
– performance figure/COP	4.7	5.0	3.1
– coolant	R 407 C	R 407 C	R 407 C
intermediate heat exchanger	plate fin type heat exchanger		
circulating pump	max. volume flow 4.8 m ³ /h;		
pressure gauge	range 2.3–11.9 bar for R407 C		
temperature sensors	DS18B20 digital thermometers; digital resolution 12 bits; 0.0625 K accuracy		

During the summer time, when the thermal storage system is operating, heat from solar radiation, receiving from the solar collectors is transferred to the water tanks by pumps and through the heat exchanger is pumped to ground vertical thermal exchangers No. 2 (Fig. 1, 2).

Fig. 2. Location of vertical ground heat exchangers and control probes.

During the winter season, when GSHP works [19], the heat exchanger transferring heat from water tanks to VGHE does not work. The heat from the sun is pumped to water tanks and the heat from ground is pumped to heat pump, as on Fig. 1. Stored heat was extracted by VGHE for building heating.

The aim of the experiment was to check the possibility of soil regeneration by increasing the ground temperature in the vicinity of the VGHE. The measurements were carried out after the winter season 2017/2018. The thermal storage system was operating from April 14, 2018 to November 30, 2018. During the experiment, the data recording of temperature sensors in VGHE No. 4 failed.

3 Results and discussion

For all boreholes the undisturbed ground temperatures were measured. The data acquisition system ran from January 2016 to December 2016. The ground structure profile for all boreholes is similar. The undisturbed, initial temperature profile is presented in Fig. 3. The ground temperature varies with time and the seasonal change in the first zone, up to depth about 12 m. In the February the temperature profiles achieved the lowest values. In the August the temperature profiles achieved the maximum values. On the depth about 60 m a groundwater occurs, where there are aquifers in this area.

Fig. 3. Undisturbed average, initial temperature profile.

The thermal storage system was launched on April 14, 2018 and it was stopped November 30, 2018. During the experiment only one VGHE No. 2 was operating. The hot fluid, about minimum and maximum inlet temperature, 17.3°C and 30.3°C respectively, was pumped by VGHE no. 2. Energy transfer process by the SAGSHP has great significance for calculating the thermal storage quantity. Energy equilibrium equation for the thermal storage process can be described as follows:

$$E = \left[c_p \sum_{i=1}^N m_i (T_{i,in} - T_{i,out}) t_i \right] / (3,6 \cdot 10^6) \quad [\text{kWh}] \quad (1)$$

where c_p – specific heat at constant pressure of the glycol, J/(kg°C); m – mas flow rate, kg/s; t – operation time, in the study every five minutes, s; i – operation period; N – number of cycles in the analysed period.

An annual sunshine hour in Bialystok in 2018 was 1,760 hours. The sum of global irradiation for Bialystok during the year is equal 1,212.4 kWh/m². The sum of global irradiation from April to November is 1,007.0 kWh/m². The sum of global irradiation for the analysed time is 10,775.0 kWh. Based on measurements (eq. 1), the total thermal quantity transferred to the soil was 6,308.8 kWh. The solar energy utilization efficiency is 59%.

The supply and return (heat exchanger before VGHE No. 2) temperature was relatively stable. The operating temperature of VGHE No. 2 at selected depth 70 m was presented on Fig. 4a. Similarly, the minimum and the maximum outlet temperature were 8.7°C and 28.6°C, respectively (Fig. 4b). Some deficiencies in measurements are visible between August 1 and August 11. This time, the data of temperature sensors in VGHE No. 2 were not recorded. The graph shows that during the last two months the process of loading the soil occurs sporadically. During this period, the sun is low over the horizon and the sky was often overcast.

Fig. 4. a) The operating temperature of VGHE No. 2 at depth 70 m, b) The fluid operation parameters at the heat exchanger.

