Analysis of rock mass borehole temperatures with vertical heat exchanger

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Abstract

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The goal of the article is to analyze the distribution and changes of temperatures in boreholes with the rock mass/fluid tubular heat exchangers used as an energy source for the heat pump. It also aims at documenting changes of temperatures in the rock mass during stagnation and heat extraction, and to compare the temperatures in the active and referential borehole. The testing results showed that temperatures of the rock mass reached a minimal value of 1.3°C at depths of 9 m and 20 m with maximal heat extraction corresponding to minimal air temperatures. The temperatures of the rock mass increased near the end of the heating season to values which correspond to the initial values. The temperature differences of the rock mass between the reference borehole and active boreholes increased to up to 10.5 K during the heating season. However, the temperature differences at the end of the heating season between the reference and active boreholes dropped back to 0.5–1.1 K.

Keywords: geothermal; heat pumps; temperature laps rate; thermal conductivity; thermal resistance; heat capacity

Similarly to other branches of the national economy, agriculture is also under pressure of prices of fossil fuels and environmental protection to focus on energy systems utilizing renewable energy sources. Heat pump technology is one such energy source. Heat pumps in agriculture may be used to heat and ventilate large-capacity stables and greenhouse complexes, for drying agricultural products, heating water and other technological processes of plant and livestock production. It is also used in the countryside to heat homes and other buildings.

Agricultural operations, especially in rural areas, may use energy from the air, water and the rock mass for heat pumps. Small and middle thermal output heat pumps – up to 100 kW – fueled by the exhaust air present an optimal source for heating and ventilating stables. Use of surface or underground water is severely limited by their availability, complex legislature, variability of water flow and instability of the heat capacity. For capacities of over 100 kW it seems that the rock mass is the best energy source. Heat is transferred from the rock mass via horizontal or vertical heat exchangers. A limiting factor for the heat obtained via horizontal heat exchangers is the area available for the exchanger, interference with growing agricultural products and disadvantaging the plot with respect to future construction plans. The most widespread sources for low-potential heat of such capacities are vertical exchangers installed into depths of 100–300 m. Vertical heat exchangers provide (contrary to other sources) a stable heating factor and thus stable output of the heat pump, without

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regard to the local climate and season. These energy sources are used for heat pumps with high outputs. An example of the implementation of this technology is a sports hall and hotel in Opava, Czech Republic. The heat source for 8 heat pumps with a total thermal output of 455 kW is 81,100-m boreholes. In Oslo, Norway, 180,200-m boreholes provide a heat source for heat pumps heating a university and an administrative and housing complex with a total built-up area of 180,000 m^2.

Vertical boreholes seem to be perspective sources of energy for heat pumps with thermal output exceeding 100 kW, and could be used in agriculture especially in technological processes requiring a stable heat capacity.

The goal of the article is to analyse the distribution and changes of temperatures in boreholes with rock mass/fluid type tubular heat exchangers used as an energy source for the heat pump. It also aims to document changes of temperatures in the rock mass during stagnation and heat extraction, and to compare the temperatures in the active and referential borehole.

