ENERGY EXTRACTION FROM ROCK MASS USING VERTICAL HEAT EXCHANGERS

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Abstract
The aim of the verification study was to determine and analyse the temperatures of the rock mass, specific heat capacities and specific energies extracted from the rock mass by two types of vertical heat exchangers namely single U-tube heat exchanger (U1) and double U-tube heat exchanger (U2). The exchangers were used as low-potential energy source for heat pumps. Design and operating parameters influencing the process of heat transfer between the rock mass and the heat-transfer fluid were also evaluated. The results demonstrated the advantages of using double U-tube heat exchanger U2 both in terms of its impact on the performance factor of the heat pump, and in terms of specific heat outputs and specific energies extracted from the rock mass. The average daily temperatures of the heat-transfer fluid in heat exchanger U2, specific heat outputs and specific energies extracted from the rock mass were higher by 4.5%, 26.8% and 25.6%, respectively than in the heat exchanger U1.

Key words: thermal energy; thermal power; ground loop heat exchanger; heat pump; rock mass.

INTRODUCTION

We can efficiently gain low potential energy contained in the rock mass, usable as low-temperature energy source for heat pumps evaporators, via vertical rock mass heat exchangers. These exchangers, using geothermal heat of the rock mass are usually installed in Central Europe at depths of 50-150 m. Effective usability and service life of these relatively investment-costly low-potential energy sources are considered in dozens years. It is therefore realistic to expect that after the end of life of one heat pump energy system there will be a new modern one connected to the vertical heat exchanger. This concept increases the efficiency of the entire system in terms of return of the investment on heat exchanger implementation. These reasons have led us to operational verification of vertical heat exchangers, the aim of which was to monitor and analyse:

- Differences of operating parameters of U1 and U2 heat exchangers;
- Rock mass temperatures and temperature changes during the heating period and the period of heat exchangers stagnation;
- Specific heat flows and specific energies extracted from the rock mass during the heating period.

PLATELL (2006) identified, according to the configuration, four main types of vertical rock heat exchangers: GLHE (Ground Loop Heat Exchangers) U-shaped exchangers with one or two loops; TIL (Thermal Insulated Leg) coaxial heat exchangers with several loops and a common thermally insulated centre; coaxial tube heat exchanger, and coaxial heat exchangers with reduced permeability of a rock wall; SCW (Stab Water Column) coaxial heat exchangers with permanent water column. In Central Europe, GLHEs with one or two U-shaped loops is mostly used.

BANKS (2012) analysed the process of heat transfer between the rock mass and the heat-transfer fluid on a base of a thermal resistance of the rock mass and a thermal resistance of the borehole; the border between the two resistors being the borehole wall. The volume of the rock mass thermal resistance is dependent on the rock mass thermal characteristics: coefficient of thermal conductivity λ ($W\cdot m^{-1}\cdot K^{-1}$), volumetric thermal capacity C ($J\cdot m^{-3}\cdot K^{-1}$) and coefficient of temperature conductivity (thermal diffusivity) a ($m^2\cdot s^{-1}$). The thermal characteristics have a dominant influence on temperatures and temperature distribution across the rock mass, vertical heat exchanger capacity and the duration of use of the exchanger.

