Variability of Soil Temperatures During 5 Years of a Horizontal Heat Exchanger Operation Co-operating with a Heat Pump in a Single-Family House

Joanna Piotrowska-Woroniak and Wiesław Załuska

Abstract The paper presents the results of measurements of the temperature distribution of the ground source heat with the brine-water heat pump and a horizontal ground heat exchanger. The research was carried out for a period of 5 years. The horizontal ground heat exchanger is a ground source for a heat pump with the measured average heating output of 9.53 kW and cooling capacity of 7.8 kW, installed in a single-family house located in the north-eastern part of Poland. A heat exchanger with the area of 253 m^2 is located at a depth of 1.9 m in the groundwater layer being in hydraulic contact with the waters of Lake Elk. During the first four years, each year it can be observed that soil of the ground heat source is chilling at a depth of 1.9 m, due to working heat pump. Between January and April heat pump was working with the ground source frozen, where the temperature ranged from −0.6 to −2.1 °C. Subsidence and cooling of the soil was caused by a relatively small active area of ground source of heat which was 253 m^2 with the dimensions of 11 m × 23 m, as well as inadequate spacing between sections of the spiral heat exchanger amounting to 0.1 m. After operational testing of the heat pump and the ground source of heat, the "microBMS" a control and optimization system, working independently from the heat pump control was introduced into the building in January 2014. Its introduction has significantly increased that lower minimum flow temperature of the heat exchanger to +0.3–0.9 °C. There was also an increase of the minimum temperature of the ground source heat exchanger by the value of +1.3–3.0 °C and decrease in cooling of the soil in August—an increase of temperature by about 0.7 °C. Operational tests of heat pump system working with an unusual and original application of horizontal spiral heat exchanger have shown that in the first period introduction of an additional heat exchanger was considered. In subsequent years of heat pump operation and after the introduction of its independent monitoring and optimization, the study showed good properties of ground source and its complete recovery in the summer. Ground source, chilled properly to a temperature

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of about 0 °C became a very good cooling reservoir during periods of spring and summer heat. The use of the Earth's heat helps to improve the environment, while in some way it violates the natural thermal and agrophysical condition of the ground. Operation of ground source heat pump affects the periodic changes of agro-thermal parameters of soil. The delay of the vegetation period above the horizontal heat exchanger of heat pump is about 13 days and is caused by postponed thawing of ground observed at 0.05 m.

Keywords Temperature distribution · Horizontal ground heat exchanger
Ground · Heat pump

1 Introduction

Horizontal ground heat exchanger is one of the simplest forms of energy stored in soil.

The ground temperature varies with depth, intensive change can be observed in the subsurface layers, where the accumulation of solar heat, and the temperature variation depends on the season. The temperature in these layers is influenced by weather factors, i.e.: precipitation, solar radiation, air humidity and velocity, atmospheric pressure, and the type of ground cover [1]. Temperature fluctuations associated with the change of seasons decline beneath the depth of frost penetration. In agrotechnics, the area used for cultivation is the ground area of the soil which is characterized by intense temperature fluctuations.

Temperature changes of subsurface layers related to climate change have a significant impact on the amount of heat flow [2], and the depth and structure of soil affects the volume of obtained heat.

The researches on soil temperature were carried out, among others, in Montana [2], Japan [3], the UK [4], New Zealand [5] or Cyprus [6] Predicting the ground temperature is an important element for the analysis of the assessment of energy resources. Huining and Spitler [2] studied the effects of moisture, residual layer of snow, freezing and thawing of soil temperature changes in the soil at different depths and times of the year.

Heating systems based on heat pumps with horizontal ground heat exchangers use the heat stored in soil and water environment. In case recommended minimum spacing between the horizontal coils or vertical ground exchangers is not maintained, installations can locally affect the environment by lowering the temperature of the soil–water source, from which heat is collected [7, 8].

This can cause a shift in the vegetation period of plants. The soil temperature has a major impact on plant growth, at a temperature below 0 °C root system is not able to draw water and thereby to develop. Plants for the passage of a full cycle of growth and development not only require a certain amount of heat, but also the appropriate exposure time of thermal conditions. Ground heat exchangers intensively exploited may affect the growing period of some plants.

The greatest temperature changes are noticeable in shallow layers, where the frost penetrates the ground, which is related to the rapid reaction of the subsurface area to daily and short-term weather changes [1].

The vegetation period of the plants, which is calculated on the basis of the number of days in a year in which the average temperature is at least 50, ranges from 185 to 225 days in Poland, the longest one is in the Odra valley and in the Tarnów area (220 days) and the shortest one is in Masuria Lake District (less than 200 days) and in the mountains (less than 190 days).