Kharsen and Nordell (2011) list the results of a study of utilizing vertical heat exchangers and solar PV collectors for heating and cooling stables in a broiler chicken farm in Syria. Winter temperatures in these areas reach the freezing point while rising to 45°C or above during summer. The proposed energy system would reduce the expenses for heating and cooling the stables by 69.2% and the economic return period for the investment would be 5.3 years. Partenay et al. (2011) study the changes in temperatures of the rock mass of the borehole used for heating and cooling. They conceptualize a simulation model for analysing the steady-state and intermediate phenomena with a goal of finding characteristic long-term phenomena. They propose hybrid experiments and simulations for quantifying the effects of temperature changes in the rock mass on the operation and efficiency of the whole energy system. Javed and Fahlén (2011) describe the results of heat reaction tests in nine 80-m deep boreholes. They documented the effects of heat characteristics of the rock mass in the boreholes on the temperature distribution. They also performed a sensitivity analysis on the effects of the thermal conductivity coefficient of the rock mass. The effects of the underground water flow on rock mass temperatures and imparted heat flows in vertical exchangers are studied by Gustafsson and Westerlund (2011). The results of their experiments show that the heat flow transferred by convection changes with the temperature of underground water. High heat flow values were obtained for waters nearing 0°C and when the water froze into ice. The method of heat transfer intensification via convection in borehole heat exchangers by injecting and circulating air was patented by German researchers (Xiaolong, Grabe 2011). The effects of the diameter of absorption pipes of vertical heat exchangers and the temperature of the heat transfer fluid were studied by Khalajzaden et al. (2011), who concluded that these two parameters have a greater effect on the output of the exchanger than the depth of the borehole. The problem of the heat characteristics of ground and rock masses is studied by Ress et al. (2000), analysing the effects of temperature changes in rock masses and especially of the state of water on the thermal conductivity coefficient, heat coefficient and the specific heat capacity of the rock mass. Abu-Hamdeh et al. (2001) list that the tests of heat reverberations in vertical boreholes prove that the thermal conductivity coefficient of the rock mass is greater when heating than when cooling.

MATERIAL AND METHODS

Theoretical analysis

The effect of sunlight on the ground temperature can be expressed by the attenuation depth L (Brandl 2006; Kutílek 1978):

$$L = \left(\frac{2a}{\omega}\right)^{\frac{1}{2}} \quad \text{(m)} \tag{1}$$

where:

a – thermal conductivity coefficient (m^2/s)

$\omega = \frac{2\pi}{\tau}$ – circular frequency (1/s)

τ – period (s)

In the Eq. (1) for daily angular frequency we substitute $\omega = 7.27 \times 10^{-5}$ (1/s) and for annual angular frequency 1.99×10^{-7} (1/s) (Kutílek 1978). Thermal conductivity coefficient is calculated from the relation:

$$a = \frac{\lambda}{\rho \times c} \quad (\text{m}^2/\text{s}) \tag{2}$$

where:

λ – thermal conductivity coefficient (W/m K)

ρ – soil density (kg/m^3)

c – specific heat capacity of the soil (J/kg K)

Literature (Kutílek 1978) states that in depth $z = L$ the soil temperature amplitude is 0.37 of the surface amplitude and in depth $z = 3L$ the soil temperature amplitude decreases to 0.05 of the surface amplitude.

The mechanism of heat transfer in the rock mass includes conduction, convection, radiation and state changing processes. Brandl (2006) states that if the sizes of soil fraction grains and of voids are negligible in comparison with the rock mass volume, the whole process of heat transmission may be reduced to heat transfer through conduction, which is dominant in this case. In the sense of the Fourier law we can determine the following equation for the heat flux q_τ:

$$q_\tau = -\lambda\frac{\partial T}{\partial n} = -\lambda\left(\frac{\partial T}{\partial x}e_x + \frac{\partial T}{\partial y}e_y + \frac{\partial T}{\partial z}e_z\right) = -\lambda \times gradT \quad (\mathrm{W/m^2}) \quad (3)$$

where:
$\frac{\partial T}{\partial n}$ – thermal gradient in the direction n of the heat flux q_τ

Temperature change caused by a change of the heat flux will produce a change of the specific internal energy (Brandl 2006):

$$-\rho\times c\frac{\partial T}{\partial \tau} = \frac{\partial q_\tau}{\partial x} + \frac{\partial q_\tau}{\partial y} + \frac{\partial q_\tau}{\partial z} \quad (\mathrm{W/m^3}) \quad (4)$$

By differentiation of Eq. (3) and substitution in the Eq. (4) we get (Eskilson 1987):

$$\frac{\partial T}{\partial \tau} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = a\times div(gradT) = a\Delta T \quad (\mathrm{K/s}) \quad (5)$$

If there exists an internal source of heat q_τ (W/m^3) in the calculated rock mass volume, then the basic equation for the heat transferred through conduction will have the following form (Brandl 2006):

$$\frac{\partial T}{\partial \tau} = a\Delta T + \frac{q_\tau}{\rho\times c} \quad (\mathrm{K/s}) \quad (6)$$

where:
τ – time (s)

