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The Solar-Assisted Vertical Ground Source Heat Pump System in Cold Climates—A Case Study †

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Abstract: In this paper, experimental studies were performed for a solar ground source heat pump system (SGSHPS) with a vertical ground heat exchanger (VGHE). The experiment was operated during the summer in 2018. The heat from the solar collector was monitored by measuring the inlet and outlet temperatures and flow rate of the heat transfer fluids. An energy equilibrium balance carried out indicates heat extraction from the solar collector to the ground heat exchanger. It has been established that clear impact is achieved within a radius of 5 m. The average temperature of the actively regenerated borehole was higher than that of the undisturbed profile, which has a direct impact on the significant benefits of the coefficient of performance (COP) of the ground source heat pump system (GSHPS) and effectively helps soil regeneration. The average efficiency ratio of the heat transferred from solar radiation to soil in the SGSHPS was 42.3%.

Keywords: vertical ground heat exchanger; ground source heat pump system; solar ground source heat pump system; solar energy

1. Introduction

Nowadays, heat pumps are used for heating and cooling in many kinds of building. Systems with heat pumps are regarded as technology of renewable energy [1]. Currently, the most popular way of receiving heat is via the ground. In Poland, the most popular and common way of extracting heat from the ground is with a vertical ground heat exchanger (VGHE) and a horizontal ground heat exchanger (HGHE). The ground is a suitable source of heat for a heating system based on heat pump [2]. The vertical ground heat exchanger has a near-constant flow temperature in a short period with a minimally changeable flow temperature during the heating season. Radial ground cooling occurs in the distance of a few meters around the borehole [3]. Active soil regeneration during summer time is crucial for the coefficient of performance (COP) of the ground source heat pump system (GSHPS).

Poland has a heating-dominated climate. The north-eastern part of Poland has a colder climate compared to western and southern Poland. As a result, the heating season is longer and the GSHP performance can become less efficient. [4]. This problem is obvious, especially in cold regions [5]. Furthermore, the heating and cooling systems based on the heat-pump are expected to be reliable for 20 years, while the buildings are designed for 50 years [6]. The GSHPS performance may become more efficient when using a solar thermal energy storage system [7]. Seasonal storage of solar thermal energy coupled with a heat pump has been the subject of many investigations.

Researchers in northern European countries also began investigating seasonal solar thermal energy storage systems in the 1970s [8]. The idea of the solar ground source heat pump system (SGSHPS), which combines the use of a solar collector and a ground heat exchanger (GHE) so that the excess solar energy collected during the day time can be saved in the ground by the GHE, was firstly put forward by Penrod [9]. Penrod has made a detailed study regarding the problem of soil as a heat source. The temperature of undisturbed and disturbed soil was measured and compared. A complete procedure for designing the proposed SGSHPS was introduced by [10].

The engineering project, in which the integration of a solar system and geothermal energy was presented, can be found in [11–14]. These papers present detailed descriptions of the comprehensive review on research and developments on solar-assisted compression heat pump systems, mostly reported during the last two decades. According to the papers, solar thermal collectors can balance ground loads over a yearly cycle and can assist in maintaining more efficient heat pumps. Experimental studies on a solar-assisted heat pump water heating systems were performed in [15]. According to the authors, the temperature resumption of ground surrounding the VGHE can be achieved due to the intermittent heat extraction of a VGHE or by feeding solar heat into the ground.

Pärisch et al. [16] investigated the heat pump behaviour under non-standard conditions for the operation of a GSHP in combination with solar collectors. The results showed that rising source temperatures only significantly increase the COP of a heat pump if the source temperature is below 10–20 °C. Some of the influential parameters on the energy efficiency of a novel solar-assisted absorption ground-coupled heat pump in its cooling mode operation are presented in [17]. Experimental investigation of a solar-assisted ground source heat pump SGSHP system was carried out from morning to evening for winter climatic conditions in [18]. In [19], reviewed studies indicate the effect of solar heat energy on the performance of the collector and the heat pump individually to be majorly significant.

2. System Description

The paper presents experimental studies on the performance of the SGSHPS. The experimental platform was installed in new building of the Bialystok University of Technology, named as "INNO–EKO–TECH Innovative Research and Didactic Centre for Alternative Energy Sources, Energy Efficient Construction and Environmental Protection", northeast Poland. The SGSHPS works as two independent sub-systems: the first, during the summer, as a ground thermal storage system; the second, during the heating season, as a heating GSHPS with a source of energy provided by a ground heat pump system with a VGHE. The exact description of the system is presented by the author in [20,21].