At present, very often the issue of analytical or numerical optimization of horizontal ground heat exchangers, as ground source energy for heat pumps is addressed in scientific literature [9–16]. Experimental investigation of spiral ground heat exchanger running in British climate have been carried out, among others, by Wu et al. [15].

One of the advantages of using low-temperature geothermal systems on a global scale is that it contributes to reducing greenhouse gas emissions to the atmosphere and allows restrictions and more economical use of fossil fuels.

The paper presents results of temperature distribution in the soil to a depth of 1.9 m with a spiral ground heat exchanger during heat pump operation and temperature measurement of soil to a depth of 1.5 m unencumbered with work of horizontal ground heat exchanger. It also shows the results of studies carried out over five years on spiral ground heat exchanger, experimentally arrangement at intervals of 0.1 m from each other, which resulted in a design of an innovative, almost no-cost, heat and cold container.

2 Object of the Study

A horizontal ground heat exchanger subjected to tests is a ground source of heat for brine-water heat pump, with heating output of 9.53 and 7.8 kW of cooling capacity. Is made with polyethylene pipes with a diameter of 25 mm. It was laid at a depth of 1.9 m below the freezing zone. The heat exchanger was made in the form of 10 spiral collectors with a width of 1 m and length of 100 m each. Spacing between heat exchangers amounted to 0.1 m. The design also included a collection sump with 10-pipe manifold joining all loops.

Experimentally reduced distance between spiral heat exchangers was due to residues of groundwater remaining in hydraulic contact with the waters of Lake at this depth. Possible freezing of land and shift of the vegetation season were expected. Introduction of supplementary horizontal heat exchanger or vertical probes placed in the ground as an additional ground source of heat for the heat pump was considered in case of insufficient output of the ground source or drop in temperature of the heating medium below the critical value for the heat pump. The design recommended distance between the horizontal spiral ground heat exchanger should be at least 4 m [17].

Active area of an exchanger is 11 m × 23 m, F = 253 m^2. Ground heat exchanger due to the high groundwater level occurring in this area was arranged in a layer of water. Ground heat exchanger is located about 200 m away from Lake. View of ground heat exchanger location near Lake is shown in Fig. 1.

The heat pump was installed in February 2010 and it operates in a monovalent system providing heat for central heating and hot water for domestic use.

The method of laying of the exchanger is shown in Fig. 2.

Figure 3 presents the area that is taken by a horizontal spiral ground heat exchanger, along with the location of measuring probes.

The ground heat exchanger research was conducted over a period of 5 years.

For measuring the soil temperature above the ground source exchanger at depths: 0.05, 0.5 and 1.8 m and in an inspection hole at depths 0.05, 0.5 and 1.5 m temperature sensors DS18B20 type by Dallas were used.

The applied temperature sensors type DS18B20 provide a temperature measurement with a resolution set in a range from 9 to 12 bits. Temperature range is from −55 to +125 °C. For the measurement of the temperature, sensors were calibrated in the temperature range with an accuracy of ±0.1 °C. Calibration of sensors allowed to avoid errors occurring due to overlapping of deviations in the final reading. Placing sensors in a relatively thermally stable environment (ground) and using measuring system with simultaneous statistical processing of temperature signals sampled every minute, resulted in an additional and surprising possibility to

Fig. 1 Location of a ground exchanger nearby Lake (photo by authors)

Fig. 2 Laying the ground source heat pump system at a depth of 1.9 m, 10 loops 100 m each, active area of the exchanger is 11 m × 23 m (photo by authors)

increase the sensitivity of the dynamics of the processes of registration to the value of ±0.01 °C.

Figure 4 shows an exemplary recorded dynamics of the heat exchanger work with its gradual cooling from 9 March to 16 March with an accuracy of ±0.01 °C.

3 Results of the Studies and Analysis

From 2010 to 2015 year, soil temperature measurements were carried out over the ground heat exchanger at depths: 0.05, 0.5 and 1.8 m, as well as temperature measurements of ground undisturbed by work of heat exchanger at depths of 0.05, 0.5 and 1.5 m in a control hole and operation of the heat pump was monitored. The heat pump provides heat for central heating and hot water for domestic use.

Changes of temperature of ground source of heat within five heating seasons and running time of the heat pump in each month is shown in Fig. 5.