Basic boundary condition in the borehole (Eskilson 1987):

$$T(r, z, \tau) = T_b(\tau) \quad (\mathrm{K}) \quad (7)$$

where:
r – borehole radius (m)
z – depth (m)
$T_b(\tau)$ – borehole wall temperature depending on the time (K)

Average heat flux $q_{\tau,t}$ channeled through 1 m of pipe can be expressed by the following equation (Eskilson 1987):

$$q_{\tau,t} = \frac{1}{H}\int_0^H 2\pi r_b \lambda \frac{\partial T}{\partial r}dz \quad (\mathrm{W/m}) \quad (8)$$

where:
H – borehole depth (m)

During borehole heat extraction under the above described conditions the rock mass isotherms in the borehole surroundings take the shape of circular ellipsoids (Rybach, Sanner 2000).

Thermal response of the rock mass reacting to extracted heat capacity for the given time interval is converted to a set of dimensionless coefficients, referred to as g-functions. The total borehole heat extraction is converted to a set of time limited heat pulses that are composed on the basis of the superposition principle. The size of g-function is greatly influenced by the number and placement of boreholes (Gehlin 2002), from which the heat is extracted. Rock temperature on the borehole wall at any given time is determined by assigning g-functions to these extraction pulses (Eskilson 1987):

$$T = T_g + \sum_{i=1}^{n}\frac{q_{\tau,i} - q_{\tau,i-1}}{2\pi\lambda}g\left(\frac{\tau_i - \tau_{i-1}}{\tau_s};\frac{r}{H}\right) \quad (\mathrm{K}) \quad (9)$$

$$\tau_s = \frac{H^2}{9a} \quad (\mathrm{K}) \quad (10)$$

where:
T_g – average temperature of rock mass in the surroundings of the borehole from which the heat is extracted (K)
$g\left(\frac{\tau}{\tau_s};\frac{r}{H}\right)$ – g-function describing temperature response in the rock mass caused by the thermal output extraction from the borehole in the given time interval
$q_{\tau,i}$ – thermal output extracted from the borehole for the duration of the i^{th} temperature pulse (W/m)
τ_i – end of i^{th} heat pulse in time (s)
τ_s – relative borehole heat extraction time (s)

Provided (Adam, Markiewicz 2002) that absorption pipes walls in the borehole have the same temperature as the surrounding cement-bentonite mix, or rock mass, then the whole thermal process is reduced to convection heat transfer between the inner absorption pipe wall and the heat transfer fluid. Assuming the above, the heat transfer coefficient α is the limiting factor for ground heat flux.

The criteria equation according to Oertel (2001) has the following form for this case:

$$Nu = \frac{\frac{\xi}{8}(Re - 1{,}000)Pr}{1 + 12.7\sqrt{\frac{\xi}{8}} \times \left(\sqrt[3]{Pr^2} - 1\right)} \times f = \frac{\alpha \times d}{\lambda} \quad (-) \qquad (11)$$

$$f = 1 + \sqrt[3]{\left(\frac{d}{L}\right)^2} \quad (-) \qquad (12)$$

The equation is valid for:

$0.5 < Pr < 10^4$; $2{,}300 < Re < 10^6$; $0 < d/L < 1$

where:

- ξ – absorption pipes pressure drop coefficient (–)
- Nu – nusselt number (–)
- Pr – prandtl number (–)
- Re – reynolds number (–)
- d – absorption pipe diameter (m)
- L – absorption pipe length (m)
- λ – head conductivity coefficient for the heat transfer fluid (W/m K)

Measurement methods

The measurement took place on a site of VESKOM, Ltd., Prague, Czech Republic. VESKOM, Ltd., created a large experimental workplace on its premises used for verification of earth sources for heat pumps including heat pumps, horizontal heat exchangers and the SLINK type of exchangers. There are nine boreholes (VT1 to VT9) reaching the depth of 113 m in the area. Within the measurement the temperatures of ground and rock mass in 3 active boreholes equipped with heat exchangers (VT2, VT3 and VT4) and in a referential borehole without exchanger (VT9) were monitored.