Figure 1 presents the SGSHPS. The SGSHPS in mainly composed of six parts: two types of solar collectors, a heat pump, a water tank, a vertical ground heat exchanger and a measurement system.

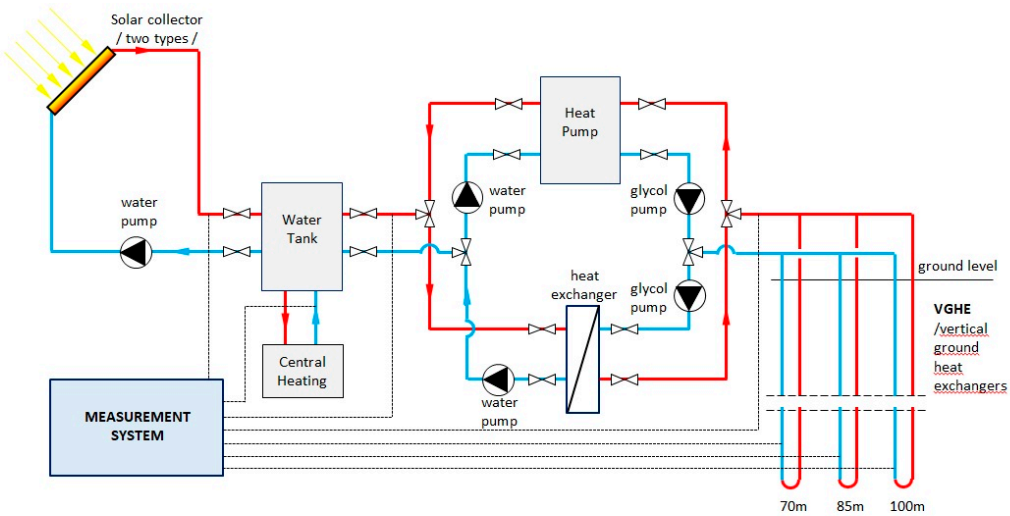


Figure 1. A ground source heat pump seasonal storage system based on a heat pump.

For each VGHE, there are measurement sensors of up to 100 m in depth that verify the ground temperature profile. The undisturbed ground temperatures were measured in each borehole. The probes were 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.

3. Experimental Data Analysis

The temperature profiles for each borehole were obtained directly from the ground temperature measurement system. The undisturbed ground temperature is very important data for the design of boreholes connected with heating and cooling systems based on ground source heat pumps. The undisturbed ground temperature is presented in Figure 2. Importantly, the thermal characteristics do not correspond to the most common soil type in Poland.

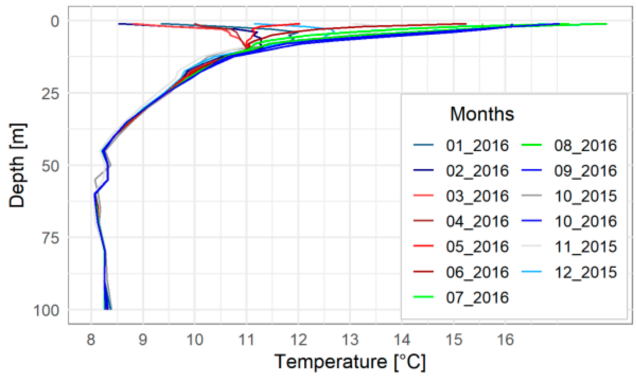


Figure 2. The undisturbed ground temperature profile.

To calculate the energy transfer from solar radiation to soil as storage heat quantity during the performance of the SGHPS, the flow rate and the temperature input and output of the water tank were measured. The energy equilibrium equation for the thermal storage process can be described as follows:

$$\begin{aligned} E_S &= E_{VGHE} + E_D \\ E_D &= E_{D\_SC} + E_{D\_WT} + E_{D\_Comp} \end{aligned} \quad (1)$$

where:
E_S—heat quantity from solar radiation;
E_{VGHE}—heat storage quantity transferred by the VGHE to the soil;
E_D—dissipated heat quantity, on the solar collectors, E_{D_SC}; on the water tank, E_{D_WT}; and on other infrastructure components, E_{D_Com}. The measurement system allowed for the measurement of heat quantity from the solar collector, independently. Thus, Equation (1) in the experiment can be written as:

$$E_C = E_{VGHE} + E_{D\_WT} + E_{D\_Comp} \quad (2)$$

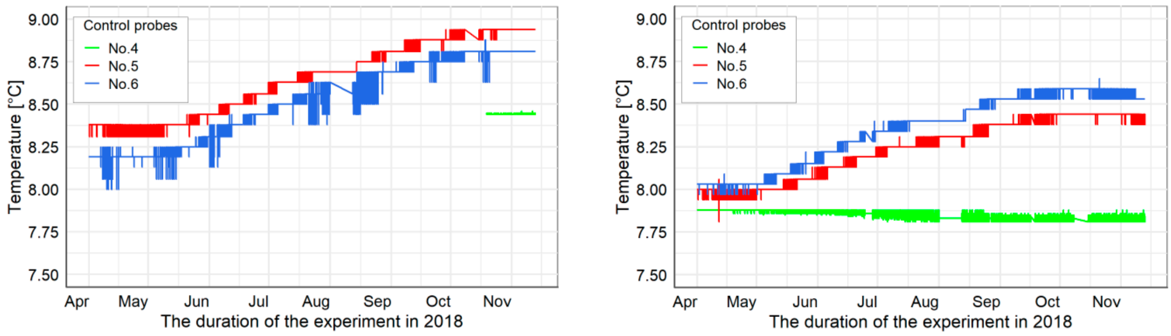
where: E_C—the heat quantity from the solar collector. It is important to research the energy transfer process for the real amount of heat obtained from solar radiation. Heat quantity E_D was determined in the experiment as the difference between the heat supplied to the water tank and the heat supplied to the vertical ground heat exchanger. Heat quantity E_{VGHE} was determined from Equation (3):

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

where:
c_p—specific heat at a constant pressure of the glycol, J/(kg °C);
m—mass flow rate, kg/s;
t— measurement frequency, every five minutes; ;
i—operation period;
N—number of cycles in the analysed period.

In the experiment, one vertical ground heat exchanger—No. 2—was a source of energy for the ground. From 1 April 2018 to 12 November 2018, the total amount of heat quantity from the solar collector during the experiment was 7066.4 kWh. The average efficiency ratio of the heat transferred from solar radiation to the water tank in the SGSHP system was respectively 61.3% for the heat-pipe collector and 39.1% for the flat collector. The total heat quantity in the thermal storage experiment time was calculated from (3) and equalled 5785.3 kWh. The average efficiency ratio of heat transferred from solar radiation to the soil mass in the SGSHPS system was 42.3%. The supply temperature fluctuates from near 25 °C to 30 °C in the summer.

The temperature profiles for each borehole were obtained directly from the ground temperature measurement system. The examples of the disturbed ground temperature, for control probes No. 4, 5 and 6, for depth of 40 and 70 m, are presented in Figure 3a,b. Some information regarding control probe No. 4 was unavailable.



(**a**) (**b**)

Figure 3. (**a**) The disturbed ground temperature profile for control probes No. 4, No. 5 and No. 6 at a depth of 40 m. (**b**) The disturbed ground temperature profile for control probes No. 4, No. 5 and No. 6 at a depth of 70 m.

4. Conclusions

In this paper, an experiment with a solar ground source heat pump system (SGSHPS) in a heating-dominated climate zone was presented. The SGSHPS can be treated as active ground regeneration. The method provides a higher effect than the natural return to the initial temperature profile. The average temperatures of the actively regenerated a borehole that was higher than the undisturbed profile.

The SGSHPS was operating over 221 days. The total solar radiation quantity was 13,679.7 kWh. The total amount of heat quantity from the solar collector was 7066.4 kWh. The heat quantity that was transferred to the soil was 5785.3 kWh. The average efficiency ratio of the heat transferred from solar radiation to the soil in the SGSHP system was 42.3%.

The rise in temperature causes a significant increase in the COP of the GSHPs. The influence of this regeneration on heat pump performance will be visible during heat pump operation in the next heating season. Effectiveness of the regeneration capabilities of the ground mass in the summer period by using the SGSHPS was confirmed.

An objective for the future is to analyse the efficiency of the GHPS and the economic efficiency based on the data from the following seasons.

This paper shows that SGSHPS technology causes soil to be in a state of thermal equilibrium and improves efficiency of the GSHPS in the winter season of a heating-dominated climate like in Poland.

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