Fig. 3 A view of the area taken by a ground source heat exchanger (photo by authors)

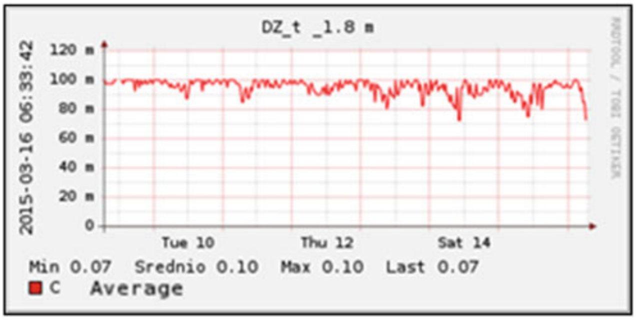

Fig. 4 A graph representing dynamics of temperature changes of the ground source registered at a depth of 1.8 m from 9 until 16 March 2015

During several years of operation of ground heat exchanger (Fig. 5) its cyclical character can be noticed. Four clear periods of work can be noticed: (1) cooling period September–January, (2) period of work with the ground source frozen January–April (approximately 64–107 days), (3) ground source recovery period May–August, (4) re-cooling of the ground, starting with the beginning of the heating season from the second half of September.

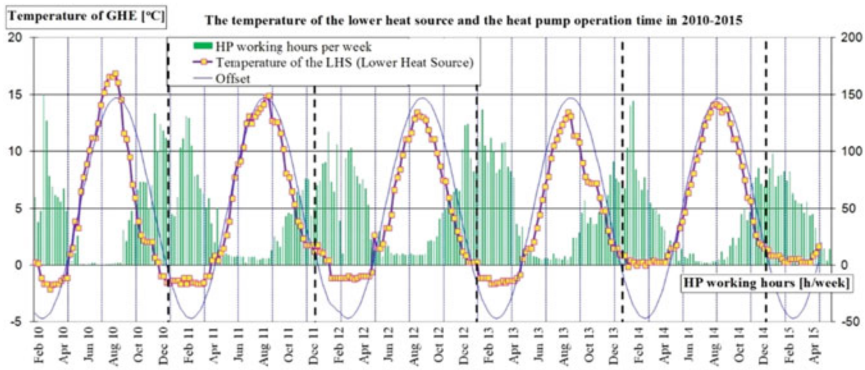

Fig. 5 Comparison of seasonal temperature distributions during the ground heat exchanger operation and the number of the heat pump operating hours

During the first four years, each year it can be observed that soil of the ground heat source is chilling at a depth of 1.9 m, due to working heat pump. Between January and April heat pump was working with the ground source frozen, where the temperature ranged from −0.6 to −2.1 °C. Subsidence and cooling of the soil was caused by a relatively small active area of ground source of heat which was 253 m^2 with the dimensions of 11 m × 23 m, as well as inadequate spacing between sections of the spiral heat exchanger amounting to 0.1 m.

Figure 6 shows the work of ground source of heat in 2013 and running time of the heat pump. The freezing of soil in 2013 to approximately −1.6 °C took place in mid-February, and in March the temperature remained at −1.5 °C to drop in April to −0.8 °C. Working time of ground source at freezing temperatures was 99 days.

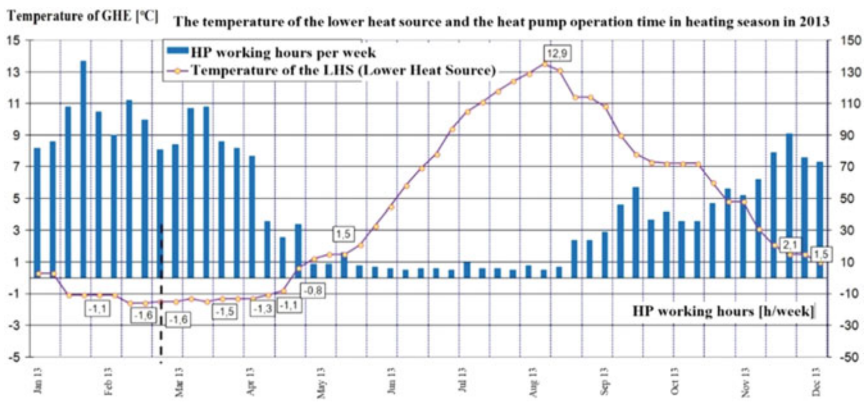

Fig. 6 Changes of temperature of ground source of heat from and running time of the heat pump in 2013

The temperature above zero was not recorded in 2013 until 5 May and amounted to +0.6 °C. In earlier years ground source was also working in freezing temperatures.

In 2010 the lowest temperature occurred on March 21 and was −2.1 °C, which indicated intense operation of the ground source. Subzero temperature of the ground source remained from 28 February to 2 May and ranged from −1.1 to −2.1 °C (64 days). There were finishing works of the building in progress at that time so more energy was consumed for heating and removal of the so-called technological moisture which resulted in grater exploitation of the ground source. The heat pump should only be switched on after the building has been dried thoroughly. The temperature above zero at a depth of 1.9 m was not recorded until 9 May and it was +1.0 °C.