Results of geological research carried out by GESTEC, Ltd., Prague, Czech Republic, in cooperation with Stavební Geologie – Geosan, Ltd., Nučice, Czech Republic proved the following composition of layers:

VT2 – borehole equipment (PE 100RC pipeline (LUNA PLAST a.s., Hořín, Czech Republic), 4 pipes, pipe outer diameter 32 mm, pipe wall thickness 2.9 mm); 0.0–1.0 m: man-made ground, loamy-sandy gravel, brick chips and rubble; 1.0–2.0 m: man-made ground, sandy clay soil; 2.0–4.5 m: man-made ground sandy clay gravel; 4.5–7.5 m: man-made ground, clay loam with gravelly mixture and small brick chips; 7.5–9.5 m: man-made ground, sandy clay with small flint chips; 9.5–10.5 m: weathered wacke; 10.5–13.0 m: weathered clay shale, soft; 13.0–113.0 m: fresh clay shale with dust mixture.

VT3 – borehole equipment (PE 100RC pipeline, 2 pipes, pipe outer diameter 40 mm, pipe wall thickness 3.7 mm); 0.0–4.0 m: man-made ground, loam with high portion of sand, gravel and chip bricks; 4.0–5.5 m: man-made ground, sandy loam; 5.5–8.5 m: man-made ground, clay sandy soil with rock chips and gravel; 8.5–13.0 m: slightly weathered clay shale; 13.0–113.0 m: fresh clay shale.

VT4 – borehole equipment (PE 100RC pipeline, 4 pipes, pipe outer diameter 32 mm, pipe wall thickness 2.9 mm); 0.0–4.0 m: man-made ground, loam with gravel and brick chips; 4.0–5.5 m: man-made ground, sandy loam; 5.5–10.0 m: man-made ground, clay sandy gravel; 10.0–14.0 m: weathered clay shale; 14.0–113.0 m: fresh clay shale.

VT9 – without equipment; 0.0–3.5 m: man-made ground, coarse-grain gravel, crushed stones, brick chips; 3.5–7.0 m: man-made ground, sandy gravel with brick chips; 7.0–15.0 m: weathered clay shale, soft; 15.0–113.0 m: fresh clay shale.

Thermal response test of the rock environment yielded the following results:

λ = 2.9 W/m K – rock mass heat conductivity coefficient;

Rb = 0.137 K m/W – borehole rock mass thermal resistance.

The temperature was taken at a depth of 0.2 m below the surface for each borehole. Four heat-sensing units Pt 1000A with electric conductors were installed for each borehole at a depth of 9, 20, 50, and 100 m. The conductor is resistant to mechanical damage and humidity. Depth location of sensing units is designed to best cover the whole geological profile. The sensors are installed between the ascending and descending branch of absorption pipes. Outside temperature was recorded by the ATF 2 KTY 81.210 sensing unit placed at the height of 2 m on the east side of the building. Signals from heat-sensing units were presented on switch board, from which they were recorded weekly between 3 and 4 p.m. during the period from 7th June 2010 to 23rd May 2011.

Boreholes function as source of thermal energy for 3 heat pumps 2× IVT GREENLINE HT PLUS E17 with thermal output 16.2 kW determined at a temperatures 0/35°C and 1× IVT PREMIUM-LINE X15 with thermal output 11.7 kW (Industriell Värme Teknik, Tnanas, Sweden). In the primary circuit of the heat pump the mixture 70% H_2O and 30% $C_2H_6O_2$ is used as the heat transfer fluid.

Monitored boreholes are used as heat sources for heating administration and service buildings and for heating of hot water. They are not used for cooling objects. The energy system with heat pumps entered operation in September 2008.

RESULTS AND DISCUSSION

Rock mass temperatures in the referential borehole

For sand – clay soil, or more precisely sand – clay gravel, that appear throughout the whole profile up to the depth of 9.5 m of all monitored boreholes we consider heat conductivity coefficient $\lambda = 1.9$ W/m K and specific heat capacity $C = \rho \times c = 3.47 \times 10^6$ J/m^3 K (Drbal 1986).

