CHANGES IN TEMPERATURE AND ENERGY IN THE GROUND MASS WITH LINEAR HORIZONTAL HEAT EXCHANGER

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Abstract
The aim of the verifications was to analyze the temperature changes of the ground mass with linear HGHE in the heating period, determine the values of the heat flows and energies extracted from the ground mass via linear HGHE and evaluate the temperature regeneration of the ground mass during the HGHE stagnation. The linear HGHE is made from polyethylene piping PE 100RC 40×3.7 mm. HGHE with a total length of 330 m was installed at a depth of 1.8 m in three loops with a spacing of 1 m. Monitoring and analysing the linear HGHE showed that the average daily ground mass temperatures with linear HGHE were above zero in the heating season and energy extraction from the ground mass reached 16.98 $kWh \cdot m^{-2}$. Temperature difference of the ground mass within the linear HGHE area at the beginning of the heating seasons 2013/2014 and 2012/2013 was quite insignificant.

Key words: heat pump, ground mass, horizontal ground heat exchanger, temperature, heat flow, thermal energy, thermal characteristics of the ground mass.

INTRODUCTION

The energy potential of the ground mass is used via horizontal ground heat exchangers (HGHE) or vertical ground heat exchangers (VGHE), where a heat-transfer fluid is wormed up by the heat contained in the ground or rock mass, and supplied to the evaporator of the heat pump; thereby it performs a function of its low-potential source. According to BRANDL (2006), HGHE are made linear, helical or spiral; they require larger land area than VGHE but demand smaller investment costs. They present a compromise between high efficiency and investment costs. Mainly linear HGHE are widespread in the Czech Republic. In terms of usable energy potential, HGHE durability and good performance of the whole energy system, the knowledge of thermal characteristics of the ground mass, temperatures, extracted heat and heat flows at a given HGHE configuration are important. Especially knowledge of mutual interconnections is of essential importance, allowing optimizing HGHE design and operation and the operation of the entire system. Also the knowledge of the regeneration capabilities of the energy potential in the stagnation period or during its partial use in summer period is important.

One of the most important variables influencing the effect of the heat pump is the temperature of the medium of the low-potential energy source supplied to the evaporator of the heat pump. This results from the reversed cooling Carnot cycle. Its effect, which is expressed by the heating factor for a heat pump, is the higher, the smaller the temperature difference at which we supply and drain the heat of the cycle. Results of our verifications NEUBERGER ET AL. (2014), ADAMOVSKÝ ET AL. (2015) as well as verifications and modelling of foreign authors INALLI AND ESEN (2004), KUPIEC ET AL. (2015) showed that for most of the heating period the temperatures of the ground mass are higher than the ambient air temperatures. In the summer period, the ground mass temperatures are on the contrary lower than the ambient air temperatures. This fact makes more favourable ground mass, in comparison to the ambient air, as stable low-potential source for the heat pumps for heating of the buildings in the winter period and for their cooling in the summer period.

The aim of the verifications was to:

- Analyze the temperature changes of the ground mass with linear HGHE in the heating period;
- Determine the values of the heat flows and energies extracted from the ground mass via linear HGHE in the heating period;
- Evaluate the temperature regeneration of the ground mass during the HGHE stagnation.

The following hypotheses were verified:

a) The ground mass temperatures in the heating period will be mostly above zero. The ground mass temperatures in the HGHE area will be below zero only in exceptional cases;
b) The ground mass temperatures in the heating period in the HGHE area will be lower by maximum 4 K than the reference temperature of the ground mass;
c) The ground mass temperatures in the heating period will comply with the VDI STANDARDS (2001);
d) The energies extracted from the ground mass will comply with the VDI STANDARDS (2001);
e) The temperature difference of the ground mass at the beginning of the heating period will not be significant.