In 2011, the lowest temperature of ground source occurred in February and amounted to −1.6 °C. The first temperature above zero was only recorded on 24 April and amounted to +5 °C. The subzero temperature of the ground source sustained from 1 January to 17 April and ranged from −0.90 to −1.60 °C (107 days).

In 2012, the lowest temperature of the ground source was registered on 18 March and amounted to −1.2 °C, the temperature above zero was first recorded on 6 May and it amounted to +2.7 °C. The temperature of the ground source remained below zero from 2 February to 29 April, and ranged from −0.6 to −1.2 °C (88 days).

Despite intense cooling of the ground, or even freezing (−0.6 to −2.1 °C) for a period of nearly three months, ground source remained fully sufficient to supply a residential building with a usable area of 135 m^2 and an outbuilding of 75 m^2. Temperature maintained in the residential part amounted to +23 °C. Additionally run full monitoring of the heat pump helped to define the parameters of the heat pump and its Seasonal Performance Factor (SPF), which in 2014 amounted to 3.26.

The temperature of the ground source would probably be much lower during the heat pump operation, were it not that the heat exchanger was arranged in a layer of groundwater being in hydraulic contact with waters of Lake. The incoming water from the lake probably caused a rise in ground temperature. Horizontal ground heat exchanger is located about 200 m from the lake's shoreline (Fig. 3), hence the emphasis of a very large impact on ground heat exchanger work made by the waters of Lake.

Additionally, during the soil freezing, the ice cover on the spiral heat exchanger could increase its heat exchange surface. On the heat pump market appeared a solution using, as the ground source for heat pumps working on brine–water, instead of horizontal heat exchanger or vertical probes the energy storage device, called the ice tank [18] which allows to collect heat from the cooled water near 0 °C using the phase transformation of water–ice. This solution has already been used in heat pumps systems ACES (Annual Cycle Energy Systems) [19].

In this case, alongside using the original solution of spiral horizontal heat exchanger arranged with very small gaps in an aquifer it was possible to construct an almost cost-free, eco-friendly heating and cooling tank, thus increasing the efficiency of horizontal ground heat exchanger. A large amount of energy obtained

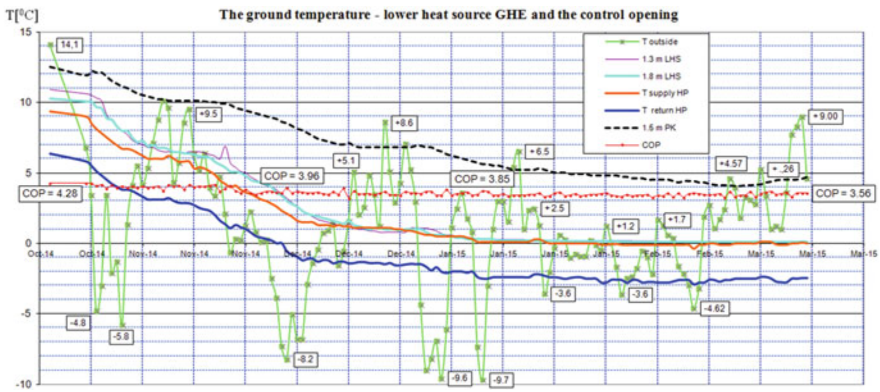

Fig. 7 Temperatures at different depths in the ground exchanger and the undisturbed soil in the period from October 2015 to April 2015, acronyms of term associated with temp. measurement: LHS—Lower Heat Source, supply HP—brine temperature at the entrance to the heat pump, return HP—brine temperature at the return from heat pump, PK—control measurement of soil

at a constant temperature close to zero corresponds to the cooling occurring at the phase change water–ice. It seems that the influx of underground waters being with permanent hydraulic contact with the waters of Lake acts as the auxiliary heat source used to melt unnecessary ice or its excessive quantities. In case of ice tanks, the additional source can be e.g. solar collectors.

Cyclical changes shown in Fig. 5, are very close to the theoretical sinusoid of annual changes of the temperature area on the test soil depth determined, among others by Baggs [20], Popiel et al. [21]. By introducing disturbance to the natural soil temperature area with the use of a horizontal ground heat exchanger, occurrence of different temperature areas can be noticed. Also, the amplitude of sinusoidal changes of ground source temperature has increased along with the rapid collapse at −2.1 to −1.6 °C. During the first four years of research the ground heat exchanger cooled down to below −1.6 °C.

Comparison of soil temperatures at different depths undisturbed by the heat exchanger and soil temperatures above the ground heat exchanger is shown in Fig. 7. According to the graph there was a reduction of soil temperature with the ground heat exchanger in relation to the ground in the undisturbed state. The undisturbed ground temperature is higher than the temperature of the ground with the ground heat exchanger.