After substituting these values into Eqs (2) and (1) we get:

$a = 0.547 \times 10^{-6}$ m^2/s

$L_d = 0.123$ m – attenuation depth for daily temperature variation

$L_r = 2.34$ m – attenuation depth for annual temperature variation

That means that daily temperature variations cannot be in fact registered at a depth of 0.37 m and annual temperature variations at a depth of 7.1 m. Attenuation depth for annual year variation as we verified is consistent with the value stated in literature (Brandl 2006), i.e. 19.2 times greater than the attenuation depth for daily temperature variation.

It follows from the rock mass temperature development in the referential borehole VT9 as displayed in the graph in Fig. 1 that temperature differences in different depths are not significant and temperatures correspond to the values measured in various European locations (Brandl 2006).

Table 1 lists limit and average values of rock temperature monitored in the period between 7[th] June 2010 and 23[rd] May 2011. As the measured and calculated rock mass temperature values show, it is efficient to implement energy heating and cooling system with the vertical boreholes source. Unnoticeable rock mass temperature variations during year seasons do not negatively affect the heat pump performance or the economic results of the energy system.

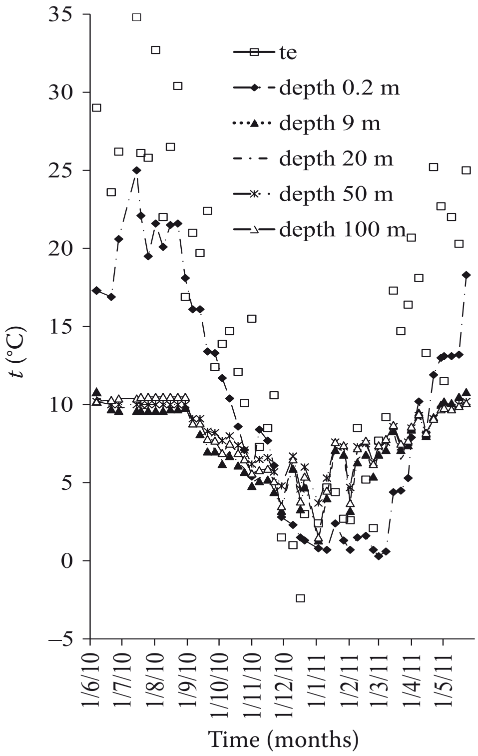

Fig.1. Rock mass temperature development in referential borehole VT9

Rock mass temperatures in active boreholes

Graphs on Figs 2 and 3 indicate that in summer (7[th] June 2010–2[nd] September 2010) the rock mass temperatures were constant in different depths. Table 2 shows average temperatures in boreholes during monitored summer season.

Table 1. Limit and average rock mass temperatures in the referential borehole (7[th] June 2010–23[th] May 2011)

	Depth (m)			
	9	20	50	100
Min. temperature (°C)	9.9	9.9	10.1	10.7
Max. temperature (°C)	11.8	10.5	10.7	11.6
Avg. temperature (°C)	10.94	10.22	10.40	11.16
Standard deviation	0.60	0.17	0.15	0.25

Rock mass temperatures in both active boreholes in the monitored period are lower than the temperatures in the referential borehole VT9. The temperature differences, however, are not significant. Decrease of active boreholes temperatures occurred in the course of 3 years of operation. In comparison with the referential borehole the decline in average rock temperatures amount to 0.113 K per year in borehole VT2 and 0.16 K per year in borehole VT3. If we consider that the temperature of the heat transfer fluid brought to heat pump evaporator can reach the temperature of –5°C (Čížek 2005), we can estimate the operation time of active boreholes to 100 or 110 year provided that the annual heat extraction remains the same. Were the boreholes used for cooling of administration and production areas during the summer months, their operation time would be significantly extended.