Heat exchanger configuration, pipe size and material, diameter of the borehole, grouting material and type of heat-transfer fluid flow determine the thermal resistance of the borehole. The influence of the heat exchanger configuration and other parameters on the thermal borehole resistance was addressed by HUANG ET AL. (2015). SELÇUK AND BERTRAND (2014) evaluated thermal hydraulic and mechanic properties of the grouting material. SANNER AND MANDS (2003) and SANNER ET AL. (2000) reported on the basis of performed thermal response tests in Germany, borehole thermal resistance values between 0.06 and 0.50 $K \cdot m \cdot W^{-1}$. All tests except two of them have proved values of 0.12 $K \cdot m \cdot W^{-1}$ or less. Therefore they consider thermal resistance being appropriate < 0.11 $K \cdot m \cdot W^{-1}$ and unsatisfactory > 0.14 $K \cdot m \cdot W^{-1}$. Analysis of temperature areas and heat transfer in the rock mass with a single and double U-tube heat exchanger was carried out by CARLI ET AL. (2010). They also evaluated types of flow and temperatures of heat-transfer fluid. GEHLIN AND HELLSTRÖM (2003) focused on temperature distribution and heat accumulation into the rock mass by vertical heat exchanger. MARCOTTE AND PASQUIER (2009) have proved that a slight inclination of the borehole has a positive influence on heat exchanger capacity. BANKS (2012) indicated a specific energy extracted from the rock mass of 159 $kWh \cdot m^{-1}$ at an annual heat exchanger performance of 1 666-2 400 hours and an average value of specific heat output for Europe of 62 $W \cdot m^{-1}$. However, he emphasized that the values of specific energies and specific heat outputs can be only the initial information for the design of a heat exchanger.

MATERIALS AND METHODS

The vertical rock mass heat exchangers U1 and U2 were power sources for 1×IVT PremiumLine EQ E13 heat pump and 2×Green Line HT Plus E17 heat pumps (Industriell Värme Teknik, Tnanas, Sweden) used for heating the administration building and manufacturing halls of the company VESKOM Ltd. based in Prague, Dolní Měcholupy. The heat pumps were used only for heating of the buildings, but not for their cooling.

The measurements were carried out on two types of heat exchangers placed in boreholes at depth of 113 m. There is a single U-tube heat exchanger in one borehole (U1) made from polyethylene piping PE 100RC 2×40×3.7 mm (LUNA PLAST Inc., Hořín, Czech Republic) resistant to point loads and cracking. The outer surface of the heat exchanger per 1 m length is 0.2512 $m^2 \cdot m^{-1}$, inner 0.2047 $m^2 \cdot m^{-1}$. A double U-tube heat exchanger (U2) is placed in the other borehole, made from polyethylene piping PE 100RC 4×32×2.9 mm. The outer surface of the heat exchanger per 1 m length is 0.4019 $m^2 \cdot m^{-1}$, inner 0.3291 $m^2 \cdot m^{-1}$.

There were 5 temperature sensors of type Pt 1000 A (GREISINGER electronic GmbH, Regenstauf, Germany) in each borehole placed between the pipes at depths 0.2 m, 9 m, 20 m, 50 m and 100 m. The air temperature t_e above the ground was monitored by sensor ATF 2 KTY 81.210 (S+S Regeltechnik, Nürnberg, Germany) placed at a height of 2.5 m above the ground. Temperature sensors of type Pt100 were installed at the inlet and outlet pipelines of the boreholes, measuring temperature of the heat-transfer fluid. All temperatures were recorded at quarter-hour intervals. Heat exchanger outputs and energy values extracted from the rock mass were determined by an electronic heat consumption meter MTW3 (Itron Inc. Liberty Lake, USA). The heat-transfer fluid flowing through the vertical heat exchangers was a mixture of 33% ethanol and 67% water.

The upper part of the geological profile of the rock mass was made up of detritus; its thickness ranged from 4.0 to 9.5 m. The subsoil of the detritus was composed of grey-black clay slate of the Letná formation. There was solid rock mass in the deeper parts, heavily cracked in some places, as indicated by strong inflows of underground water into the boreholes. Cracked profiles were found at depths of 30 to approximately 80 m below ground. The level of underground water in all boreholes was encountered at depth of 10-12 m below ground. The results of the thermal response tests indicated the average value of coefficient of thermal conductivity of the rock mass $\lambda_{r.m.}$ = 2.9 $W \cdot m^{-1} \cdot K^{-1}$ and total thermal resistance of the boreholes 0.137 $K \cdot m \cdot W^{-1}$.

The verification of the vertical heat exchangers was performed between 19 September 2012 and 17 September 2013 and it covers the heating period (19 September 2012-22 April 2013, 216 days) and the stagnation period of the heat exchangers (23 April 2013-17 September 2013, 148 days) following the heating period.