HEPBURN ET AL. (2016) devoted to sustainability of HGHE as a low-potential energy source for heat pumps, depending on temperatures and thermal characteristics of the ground mass. Extensive measurements brought new knowledge of the influence of heat extraction by HGHE and ambient climatic conditions on the ground mass. The interaction between the ground mass and HGHE was addressed by GARCIA ET AL. (2012) and POPIEL (2001). The values and distribution of the temperatures in the ground mass with HGHE used as a low-potential energy source for a conventional heat pump with a compressor and absorption heat pump is addressed by WEI (2013). PHILLIPPE ET AL. (2010) monitored responses of the ground mass temperatures to horizontal GSHP system within four different surfaces of the ground mass. BANKS (2012) evaluated the influence of the heat-transfer fluid flow type on specific heat output of the HGHE and indicated limit values of the energy extraction from the ground mass in the heating period.

MATERIALS AND METHODS

2.1 Determination of the course of the average daily temperatures

Based on the equation of free, undamped oscillation of a mass point, NEUBERGER ET AL. (2014) formulated the dependence of the average daily ground mass temperatures in the heating period:

$$t_{GR} = \bar{t}_G + \Delta t_{am.} \cdot \sin(\Omega.\tau + \varphi)\,(°C) \quad (1)$$

Where:

t_{GR} - ground mass temperature (°C); $\bar{t}_G$ - mean ground mass temperature (°C);

$\Delta t_{am.}$ - oscillation amplitude around the temperature $\bar{t}$ (K); τ - number of days from the start of measurement (day);

φ - initial phase of oscillation (rad); Ω - angular velocity ($2 \cdot \pi / 365$ rad $\cdot$ day^{-1}).

According to BOWERMAN ET AL. (1997), a determination index I_{yx}^2 (-) was used to determine the degree of tightness in the relation between both random quantities.

2.2 Measurement methods

The linear HGHE is made from polyethylene piping PE 100RC 40×3.7 mm (LUNA PLAST Inc., Hořín, Czech Republic) resistant to point loads and cracking. HGHE with a total length of 330 m with heat transfer surface 41.473 m^2 was installed at a depth of 1.8 m in three loops with a spacing of 1 m. The length of each loop is 54.62 m. The land area with HGHE is 273 m^2.

The layout identifying the location of temperature sensors and HGHE is presented in Fig. 1 and 2.

The heat-transfer fluid flowing through the heat exchanger was a mixture of 33% ethanol and 67% water. The tested HGHE was one of the energy sources for heat pumps IVT PremiumLine EQ E17 (Industriell Värme Teknik, Tnanas, Sweden) with a nominal heat output of 17 kW (0/35 °C). The heat pumps were used only for heating, not for cooling the administration building and manufacturing halls of the company VESKOM Ltd. based in Prague, Dolní Měcholupy.

The ground mass profile, where the HGHE is deposited, consists of two layers; an arable land layer (approximately 0.25 m) and a layer of detritus (approximately 2 m), consisting of dark-brown sandy loam soil, coarse gravel, crushed rock and bricks debris.

The ambient air temperatures t_e were measured at a height of 2 m above the soil surface and at a distance of 20 m from the horizontal ground heat exchangers by sensor ALMEMO FHA646AG (AHLBORN Mess- und Regulungstechnik, Holzkirchen, Germany). The ground mass temperatures were measured by sensors GKF 125 and GKF 200 (GREISINGER electronic GmbH, Regenstauf Germany). All temperatures were recorded at half-hour intervals by measuring operators ALMEMO 5990 and ALMEMO 2890-9 (AHLBORN Mess-und Regulungstechnik, Holzkirchen, Germany). Global radiation sensor FLA613GS (AHLBORN Mess-und Regulungstechnik, Holzkirchen, Germany) was used to measure the intensity of the incident solar radiation.