The boreholes are actively used from 3rd September 2010. From this date there is a decreasing tendency of temperatures in separate depths. Minimum temperatures were recorded on 3rd January 2011. Minimal temperatures in borehole VT2 were 1.3°C (9 m), 1.3°C (20 m), 3.7°C (50 m), 1.5°C (100 m) and in borehole VT3 the temperatures were 1.3°C (9 m), 1.9°C (20 m), 1.8°C (50 m) a 1.7°C (100 m). In the following period (3rd January–23th May 2011) the rock mass temperatures increased up to the values measured in the beginning of the heating period. Changes of temperatures measured in different depths in active boreholes follow the same trend. Development of the rock mass temperatures in borehole VT2 during the monitored period (3rd September 2010 – 23rd May 2011) can be described by the following equations:

Table 2. Rock mass temperatures during summer season (7th June 2010–2nd September 2010)

Depth (m)	Average rock mass temperatures during summer season (°C)		
	VT2	VT3	VT9
9	9.75	9.40	10.07
20	9.86	9.79	10.05
50	10.02	9.88	10.33
100	10.44	10.43	10.97

Depth 9 m:

$$t = -1.08 \times 10^{-6}d^3 + 7.55 \times 10^{-4}d^2 - 1.20 \times 10^{-1}d + 9.86 \quad (R^2 = 0.818)\ (°C) \qquad (13)$$

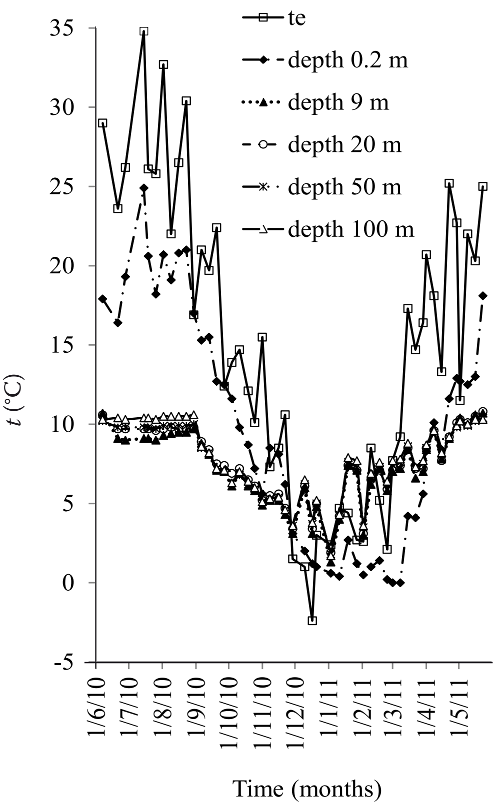

Fig. 2. Rock mass temperature development in active borehole VT2

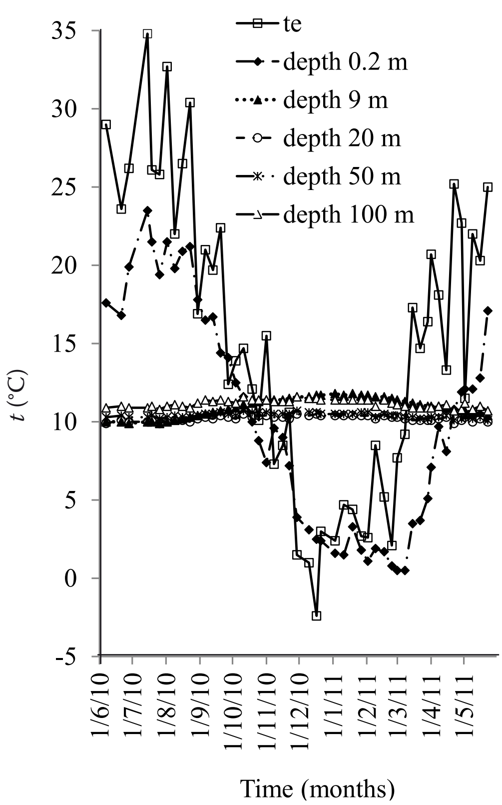

Fig. 3. Rock mass temperature development in active borehole VT3

Table 3. Differences in rock mass temperatures in active boreholes during winter season (3rd September 2010 to 3rd May 2011)

Depth (m)	Average temperature difference (K)		
	VT2–VT3	VT4–VT3	VT2–VT4
9	0.0	0.7	–0.7
20	–0.2	0.0	–0.1
50	0.6	0.1	0.5
100	0.1	0.3	–0,1