RESULTS AND DISCUSSION

Rock mass temperatures in the area of the heat exchangers

a) Temperatures during the heating period.

In Tab. 1, the average daily temperatures of the rock mass $t_{Ø}$ are summarized, the minimum temperatures of the rock mass $t_{min.}$ in individual depth levels, the average temperatures of the rock mass along the entire length of the borehole t_C, the average air temperatures t_e and the minimum air temperatures.

Tab. 1. – Average daily and minimum temperatures of the rock mass and air temperatures during the heating periods.

		Depth (m)				t_C	t_e
		9	20	50	100	(°C)	(°C)
U1	$t_{Ø}$	6.26±2.98	6.27±2.78	6.24±2.45	6.48±2.41	6.31	5.34
	$t_{min.}$	0.53	0.31	0.71	0.65	-	-15.80
U2	$t_{Ø}$	6.96±2.86	6.42±2.69	6.34±2.46	6.60±2.33	6.58	5.34
	$t_{min.}$	0.59	0.75	0.49	0.78	-	-15.80

The verification results show that the rock mass temperatures in all monitored depths in the heating period were positive. This is an important point in terms of heating factor as well as the heat pump operation. It was also found that in all monitored depths of the rock mass the average daily temperatures were lower at the single U-tube heat exchanger U1 than at the double U-tube heat exchanger U2. The greatest temperature difference in the area of the heat exchangers U1 and U2, of Δt_U = 0.69 ± 0.24 K occurred at a depth of 9 m. On the contrary, at a depth of 100 m the temperature difference of Δt_U = 0.12 ± 0.13 K was significantly the smallest. The diagram in Fig. 1 shows the monitored values and regression curves of the average daily rock mass temperatures t_C and the ambient air temperatures t_e in the heating period running between 19 September 2012 and 22 April 2013, 216 days.

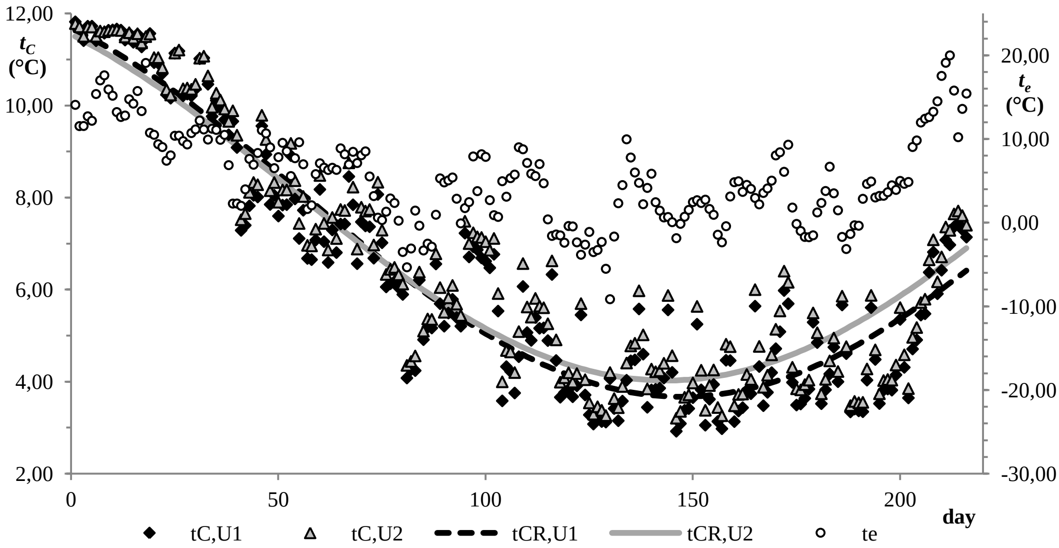

Fig. 1. – Average daily rock mass temperatures in the heating period and ambient air temperatures

At the beginning of the heating period, the average daily rock mass temperatures t_C in the area of the exchangers consistently decline with respect to increasing heat output extracted from the rock mass due to decreasing ambient air temperature. The drop in temperatures occurred approximately for 150 days with an intensity of 1 K per 18.36 days (U1 heat exchanger) and 19.20 days (U2 heat exchanger).