After operational testing of the heat pump and the ground source of heat, the “microBMS” a control and optimization system, working independently from the heat pump control was introduced into the building in January 2014. Its introduction has significantly increased that lower minimum flow temperature of the heat exchanger to +0.3–0.9 °C. There was also an increase of the minimum temperature of the ground source heat exchanger by the value of +1.3–3.0 °C and decrease in cooling of the soil in August—an increase of temperature by about 0.7 °C.

The lowest temperature of the ground source of heat in 2014 was recorded on 19 January and it was −0.1 °C. In the period from February to April, where in previous years 2010–2013, the ground source was working in sub-zero temperatures, the measured temperature ranged from 0.0 to +0.9 °C. A graph of changes of temperature of the ground source in 2014 and the heat pump running time are shown in Fig. 8.

In 2015, the lowest measured temperature of the ground source was +0.3 °C and maintained from 8 February to 12 April 2015, as it is shown on Fig. 9.

The introduction of an independent optimization of the heat pump and the heat exchanger caused a decrease in the number of hours the heat pump running in winter and summer, which had impact on electricity consumption by the heat pump and the cost of its purchase. BMS system and optimization also contributed to the stabilization of the temperature in the building and thermal comfort.

The electricity consumption of the heat pump depends on its runtime and number of activation/deactivation times. The only noticed problem with exploitation resulting from gradual cooling and heating of the ground, was the need to periodically adjust the heating curve settings for the heat pump. From several years of operating experience it has been established that for the object in question it is effective to set the heating curve at 0.2–0.3 and the raising or lowering of the curve between 0° and 7° during the cooling of the ground source and a further reduction in the curve to 0° during the Spring. The need for raising the heating curve originates from a gradual decrease in the set temperature in the building by about 1 °C which is usually evident within about two weeks. Figure 10 shows a graph of correlation between the ground source temperature and heat pump operation time in the years 2010–2015.

Directly around a horizontal ground heat exchanger, the ground was periodically frozen in the second half of the heating season (February–April) which did not adversely affect the work of the heating system, whereas prolonging period of frozen soil affected only a shift in vegetation season. Freezing of the soil was

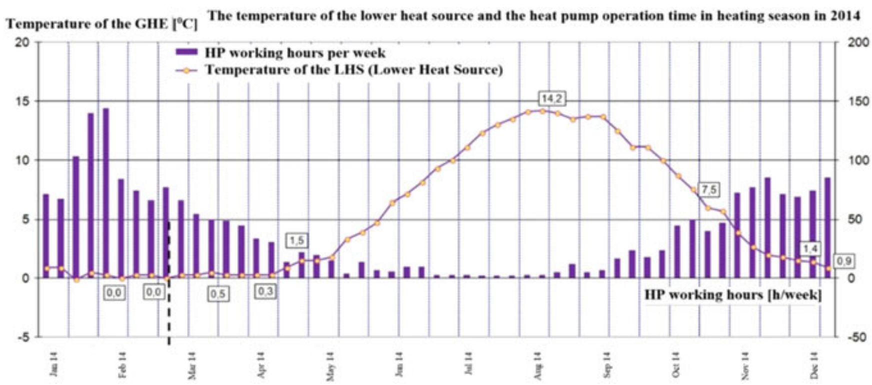

Fig. 8 Changes of temperature of the ground source and the heat pump running time in 2014

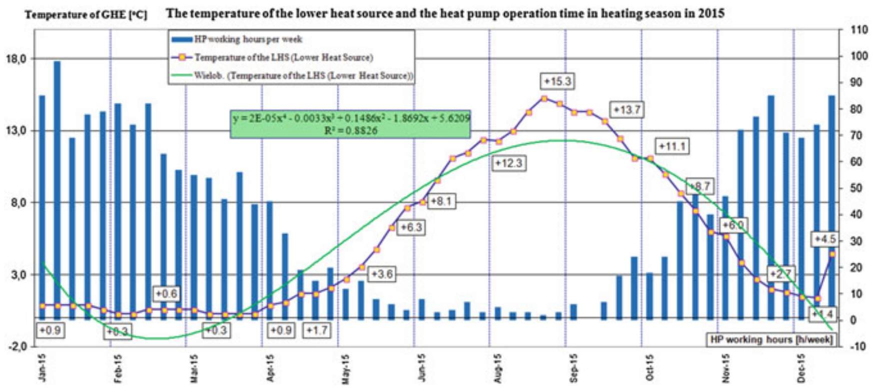

Fig. 9 Changes of temperature of the ground source and the heat pump running time in 2015