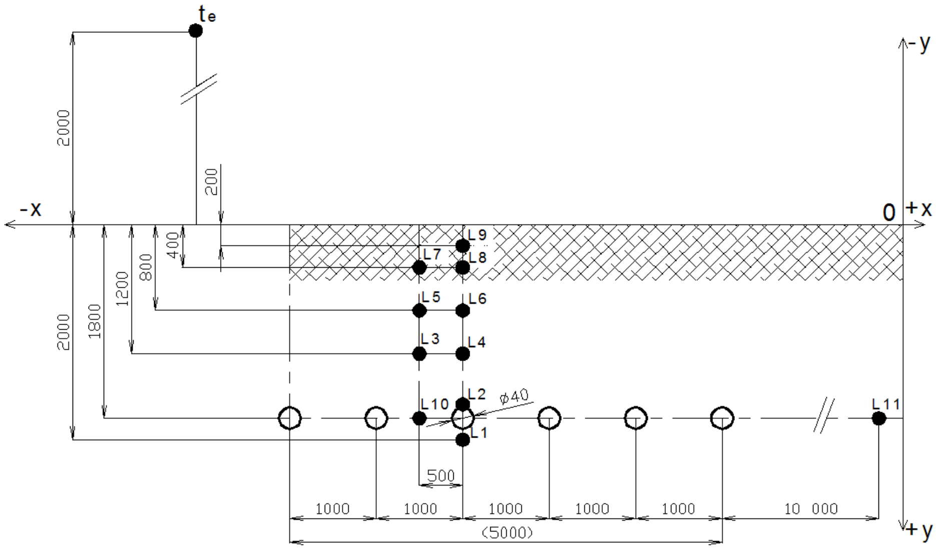

Fig. 1. – Layout identifying the location of temperature sensors in the ground mass

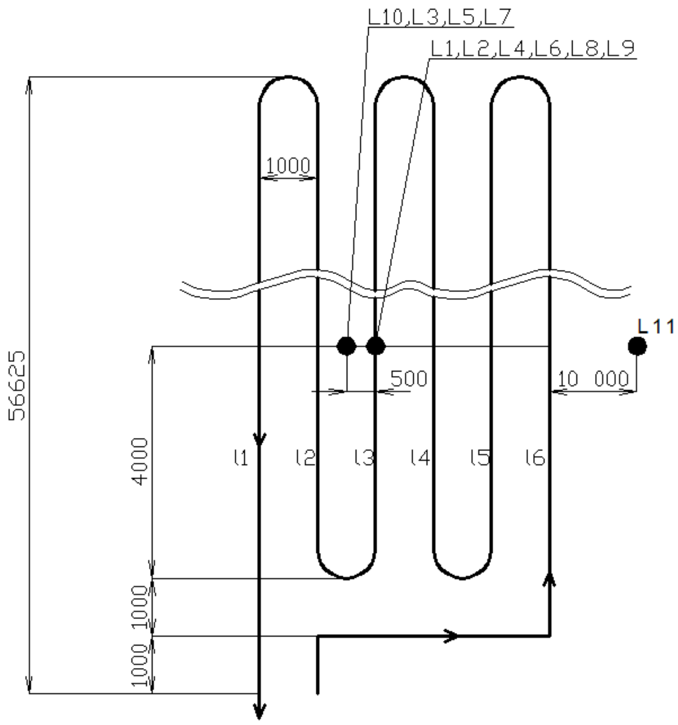

Fig. 2. – Site layout of the linear HGHE and location of the temperature sensors

Tab. 1. – Parameters of equation (1) for calculating the average daily temperatures of the ground mass with linear HGHE in the heating and stagnation period

	Δt_A	φ	$\bar{t}$	I^2_{yx}
t_{L1}	6.938	1.892	10.217	0.976
t_{L2}	7.797	2.039	9.984	0.982
t_{L3}	8.131	2.105	10.495	0.975
t_{L5}	7.961	2.24	10.066	0.953
t_{L7}	8.752	2.369	10.264	0.945
t_{L8}	9.038	2.389	10.338	0.941
t_{L9}	8.958	2.438	10.205	0.926
t_{L11}	5.525	1.826	10.806	0.988
t_e	9.542	2.563	10.137	0.776