In the next stage of the heating period, due to rising ambient air temperatures and decreasing heat consumption the rock mass temperatures increased with the same intensity as there was in the case of a decline. At the end of the heating period (on day 216), the average daily rock mass temperature reached the value of 60.40% (U1), and 62.81% (U2) of the rock mass temperature at the beginning of the heating period. The average daily rock mass temperatures during the heating period were higher than the average daily ambient air temperatures in 59.72% of the heating period in the area of the U1 heat exchanger and 62.96% in the area of the U2 heat exchanger. The course of the average daily rock mass temperatures in the heating period was expressed by NEUBERGER ET AL. (2014) by an equation based on the equation of free, undamped oscillation of the mass point:

$$t_{CR} = \bar{t}_C + \Delta t_{am.} . \sin(\Omega . \tau + \varphi) \quad (°C) \quad (1)$$

Where:

t_{CR} - rock mass temperature (°C); $\bar{t}_C$ - mean rock 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 · day^{-1}).

It is a non-linear regression of *y* on *x*, therefore a determination index I^2_{yx} (-) was used according to BOWERMAN ET AL. (1997) to determine the degree of tightness in the relation between both random quantities.

The course of the average daily rock mass temperatures $t_{C,U}$ in the monitored heating period can be in terms of equation (1) expressed by equations (2) and (3).

$$t_{CR,U1} = 8.072 + 4.399 \cdot \sin(\Omega.\tau + 2.179) \quad (°C)$$

$$I^2_{CR,U1} = 0.897 \quad (2)$$

$$t_{CR,U2} = 8.241 + 4.216 \cdot \sin(\Omega.\tau + 2.241) \quad (°C)$$

$$I^2_{CR,U2} = 0.888 \quad (3)$$

b) Course of temperatures in the period of the rock mass energy potential recovery

The ability of the rock mass energy potential to regenerate during the exchangers stagnation period, or only its partial use, can be evaluated by the rock mass temperatures at the beginning and the end of successive heating periods. The average daily rock mass temperatures at the beginning and the end of the heating periods I. (19 September 2012-22 April 2013) and II. (18 September 2013-23 May 2014) are summarized in Tab. 2.

The results show that the rock mass temperatures at the beginning of the heating periods did not change significantly. Therefore, it can be assumed that the vertical rock mass heat exchangers were stable long lasting sources of low-potential energy. Similar conclusions were reached by LUA ET AL. (2013) during operational testing of vertical heat exchangers and DARKWA ET AL. (2013) in his study °C.

Tab. 2. – Average daily rock mass temperatures at the beginning and the end of the heating period.

		Heating period	Depth (m) 9	20	50	100	Average temperature (°C)	Average temperature difference (°C)
Beginning of the heating period	U 1	I.	13.06	12.31	11.02	10.89	11.82	-0.61
		II.	12.28	11.60	10.41	10,53	11.21	
	U 2	I.	13.43	12.04	10.94	10.72	11.78	-0.49
		II.	12.67	11.51	10.53	10.44	11.29	
End of the heating period	U 1	I.	6.90	7.13	7.12	7.40	7.14	2.98
		II	10.67	10.41	9.60	9.80	10.12	
	U 2	I.	7.38	7.30	7.28	7.64	7.40	2.78
		II.	10.87	10.32	9.72	9.80	10.18	

Higher temperature difference at the end of the heating periods I. and II. emanated from lower ambient air temperatures in the heating period I. and thus increased heat consumption by both heat exchangers.

The course of the average daily rock mass temperatures t_C in the period of heat exchangers stagnation, following the heating period between 23 April 2013 and 17 September 2013, 148 days, are displayed in Fig. 2.