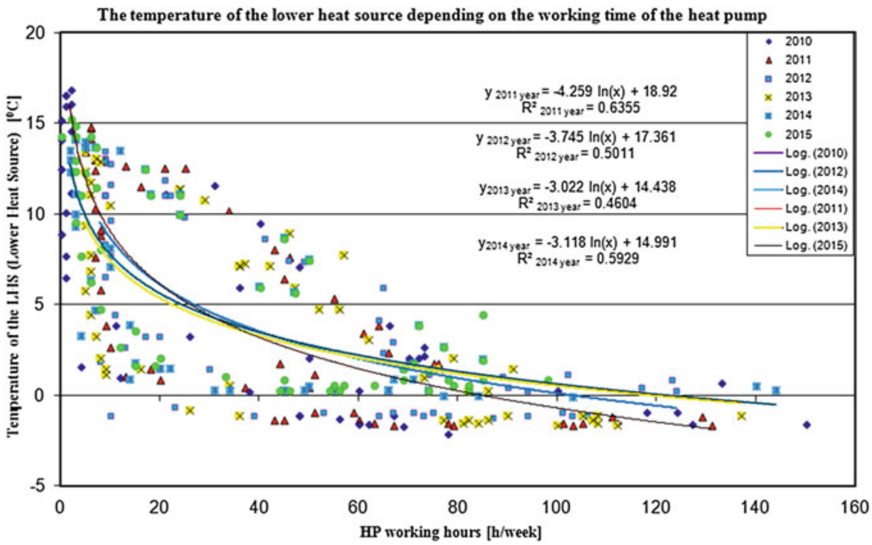

Fig. 10 Correlation between the ground source temperature and heat pump operation time within a week

affected by a too small area planned for the ground heat exchanger and too small gaps between the coils. This happens in the case of heat pumps extracting heat from the ground using horizontal ground heat exchangers which operate under full load. Overload on the heat exchanger caused a long-term decrease in temperature.

Figure 11 presents a graph of ground temperature changes for probes located above the horizontal exchanger at depths of 0.05, 0.5 and 1.8 m and in inspection hole at depths of 0.05, 0.5, 1.5 m from 11 February, 2015 to 11 March 2015.

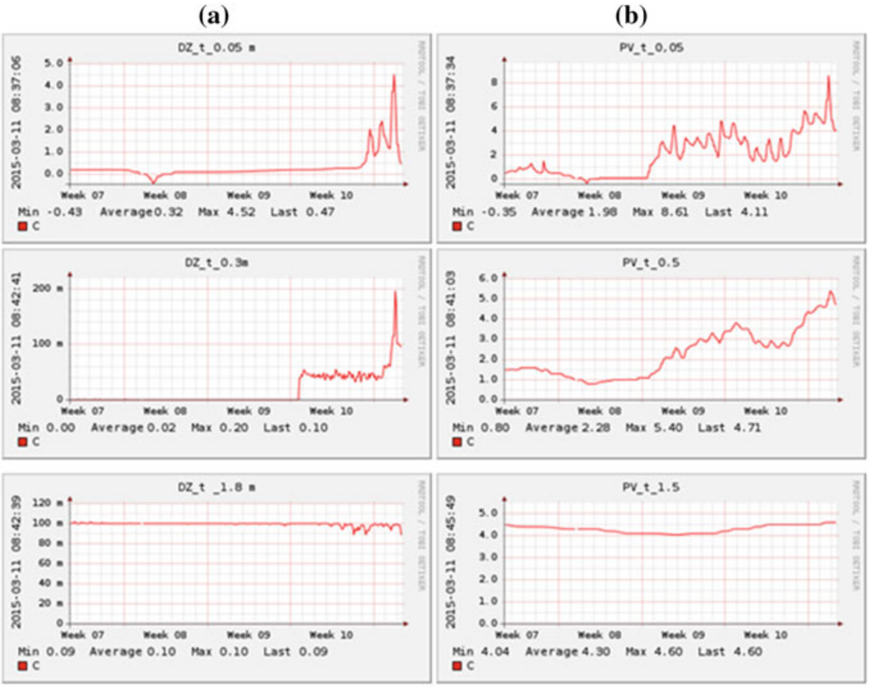

Fig. 11 Comparing of ground temperature measured: **a** above the ground source exchanger at depths: (DZ) 0.05, 0.5 and 1.8 m **b** in an inspection hole at depths: (*PV*) 0.05 m, *PV* 0.5 m and *PV* 1.5 m

While comparing the temperature changes it was noticed that a considerable increase in temperature for the inspection hole at a depth of 0.05 m occurred on 23 February, in the case of a probe above the heat exchanger thawing of the soil at a depth of 0.05 m took place on 7 March. The delay period for the soil temperature increase at a depth of 0.05 m, including the vegetation, was estimated for 13 days. Ground at a depth of 0.3 m—thawing noted earlier—on 2 March—the impact of heat from the ground while temperature drops to a depth of 1.8 m—cooling of the heat exchanger.