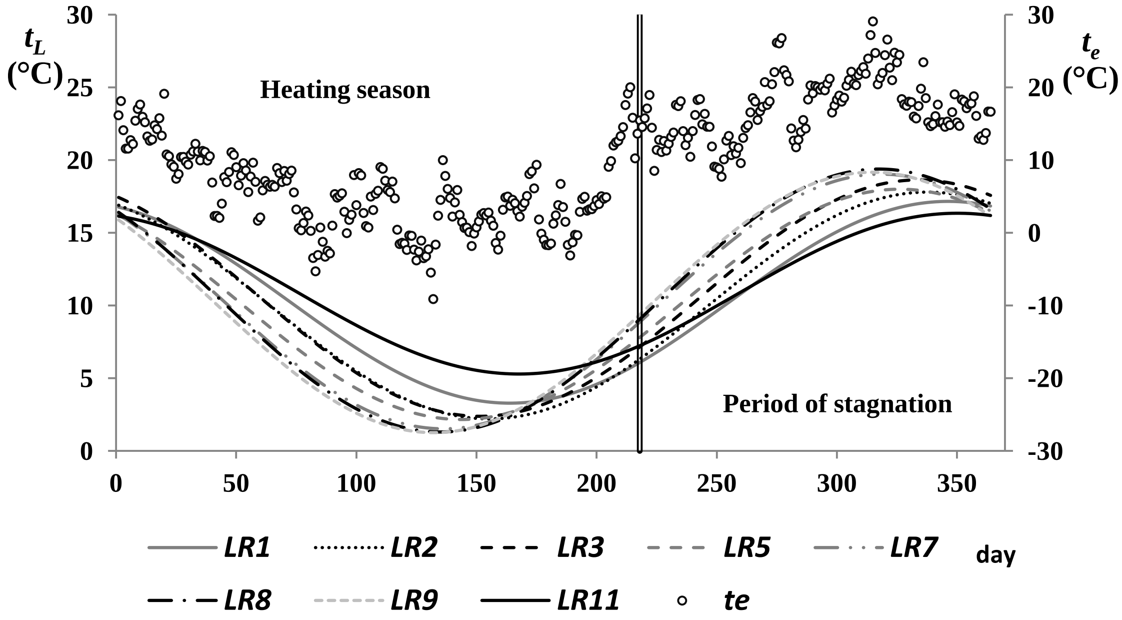

Fig. 3. – Average daily ground mass temperatures calculated from equation (1)

RESULTS AND DISCUSSION

3.1 Ground mass temperatures with HGHE

Parameters of equation (1) presented in Tab. 1 can be used to calculate average daily temperatures of the ground mass in the heating period and the period of stagnation. Fig. 3 shows the average daily temperature trends of the ground mass with HGHE in monitored depths calculated from equation (1).

The line parallel to the vertical axis in Fig. 3 separates the heating period (218 days) from the period of HGHE stagnation (146 days). The plot in this figure demonstrates that the average daily temperature of the ground mass with the linear HGHE decreased towards the ground mass surface in the heating season. The lowest temperatures were not attained in the area of HGHE but near the mass surface. Also the oscillation amplitudes Δt_A around the mean ground mass temperature $\bar{t}_G$ increased towards the ground mass surface. These trends confirmed the influence of the ambient air temperatures t_e. The relevant temperatures of the ground mass in the area of HGHE (t_{L1},t_{L2}) decreased evenly from 17.11 °C, by approximately 1 K per 13 days, up to a day 192 of the heating period when it was 2.42 °C. Subsequently, the ground mass temperatures increased and at the end of the heating period reached 5.54 °C. From the beginning of the stagnation period, the ground mass temperatures in the area of HGHE increased by approximately 1 K per

9.8 days. It reached the value of the temperatures before the heating period already on day 105 of the stagnation period. The ground mass temperatures with HGHE decreased slightly at the end of the stagnation period due to ambient air temperature decrease. The temperature difference of the ground mass in the area of linear HGHE at the beginning of the heating periods 2013/2014 and 2012/2013 were quite insignificant, it was 0.05 K. The ground mass temperatures in the area of linear HGHE were higher than the ambient air temperatures t_e during 68.8% of the heating period.