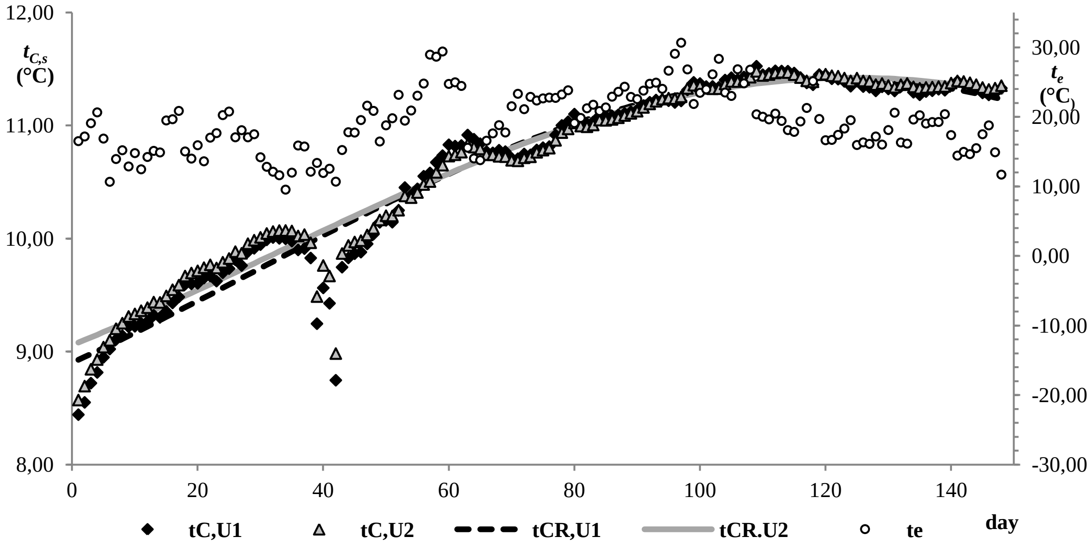

Fig. 2. – Average daily rock mass temperatures in the stagnation period and air temperatures

The diagram in Fig. 2 shows that the differences in the average daily temperatures t_C in the area of the U1 and U2 heat exchangers were not significant in the stagnation period. They were in the range of Δt_U = 0.03 ± 0.07 K. The rock mass temperatures increased approximately until day 120 of the stagnation period with an intensity of 1 K per 40 days; then it slightly decreased. The sharp drop in the rock mass temperature (day 39-42) responds to a decrease in ambient air temperature t_e and putting the heating system into operation.

The course of the average daily rock mass temperatures $t_{C,U,s}$ in the heat exchangers stagnation period can be expressed within the meaning of equation (1) by equations (4) and (5).

$$t_{C,U1,s} = 9.725 + 1.692 \cdot \sin(\Omega.\tau + 5.774) \quad (°C)$$

$$I^2_{U1,s} = 0.948 \quad (4)$$

$$t_{C,U2,s} = 9.885 + 1.538 \cdot \sin(\Omega.\tau + 5.715) \quad (°C)$$

$$I^2_{U2,s} = 0.958 \quad (5)$$

Temperatures, hydrodynamic and thermokinetic parameters of the heat-transfer fluid.

Configuration differences of U1 and U2 heat exchangers affected the mass flows of the heat-transfer fluids m_τ, temperatures of the heat-transfer fluids at the inlet t_1 and the outlet t_2 of the heat pump evaporator, temperature differences $\Delta t = t_1 - t_2$ and the minimum temperatures of the heat-transfer fluid $t_{2,min}$. The average temperatures and the mass flows of the heat-transfer fluid are presented in Tab. 3.