Figure 12 shows a thermal camera image of the area occupied by ground heat exchanger. It is visible that the temperature is clearly reduced in comparison to the surface area of the plot without the heat exchanger, which directly affects the delay of vegetation in this area.

The delay period of temperature increase and vegetation in the case of another type of ground where there were no groundwater in hydraulic connection with Lake, would probably be more than 13 days.

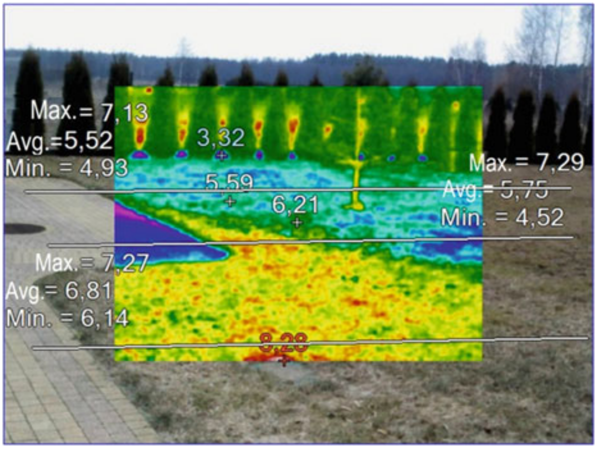

Fig. 12 A thermal camera image showing a lawn with a visible area occupied by the ground heat exchanger (photo by authors)

4 Summary

- Shift of seasonal cyclical changes of ground temperature areas were observed, caused by thermal distortion of operating horizontal exchanger of heat pump. For this particular case there was about a two-week shift in cyclical annual temperatures measured at a depth of 1.9 m.
- Operation of ground source heat pump affects the periodic changes of agro-thermal parameters of soil. The delay of the vegetation period above the horizontal heat exchanger of heat pump is about 13 days and is caused by postponed thawing of ground observed at 0.05 m.
- The soil at a depth of about 1.9 m of the exchanger is cooled to ca. 4.0 °C compared to control measurements and maintains until about mid-April. For the first four years of operation of ground heat exchanger with the ground source frozen working period lasted from January to April (approximately 64–107 days).
- The way of adjusting the heat curve and optimization of heat pump operation time influences to a great extent dynamic properties of ground source. Precise optimization of the heat pump allowed it to increase the minimum flow temperature of the ground source from −2.1 to 0.6 °C (2.7 °C increase).
- Operational tests of heat pump system working with an unusual and original application of horizontal spiral heat exchanger have shown that in the first

period introduction of an additional heat exchanger was considered. In subsequent years of heat pump operation and after the introduction of its independent monitoring and optimization, the study showed good properties of ground source and its complete recovery in the summer. Ground source, chilled properly to a temperature of about 0 °C became a very good cooling reservoir during periods of spring and summer heat.