3.2 Heat flows and energies transferred from the ground mass

Tab. 2 shows the average and extreme values of the ambient temperatures t_e, ground mass temperatures t_{L2} in the HGHE area and reference temperatures t_{L11} measured away from HGHE area in the heating period. Furthermore, specific heat outputs $q_{pL,s}$ and energies $q_{dL,s}$ calculated per 1 m^2 of the land area with HGHE and a day, intensity $I_{p,s.r.}$ and total energy of incident solar radiation $I_{d,s.r.}$ per a day are presented in this table. Trends of temperatures of ground mass and ambient air, heat flows and specific energies transferred from the ground mass via linear HGHE in the heating season is displayed in Fig. 3.

The plot in Fig. 3 and the data in Tab. 2 show that the temperatures in the HGHE area were above zero. Temperatures above zero are important in terms of the heat pump factor value as well as in terms of ice formation in the vicinity of HGHE pipes. According to BANKS (2012), ice formation can lead to connection of ice cylinders around the HGHE pipes, or their connection with naturally frozen ground mass. If this occurs, there is a serious risk that such an extensive frozen ground mass exposed to the solar radiation in the summer period will not thaw.

Tab. 2. – Average and extreme values of the temperatures, specific heat outputs and energies in the heating period.

	Heating period		
	Min.	Average	Max.
t_e (°C)	-9.15	5.44 ± 5.57	19.99
t_{L2} (°C)	2.00	7.08 ± 4.76	17.14
t_{L11} (°C)	5.23	9.30 ± 3.74	16.74
$q_{pL,s}$ (W/m^2)	0.21	5.93 ± 3.04	12.96
$q_{dL,s}$ (Wh/m^2·day)	0.34	77.88 ± 50.63	255.22
$I_{p,s.r.}$ (W/m^2)	3.52	66.27 ± 55.35	270.29
$I_{d,s.r.}$ (kWh/m^2·day)	0.085	1.61 ± 1.35	6.49

The observed difference between the reference ground mass temperature t_{L11} and the mass temperature in the area of the exchanger t_{L2} was not significant; on average 2.22 ± 1.23, maximum 4.25 K. The temperature to which the ground mass is cooled has practical meaning, especially in terms of the heat-transfer fluid temperature, the size of a land area, where HGHE is deposited and also the sustainability of the low-potential source. The average temperature of the heat-transfer fluid flowing through the linear HGHE to the evaporator of the heat pump in the heating period was 8.13 ± 4.51 °C, minimum 1.67 °C. The minimum temperature from the heat pump evaporator to HGHE was -2.09 °C, the average 5.80 ± 5.12 °C.

According to the German VDI STANDARD (2001), the temperature of the heat-transfer fluid flowing from the heat pump to the ground loop must not deviate by more than ±12 °C from the ground mass temperature at rated load conditions of HGHE or more than ±18 °C from peak load. In case of the tested linear HGHE, the average difference between the ground mass temperature away from HGHE area and the heat-fluid temperature at the heat pump evaporator was 3.48 ± 2.71 K, maximum 9.49 K. Operation of linear HGHE is in accordance with the VDI STANDARD (2001).