Tab. 3. – Average mass flows and heat-transfer fluid temperatures.

	m_τ (kg.s^{-1})	t_1 (°C)	t_2 (°C)	Δt (K)	$t_{2,min.}$ (°C)
U1	0.122 ± 0.04	7.73 ± 0.7	6.12 ± 2.2	2.49 ± 0.75	-1.76
U2	0.141 ± 0.04	8.08 ± 0.4	6.28 ± 2.2	2.61 ± 0.79	-1.60

The results in Tab. 3. indicated that the U2 heat exchanger had better thermokinetic and hydrodynamic parameters than U1 heat exchanger. Higher heat-transfer fluid temperatures of the U2 heat exchanger showed a positive effect also on the heating factor of the heat pump.

During the verifications within several heating periods, the temperatures of the heat-transfer fluids did not drop below -2 °C. Still a mixture of 33% ethanol and 67% water has been most commonly used heat-transfer fluid in the Czech Republic. At this concentration of ethanol, the freezing point according to the Engineering ToolBox (2015), is -17.4 °C. BANKS (2012) as well as BRANDL (2006) stated that higher concentration makes the hydrodynamic and thermokinetic parameters of the heat-transfer fluid more unfavourable. Based on these facts, the type of heat-transfer fluid flow and heat transfer coefficient

α (W·m^{-2}·K^{-1}) between the inner exchanger pipe wall and the heat-transfer fluid was determined. According to BRANDL (2006), the heat transfer coefficient can significantly affect the process of heat transfer between the rock mass and the heat-transfer fluid. On the basis of the facts given it is apparent that satisfactory concentration for the verified vertical rock mass heat exchangers would be 20% of ethanol, when the freezing point is -9.0 °C. The results of the verifications and calculations have shown that lowering the concentration of the heat-transfer fluid would have significant positive effect on the Reynolds criteria and the heat transfer coefficient α, but the flow rates of the heat transfer fluid were low in both heat exchangers. They were in range of w = 0.03-0.34 m.s^{-1} for the U1 heat exchanger and w = 0.02-0.32 m.s^{-1} for the U2 heat exchanger. Thermokinetically favourable turbulent flow (Re > 2 500) would be achieved at a concentration of 20% and a heat-transfer fluid flow speed of w > 0.39 m.s^{-1} for the U1 heat exchanger and w > 0.49 m.s^{-1} for the U1 heat exchanger. According to BANKS (2006), it is not necessary to achieve a turbulent flow. However, laminar flow was not effective in terms of heat transfer.

Specific heat outputs and specific energies transferred by the heat exchangers.

The average q_τ and maximum $q_{\tau,max}$ heat outputs (W·m^{-1}), specific energies q, q_{max} transferred by the heat exchangers per day (Wh·m^{-1}·day) and total energy q_Σ transferred by 1m length of the heat exchanger in the heating period (kWh.m^{-1}) at an average daily ambient air temperature t_e = 5.34 °C are given in Tab. 4.

Tab. 4. – Average and maximum specific heat outputs and specific energies extracted from the rock mass

	q_τ (W·m^{-1})	$q_{\tau,max}$ (W·m^{-1})	q (Wh·m^{-1}·day)	q_{max} (Wh·m^{-1}·day)	q_Σ (kWh·m^{-1})
U1	6.46±2.19	20.66	125.48±72.17	262.77	27.16
U2	8.19±2.73	26.57	157.54±90.73	353.16	34.10

The results of the verification summarized in Tab. 4. show that specific heat outputs q_τ, $q_{\tau,max}$ for the U2 heat exchanger as well as the specific energies q, $q_{max.}$, q_Σ extracted from the rock mass were higher than for the U1 heat exchanger. The results also showed that the maximum specific heat outputs of the heat exchangers $q_{\tau,max}$ and the total energy extracted from the rock mass q_Σ did not reach its limits as stated by BANKS (2006) and VDI 4640 (2001).

Higher specific heat outputs as well as specific energies extracted from the rock mass by the U2 heat exchanger were caused by its larger heat exchanger surface. External heat exchanger surface per 1 m length at the U2 heat exchanger was bigger by 60% than at the U1 heat exchanger. Heat outputs together with their transferred energies were in our verifications most probably limited by low value of heat transfer coefficient α caused mainly by purely laminar heat-transfer fluid flow.