Depth 20 m:

$$t = -1.02 \times 10^{-6}d^3 + 7.20 \times 10^{-4}d^2 - 1.16 \times 10^{-1}d + 9.94 \quad (R^2 = 0.789)\ (°C) \tag{14}$$

Depth 50 m:

$$t = -7.29 \times 10^{-7}d^3 + 5.41 \times 10^{-4}d^2 - 9.19 \times 10^{-2}d + 10.30 \quad (R^2 = 0.798)\ (°C) \tag{15}$$

Depth 100 m:

$$t = -1.34 \times 10^{-6}d^3 + 8.16 \times 10^{-4}d^2 - 1.24 \times 10^{-1}d + 10.50 \quad (R^2 = 0.738)\ (°C) \tag{16}$$

where:

t – rock mass temperature (°C)

d – operation day of the energy system with heat pumps from 3rd September 2010–23th May 2011

The heat transfer surface of the absorption pipes in borehole VT3 is 0.251 m^2 per 1 m of borehole length. The heat transfer surface in boreholes VT2 and VT4 is 0.402 m^2/m. However, different size of the heat transfer surface does not influence the rock mass temperature, as shown in Table 3.

This is caused by a lower value of the heat transfer coefficient α between the inner wall of the absorption pipe and the heat transfer fluid. This is confirmed by the results of Eqs (11) and (12), documenting that the heat transfer coefficient in borehole VT3 is 30% higher than in boreholes VT2 and VT4. Due to the fact that the mass flow of the heat transfer fluid is identical for every borehole, a lower value of the heat transfer coefficient has to be a result of the lower speed of the flow of liquid in boreholes with a greater number of pipes.

The thermodynamic values of the heat transfer fluid necessary for determining *Re*, *Pr*, *Nu* were computed (Šesták el al. 1993). The mass flows of heat transfer fluid were measured via flow meter installed in front of the borehole head.

Temperature differences of the rock mass between the reference and active borehole

In the tested period of 7th June 2010–23rd May 2011, the temperature differences of the rock mass in boreholes VT9–VT2 were, with 2 exceptions, positive. Tables 4 and 5 list the limit and average temperature differences.

Temperature differences in the monitored summer season of 7th June–2nd September 2010 did

Table 4. Limit and average temperature differences of the rock mass in the reference borehole VT9 and active borehole VT2 during summer (7th June–2nd September 2010)

	Depth (m)			
	9	20	50	100
Min. temperature difference (K)	0.3	0.2	0.1	0.3
Max. temperature difference (K)	–0.8	–0.6	0.4	0.7
Avg. temperature difference (K)	0.3	0.2	0.3	0.5
Standard deviation	0.37	0.25	0.09	0.12

Table 5. Limit and average temperature differences of the rock mass in the reference borehole VT9 and active borehole VT2 during winter (3rd September 2010–3rd May 2011)

	Depth (m)			
	9	20	50	100
Min. temperature difference (K)	0.5	0.2	0.5	1.1
Max. temperature difference (K)	10.5	9.1	6.8	9.9
Avg. temperature difference (K)	4.82	3.77	3.18	4.32
Standard deviation	2.33	2.05	1.57	2.03

not exceed 1 K, and may thus be considered insignificant. The results indicate that during summer seasons the temperatures in the active borehole almost reached the values of the reference borehole, with no additional heat sources due and only due to the thermal heat flows in the rock mass. Although the borehole has only been in operation for 3 years, this finding may be considered crucial.

During the tested period of the heating season of 3rd September 2010–3rd May 2011, the temperature differences in the reference and active borehole increased and reach up to 10.5 K.