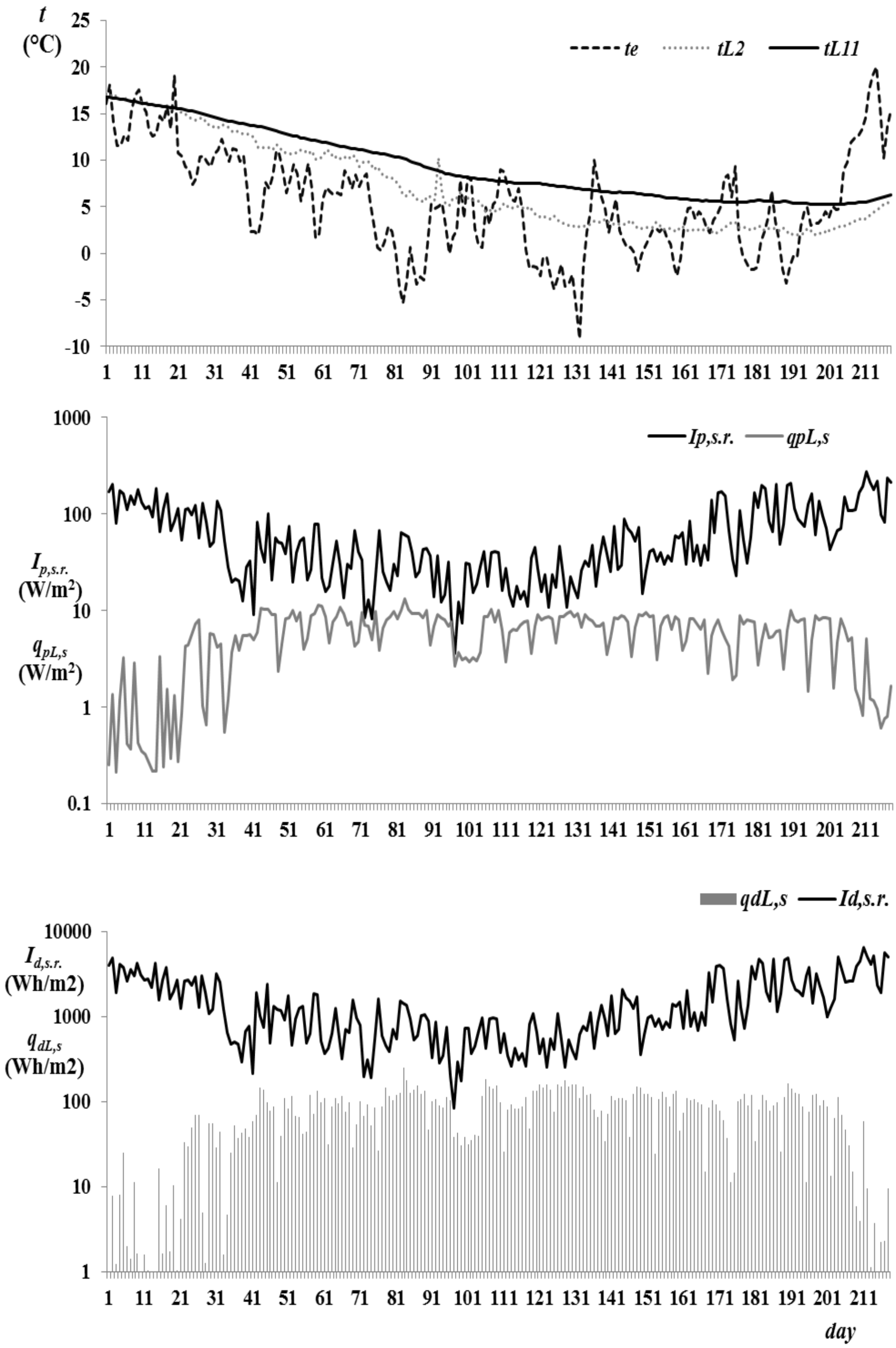

Fig. 4. – Temperatures of the ground mass and the ambient air temperatures, heat flows and specific energies transferred from the ground mass via linear HGHE

In respect of sustainability of the low-potential source, the VDI STANDARD (2001) also recommended not to exceed the total annual energy extraction from the ground mass 50-70 kWh per 1 m^2 of land area with HGHE. In the case analysed in this paper, the energy extraction from the ground mass reached only 16.98 kWh/m^2. The lower value of the energy extraction was caused by high concentration of ethanol in the heat-transfer fluid and its low flow rate.