The diagram in Fig. 3 shows the course of specific heat outputs of the heat exchangers extracted from the rock mass in the coolest day of the heating season (26.1.2013) when the average daily ambient air temperature was t_e = -9.15 ± 5.03 °C. The courses of the outputs reacted to the ambient air temperatures and the working time of the company's employees. The average specific heat outputs of the heat exchangers were higher than the average outputs for the entire heating period, but lower than that stated by the standard VDI 4640 (2001). They reached values in the range of 7.58 ± 2.54 W.m^{-1} (U1 heat exchanger) and 9.82 ± 4.06 W.m^{-1} (U2 heat exchanger). Also the specific energies transferred by the heat exchangers on this day were 186.95 Wh·m^{-1} (U1) and 241.50 Wh·m^{-1} (U2) being higher than the average values for the entire heating period.

The bar diagram in Fig. 4 illustrates the specific heat energy transferred by the heat exchangers on individual days of the entire heating period.

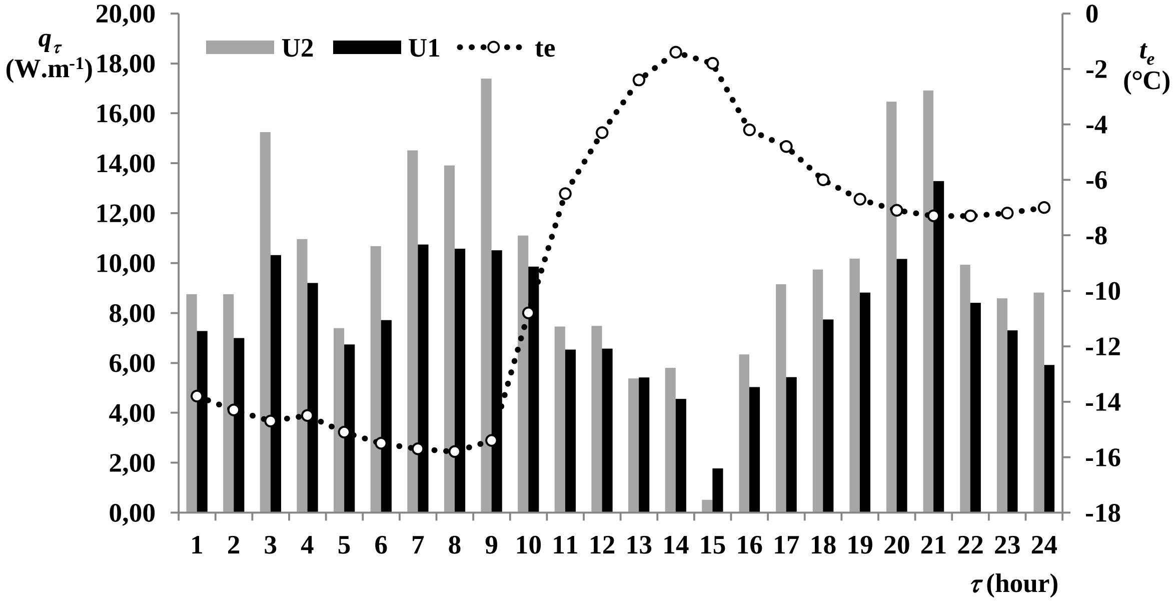

Fig. 3. – Heat outputs extracted from the rock mass in the coolest day of the heating season