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References

1. Zheng, T., Shao, H., Schelenz, S., Hein, P., Vienken, T., Pang, Z., Kolditz, O., Nagel, T.: Efficiency and economic analysis of utilizing latent heat from groundwater freezing in the context of borehole heat exchanger coupled ground source heat pump systems. Appl. Therm. Eng. **105**, 314–326 (2015). https://doi.org/10.1016/j.applthermaleng.2016.05.158
2. Huining, X., Spitler, J.D.: The relative importance of moisture transfer, soil freezing and snow cover on ground temperature predictions. Renew. Energy **72**, 1–11 (2014). https://doi.org/10.1016/j.renene.2014.06.044
3. Tarnawski, V.R., Leong, W.H., Momose, T., Hamada, Y.: Analysis of ground source heat pumps with horizontal ground heat exchangers for northern Japan. Renew. Energy **34**, 127–134 (2009). https://doi.org/10.1016/j.renene.2008.03.026
4. Gonzalez, R.A., Verhoef, A., Vidale, P., Main, B., Gan, G., Wu, Y.: Interactions between the physical soil environment and a horizontal ground coupled heat pump, for a domestic site in the UK. Renew. Energy **44**, 141–153 (2012). https://doi.org/10.1016/j.renene.2012.01.080
5. van Manen, S.M., Wallin, E.: Ground temperature profiles and thermal rock properties at Wairakei, New Zealand. Renew. Energy **43**, 313–321 (2012). https://doi.org/10.1016/j.renene.2011.11.032
6. Florides, G.A., Pouloupatis, P.D., Kalogirou, S., Messaritis, V., Panayides, I., Zomeni, Z., Partasides, G., Lizides, A., Sophocleous, E., Koutsoumpas, K.: The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus. Energy **36**, 5027–5036 (2011). https://doi.org/10.1016/j.energy.2011.05.048
7. Congedo, P.M., Colangelo, G., Starace, G.: CFD simulations of horizontal ground heat exchangers: a comparison among different configuration. Appl. Therm. Eng. **33–34**, 24–32 (2012). https://doi.org/10.1016/j.applthermaleng.2011.09.005
8. Vietel, M., Rouabhi, M., Tijani, M., Guerin, F.: Modeling heat transfer between a freeze pipe and the surrounding ground during artificial ground freezing activities. Comput. Geotech. **63**, 99–111 (2015). https://doi.org/10.1016/j.compgeo.2014.08.004
9. Fujii, H., Nishi, K., Komaniwa, Y., Chou, N.: Numerical modeling of slinky-coil horizontal ground heat exchangers. Geothermics **41**, 55–62 (2012). https://doi.org/10.1016/j.geothermics.2011.09.002
10. Kim, J., Lee, Y., Yoon, W.S., Jeon, J.S., Koo, M.-H., Keehm, Y.: Numerical modeling of aquifer thermal energy storage system. Energy **35**, 4955–4965 (2010). https://doi.org/10.1016/j.energy.2010.08.029
11. Fontaine, P.O., Marcotte, D., Pasquier, P., Thibodeau, D.: Modeling of horizontal geoexchange systems for building heating and permafrost stabilization. Geothermics **40**, 211–220 (2011). https://doi.org/10.1016/j.geothermics.2011.07.002

12. Al-Hinti, I., Al-Muhtady, A., Al-Kouz, W.: Measurement and modelling of the ground temperature profile in Zarqa, Jordan for geothermal heat pump applications. Appl. Therm. Eng. **123**, 131–137 (2017). https://doi.org/10.1016/j.applthermaleng.2017.05.107
13. Adamovsky, D., Neuberger, P., Adamovsky, P.: Changes in energy and temperature in the ground mass with horizontal heat exchangers—The energy source for heat pumps. Energy Build. **92**, 107–115 (2015). https://doi.org/10.1016/j.enbuild.2015.01.052
14. Qi, D., Pu, L., Sun, F., Li, Y.: Numerical investigation on thermal performance of ground heat exchangers using phase change materials as grout for ground source heat pump system. Appl. Therm. Eng. **106**, 1023–1032 (2016). https://doi.org/10.1016/j.applthermaleng.2016.06.048
15. Wu, Y., Gan, G., Verhoef, A., Vidale, P.L., Gonzalez, R.G.: Experimental measurement and numerical simulation of horizontal-coupled slinky ground source heat exchangers. Appl. Therm. Eng. **30**, 2574–2583 (2010). https://doi.org/10.1016/j.applthermaleng.2010.07.008
16. Dehghan, B.: Experimental and computational investigation of the spiral ground heat exchangers for ground source heat pump applications. Appl. Therm. Eng. **121**, 908–921 (2017). https://doi.org/10.1016/j.applthermaleng.2017.05.002
17. Lachman, P. (eds.): Guidelines for design, construction and commissioning of heat pump installations, part 1. Lower Heat Source Sources. Polish Organization for the Development of Heat Pump Technology, Cracow (2013) (in Polish)
18. Zheng, T., Shao, H., Schelenz, S., Hein, P., Vienken, T., Pang, Z., Kolditz, O., Nagel, T.: Efficiency and economic analysis of utilizing latent heat from groundwater freezing in the context of borehole heat exchanger coupled ground source heat pump system. Appl. Therm. Eng. **105**, 314–326 (2016). https://doi.org/10.1016/j.applthermaleng.2016.05.158
19. Hsiao, M.J., Kuo, Y.F., Shen, Ch., Cheng, Ch.: Performance enhancement of a heat pump system with ice storage subcooler. Int. J. Refrig. **33**(2), 251–258 (2010). https://doi.org/10.1016/j.ijrefrig.2009.11.002
20. Baggs, S.A.: Remote prediction of ground temperature in Australian soils and mapping its distribution. Sol. Energy **30**(4), 351–366 (1983). https://doi.org/10.1016/0038-092X(83)90189-5
21. Popiel, C.O., Wojtkowiak, J., Prętka, I.: Effect of surface cover on ground temperature season’s fluctuations. Found. Civil Environ. Eng. **1**(2), 151–164 (2002). bwmeta1.element.baztech-article-BPP1-0042-0084