According to The Engineering ToolBox, the freezing point of the used heat-transfer fluid is -17.4 °C. The measurement results showed that the minimum temperature of the heat-transfer fluid at the outlet of the heat pump was -2.09 °C. More suitable for HGHE would thus be lower concentration, e.g. 20% ethanol, when the freezing temperature of the mixture is -9.0 °C. Lowering the ethanol concentration would reduce the kinematic viscosity of the heat-transfer fluid by 47.3% (at 0 °C), increase the value of the Reynolds criterion by 44.28% and increase the coefficient of heat transfer between the HGHE inner pipe wall and the heat-transfer fluid by 13.96%. Mentioned heat transfer coefficient can be a limiting variable of heat transfer between the ground mass and the heat-transfer fluid in HGHE.

BANKS (2012) indicated that to obtain temporary turbulent flow ($Re > 2500$) in a hydraulically smooth pipe of an outer diameter 40 mm at a volume concentration of ethanol 22.5% (freezing point -10 °C), it is necessary to achieve a volume flow of the heat-transfer fluid 19.7 l/min. The heat-transfer fluid flow in the tested HGHE reached value 5.0 l/min in the first stage of the circulation pump operation and 10.32 l/min in the second stage.

CONCLUSIONS

Monitoring and analysing the linear HGHE operation during the heating and stagnation periods showed the following:

- The average daily ground mass temperatures above the linear HGHE decreased in the heating period towards the ground mass surface. Minimum temperatures were not reached in the HGHE area but near the mass surface. Major effect of ambient air temperatures $t_e$on the ground mass temperatures in the heating period was confirmed by HEPBURN ET AL. (2016) and POPIEL ET AL. (2001);
- The ground mass temperatures in the area of linear HGHE were higher than the ambient air temperatures t_e.during 68.8%. Ground mass temperatures were lower than the ambient air temperatures particularly at the end of the heating season. The importance of temperatures of the low-potential energy source for heat pumps was confirmed by DE SWARDT, MEYER (2001);
- The average daily ground mass temperatures with linear HGHE were above zero in the heating season. Temperatures below zero did not occur in HGHE area during the heating period. Hypothesis *a)* formulated at the beginning of this paper was thereby confirmed;
- The observed difference of reference ground mass temperature t_{L11} and ground mass temperature in the area of the heat exchanger t_{L2} was not significant, on average 2.22 ± 1.23 K; maximum difference reached the value of 4.25 K. A temperature difference of more than 4 K occurred in 5 days of the heating season. Hypothesis *b)* was not confirmed;
- The average daily ground mass temperatures with the linear HGHE during the heating and stagnation period can be expressed by equation (1) and parameters presented in Tab. 1;
- The temperature difference of the ground mass within the linear HGHE area at the beginning of the heating seasons 2013/2014 and 2012/2013 was quite insignificant, amounted to 0.05 K. Hypothesis *e)* was confirmed;
- The average daily temperature difference of the ground mass away from the HGHE area and the heat-transfer fluid temperatures from the heat pump evaporator was 3.48 ± 2.71 K, maximum 9.49 K. The HGHE operation is in accordance with the VDI recommendations (2001). Hypothesis *c)* was confirmed;
- Energy extraction from the ground mass during the heating period was significantly lower than the VDI limiting values (2001), it reached 16.98 kWh/m^2. The cause of lower energy extraction was high concentration of ethanol in the heat-transfer fluid and its low flow rate. Hypothesis *d)* was confirmed.

The results of the linear HGHE verification pointed out to deficiencies, inspired further research in this area and brought new knowledge usable in construction and design practice. Further studies will be aimed at increasing the specific heat output of the linear HGHE, on the base of monitoring and analysing obtained results, and at reducing the size of a land area required for ground mass energy extraction.

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