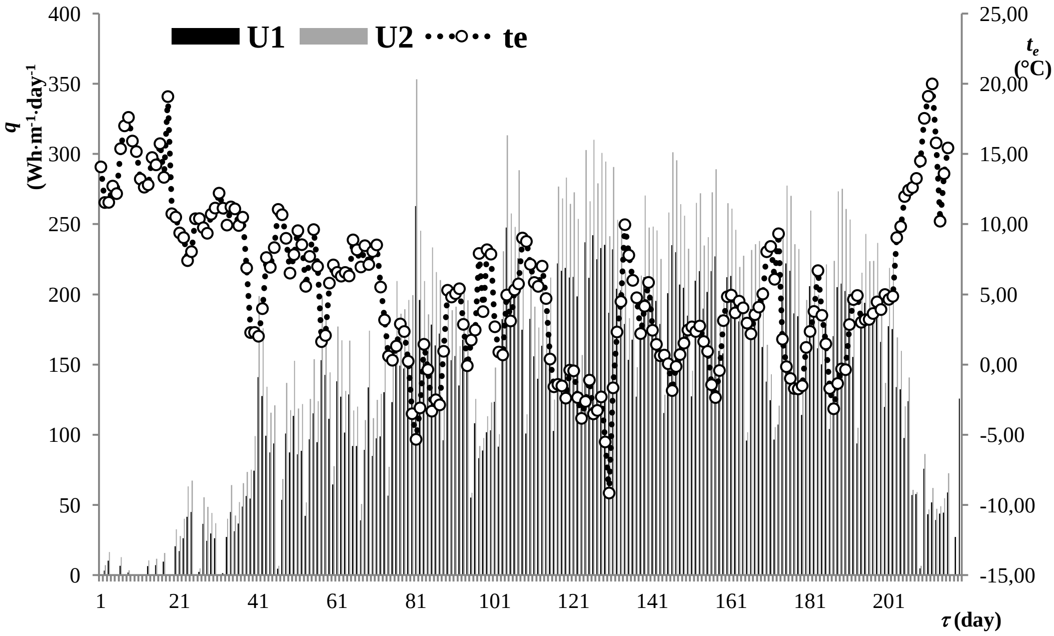

Fig. 4. – Specific energies extracted from the rock mass in the heating period

The response of the heat exchanger operation to the ambient air temperatures resulted from the course of specific energies extracted from the rock mass on individual days.

CONCLUSIONS

The study provided knowledge that can be useful for design and realization of the vertical rock mass heat exchangers. Based on the verification and monitoring the temperatures, heat outputs and heat energies extracted from the rock mass, the following conclusions were made:

- Cooling of the rock mass in the area of the U2 heat exchanger was smaller than in the case of U1. The rock mass temperatures in the area of both heat exchangers were positive.
- The courses of the average daily rock mass temperatures t_C in the heating and the stagnation period can be expressed, with sufficient accuracy, using simple equations (2), (3) and (4), (5). Knowledge of the rock mass temperature courses together with knowledge of its thermal

characteristics and ambient air temperatures revealed the important basis for controlling the energy systems with heat pumps.

- The average daily rock mass temperatures in the areas of both heat exchangers for the greater part of the heating period were higher than the ambient air temperatures (59.72% for U1; 62.96% for U2). The verification confirms the advantages of GLHEs as low-potential energy sources for heat pumps compared to the outside air.
- Rock mass temperature differences in the area of the heat exchangers at the beginning and at the end of the heating periods were not significant. The verification results thus indicated that the vertical rock mass exchangers can be considered a long-term stable source of low-potential energy.
- Specific heat outputs and specific energies extracted from the rock mass by the U2 heat exchanger were higher than at the U1 heat exchanger.
- The average and the minimum temperatures of the heat-transfer fluid in the U2 heat exchanger were higher than in the U1 heat exchanger.
- In both types of the heat exchangers U1 and U2, only laminar flow of the heat-transfer fluid was obtained. A significant cause of the disadvantageous laminar flow was a high concentration of ethanol, which does not correspond to the operating temperatures of the heat-transfer fluid.
- Decreasing the ethanol concentration had a positive influence on the type of heat-transfer fluid flow and the heat transfer coefficient between the heat-transfer fluid and the exchanger pipe walls.

Further studies will analyze and verify the possibilities of increasing the specific heat outputs of the heat exchangers by obtaining at least temporary turbulent flow of the heat-transfer fluid. The acquisition of knowledge about the impact of using GLHEs for heating and cooling buildings on a temperature field, heat outputs and specific energies extracted from the rock mass will be considered.

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