The graph at Fig. 4 indicates a gradual increase and decrease of temperature differences in the winter season. The development of temperature differences can be captured by the following equations:

Depth 9 m:

$$t = 1.21 \times 10^{-6}d^3 - 8.57 \times 10^{-4}d^2 + 1.34 \times 10^{-1}d + 1.33 \quad R^2 = 0.855)\ (°C) \qquad (17)$$

Depth 20 m:

$$t = 1.06 \times 10^{-6}d^3 - 7.25 \times 10^{-4}d^2 + 1.10 \times 10^{-1}d + 1.10 \quad (R^2 = 0.792)\ (°C) \qquad (18)$$

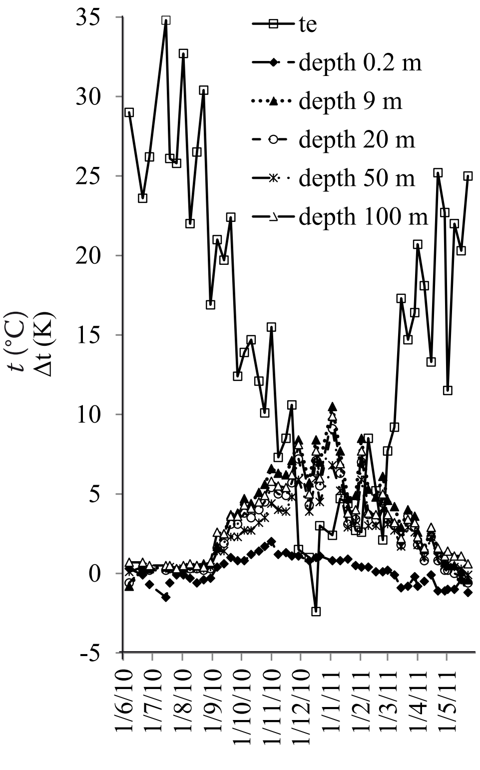

Fig. 4. Temperature differences of the rock mass in the reference borehole VT9 and active borehole VT2

Depth 50 m:

$$t = 8.45 \times 10^{-7}d^3 - 5.83 \times 10^{-4}d^2 + 9.10 \times 10^{-2}d + 0.724 \quad (R^2 = 0.805)\ (°C) \qquad (19)$$

Depth 100 m:

$$t = 1.42 \times 10^{-6}d^3 - 8.34 \times 10^{-4}d^2 + 1.17 \times 10^{-1}d + 1.61 \quad (R^2 = 0.750)\ (°C) \qquad (20)$$

CONCLUSION

Measuring the temperatures of the rock mass in the reference borehole and active boreholes has shown that:

- The locality is, due to the low values of attenuation depth of annual and daily temperature deviations as well as limit and average temperatures of the rock mass in the reference borehole, suitable for realizing borehole heat exchangers (Table 1);
- The temperatures in active boreholes before the beginning of the heating season are lower than in the reference borehole. However, the temperatures differences are not significant and do not exceed 1 K (Table 3). In comparison to the reference borehole, the average annual temperature decline during the operation of active boreholes is 0.113–0.160 K/y;
- The utilization period of active boreholes for heat extraction was, based on annual average temperature differences of the rock mass in the reference and active boreholes, estimated to 100–110 years assuming invariant annual heat extraction;
- The temperature differences of the rock mass in the reference and active borehole grow during the monitored heating season. The average temperature differences in various depths range between 3.18–4.82 K, and the maximum temperature differences range between 6.8–10.5 K (Table 5);
- The temperatures of the rock mass in active boreholes after reaching the minimal value of 1.3°C (during maximum heat extraction) have an increasing tendency, corresponding to less heat extraction near the end of the heating season. They gradually grow to the values measured in the beginning of the heating season;
- The heat flux carried by the absorption heat transfer fluid is significantly affected by the heat transfer coefficient α between the inner wall of the pipe and the fluid;
- *A* is dominantly affected by the dynamic viscosity *ν* of the absorption heat transfer fluid, i.e. the concentration of water compound and anti-freeze fluid.

Visualization of the measured data has been finished and the measurements are fully automated.

During further testing of vertical heat exchangers, we will focus on the processing and testing of the mathematical model for the created thermal field and thermal flows near the exchanger and the influence of temperature changes of the rock mass on the temperatures of absorption heat transfer fluid. In the following years, we will also study the changes of these thermal fields and flows during the reverse operation of heat pumps in the summer for cooling of current administration and production buildings.

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