Soil temperature in different depths was obtained directly from the ground temperature measurement system. Soil temperature data in different depths were picked up to analysis soil temperature change distribution over year, when the VGHE No. 2 was operating. Fig. 5 shows the temperatures changes in boreholes No. 1, 3, 5 and 6 during the regeneration period at depth 70 m. The temperatures of the boreholes significantly differ during the regeneration. The shape of the curve in the first zone differs significantly, which is related to the external environment. In the second zone, regenerated boreholes have higher temperatures after regeneration, except probe no. 4, where the distance from the heat source was the largest and is equal 10 m. For closer probes 1, 3, 5 and 6 there is visible an increase temperature in the ground after regeneration.

Fig. 5. The boreholes temperature profiles before and after the regeneration.

To determine the temperature rise in the ground in each borehole a simple linear regression was used for finding relationship between the ground temperature and the operating time. Additionally, due to the complex nature of the phenomenon in the ground, Generalized Additive Models were used to show the course of the temperature function in operating time (curve in the Fig. 6). A generalized additive model was used in the R environment using the gam function. The model allows estimating when the analyzed function is growing and when it has a flat course. The results of the analysis of temperature changes during the experiment were presented on Fig. 6.

Fig. 6. The analysis of temperature changes during the operating time.

There are relatively large temperature fluctuations for the No. 1 probe compared to the other probes. For probe No. 1 $R^2 = 0.699$ can suggest the relatively weak linear relationship between temperature and operating time. For other probes the R-squared values can indicate the model has a good fit in the analysed time period; R-squared is equal 0.938; 0.959; 0.966. In the Fig. 7 the dotted, vertical lines show the analyzed range to determine the linear regression equation. The regression equations are presented in Table 2.

Table 2. The regression equations for the analysed probes.

No. probe	regression equation; R-squared
1	$y = 7.95 + 0.00134 \cdot x; \quad R^2 = 0.699$
3	$y = 7.94 + 0.00205 \cdot x; \quad R^2 = 0.938$
5	$y = 7.91 + 0.00308 \cdot x; \quad R^2 = 0.959$
6	$y = 7.97 + 0.00363 \cdot x; \quad R^2 = 0.966$

Based on the analysis, for the assumed duration of the summer season, for the one VGHE no. 2 with output operating parameters, the mean increase in the temperature of the ground, from the heat source (as VGHE no. 2), was determined, which is:

- 0.2°C, for the probe no. 1 located at a distance of 5 m,
- 0.3°C, for the probe no. 3 located at a distance of 5 m,
- 0.5°C, for the probe no. 5 located at a distance of 2.5 m,
- 0.5°C, for the probe no. 6 located at a distance of 4.3 m.

The values above refer to temperatures at a depth of 70 m. The experimental process is beneficial to the COP of the GSHPs.

5 Conclusions

The aim of this work was to analyze the SAGSHP in heating-dominated climate during the regeneration process. The analyzed SAGSHP is located in “INNO-EKO-TECH Innovative Research and Didactic Center for Alternative Energy Sources, Energy Efficient Construction and Environmental Protection” in the Bialystok University of Technology.

The VGHE No. 2 was used to ground regeneration. During the summer time – the operating time in experiment allows to determine the increase the ground temperature in the

vicinity of source of heat. The total soil thermal storage quantity was 6,308.8 kWh. The solar energy utilization efficiency is 59%. There is the increase of the ground temperature within a radius of up to 5 m. At this distance, the temperature has increased by 0.2; 0.3°C. In the case of closer distances, 2.5 m and 4.3 m, the temperature has increased 0.5°C.

Thermal storage process can be used in transition season. In cold climate can make full use of solar energy in transition season, set ground in thermal equilibrium and improve efficiency GSHP operated efficiently in winter.

In future study determination of effectiveness of the ground thermal storage is necessary. The advanced configuration types of SAGSHP systems were found to be considerable interest for further investigations. Reviewed studies indicate that the effect of solar heat energy on the performance of both collector and heat pump is significant.

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