VERTICAL GROUND HEAT EXCHANGERS – LOW-TEMPERATURE ENERGY SOURCES

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Abstract
The most widely used types of ground exchangers in Europe, single (A) and double (B) U-tube exchangers, installed in 113 meters deep boreholes were verified during our research. The monitored parameters included the temperatures of heat carrier fluids, thermal resistances, specific outputs and extracted energies of vertical rock exchangers used as low-temperature energy sources for heat pumps. It is apparent from the results of the verification that the single U-tube exchanger was more effective than the double U-tube exchanger in terms of the monitored parameters. Temperatures of the fluids were higher for exchanger B and their distribution was more favourable. However, differences in average temperatures were only 0.35 K. The specific heat outputs per 1 m^2 of heat exchange surface area and specific energies extracted from the mass were higher at exchanger A than at B by 11.17 W and 370 kJ/m^2·day, respectively.

Key words: *temperature; heat carrier fluid; heat exchanger; heat output; heat resistance; energy extraction.*

INTRODUCTION

Heat pump energy systems use mainly low-temperature renewable energy sources contained in ground or rock mass, water or ambient air. At the same time, unlike other energy systems, they also make it possible to use anergy, the part of energy that is unusable in the sense of the 2nd Law of Thermodynamics. These facts evoke an urgent need for research into heat pump energy systems, especially in terms of renewability and sustainability of their low-temperature energy sources. This paper is focused on a rock mass as a low-temperature source for heat pumps. The energy contained in the rock mass is utilized by vertical tubular heat exchangers (VGHE), mostly U-shaped, stored in boreholes with depths up to 150 meters. The VGHEs heat carrier fluid temperatures, the extracted heat outputs and the energy values extracted from the rock mass are important parameters influencing the renewability and sustainability of the low-temperature energy source, as well as the overall effect of the energy system.

Michopoulos, Kyriakis (2009) developed and experimentally verified prediction model of the heat carrier fluid temperatures at the VGHEs output. The model demonstrated satisfactory accuracy during the whole verification procedure. *Mesaha et al. (2017)* focused on the temperature changes of the heat carrier fluids, heat outputs and energy values extracted from ground mass in dependence on the VGHEs pipe lengths. Numerical analysis of the VGHEs single and double U-tube dimensional model was performed by *Zeng et al. (2003)*. The results of their verification showed that double U-tube exchangers had higher specific heat output and lower thermal resistance per 1 m of borehole than single U-tube exchangers. *Ren et al. (2018)* monitored the temperatures of the heat carrier fluids, outputs and extracted heat of the VGHEs with steel and polyethylene pipes. Both the outlet temperatures and outputs were higher at the VGHE with steel pipes that those with polyethylene pipes. Long-term operation of VGHE in both heating and cooling modes was simulated by *Choi et al. (2018)* as well as by *Remiorz et al. (2015)*. Verification demonstrated that temperature of the heat carrier fluid and the VGHEs output in the winter period increased significantly when the heat was accumulated in the cooling mode during the summer. The causes of VGHEs degradation indicated by the thermal imbalance of the ground mass were discussed by *You et al. (2016)* and also by *Liet al. (2018)*. They elaborated a very detailed overview of the main problems caused by the thermal imbalance of the mass and what causes it to arise. In case of disruption of the balance, *Dai et al. (2015)* recommended to supplement VGHEs with a solar system used for ground mass regeneration.

The aim of this article was to analyze and compare the temperatures of the heat carrier fluids supplied to the heat pump evaporator, the VGHEs thermal resistances, their specific outputs and energies extracted by VGHEs from the ground mass during the heating season.

MATERIALS AND METHODS

Two types of VGHEs installed in a boreholes with a depth of 113 m were tested. VGHE A in a form of single U-tube was the first one, made of polyethylene piping PE 100RC 40 x 3.7 mm with a total length of 226 m (28.40 m^2). The second was VGHE B in a form of double U-tube made of polyethylene piping PE 100RC 32 x 2.9 mm with a total length of 452 m (45.44 m^2). The piping is resistant to point loads and cracks. Both VGHEs, together with horizontal ground heat exchangers, are sources of low-temperature energy for two heat pumps GreenLine HT Plus E 17 (heat output 2x 16.2 kW at 0/35 °C) and one pump IVT PremiumLine EQ E13 (heat output 13.3 kW at 0/35 °C), (Industriell Värme Teknik, Tnanas, Sweden). The heat pumps are used for heating of administrative building and service halls of VESKOM s.r.o. based in Prague Dolní Měcholupy. The following computation values were used for this location: outdoor temperature t_e = -12 °C, average temperature in the heating season 4.0 - 5.1 °C and the heating system operation time 216-254 days. The temperatures of the heat carrier fluids were measured at quarter-hour intervals on the VGHEs outlet and inlet pipes with Pt100 sensors and recorded by ALMEMO 5990 measuring device (AHLBORN Mess- und Regulungstechnik GmbH, Holzkirchen, Germany). The reference temperature of the ground mass was measured at a depth of 50 m in an empty non-operating borehole. The ambient temperatures t_e were recorded at a height of 2.5 m above the ground surface with ATF 2 KTY 81.210 sensor (S + S Regeltechnik, Nürnberg, Germany). Specific heat outputs ($q_{\tau,a}$, $q_{\tau,max}$) and energy extractions (q_a, q_{max}) were determined on the basis of the difference of heat carrier fluid temperatures, heat carrier fluid flow rates (V_τ) measured by MTW 3 electronic meters (Itron Inc. Liberty Lake, USA), specific heat capacities and densities corresponding to the medium temperature of the heat carrier fluid. The measurement took place during the heating season 2012/2013 from 17 September 2012 to 22 April 2013 (218 days). STATISTICA program (StatSoft, Inc. 2013) and MS Excel 2016 were used to evaluate the measured quantities.

RESULTS AND DISCUSSION

1. Temperatures of heat carrier fluids

The average daily temperatures of heat carrier fluids of VGHE A (t_A) and B (t_B) are shown in Figure 1. It presents an important observation that the temperatures of fluids did not reach negative values during the monitored period. The reaction of temperatures of the heat carrier fluids to the ambient temperature is evident here. The temperature course indicated an insignificant difference between temperatures t_A and t_B. Heat carrier fluid temperatures of VGHE A were higher on average only by 0.35±0.32 K. The output temperatures of VGHE type A were the same as those monitored by *Remiorz et al. (2015)* when testing similar type of VGHE.

The quadratic equations for the temperature trend lines of the VGHEs are in the form of (1) and (2). Determination coefficients R^2 correspond to the data very well. τ_d in equations (1) and (2) indicates the length of the heating period from its beginning, expressed in days.

$$t_A = 0.0004.\tau_d^2 - 0.1206.\tau_d + 14.731 \qquad (R^2 = 0.908) \qquad (1)$$
$$t_B = 0.0004.\tau_d^2 - 0.1321.\tau_d + 15.798 \qquad (R^2 = 0.936) \qquad (2)$$

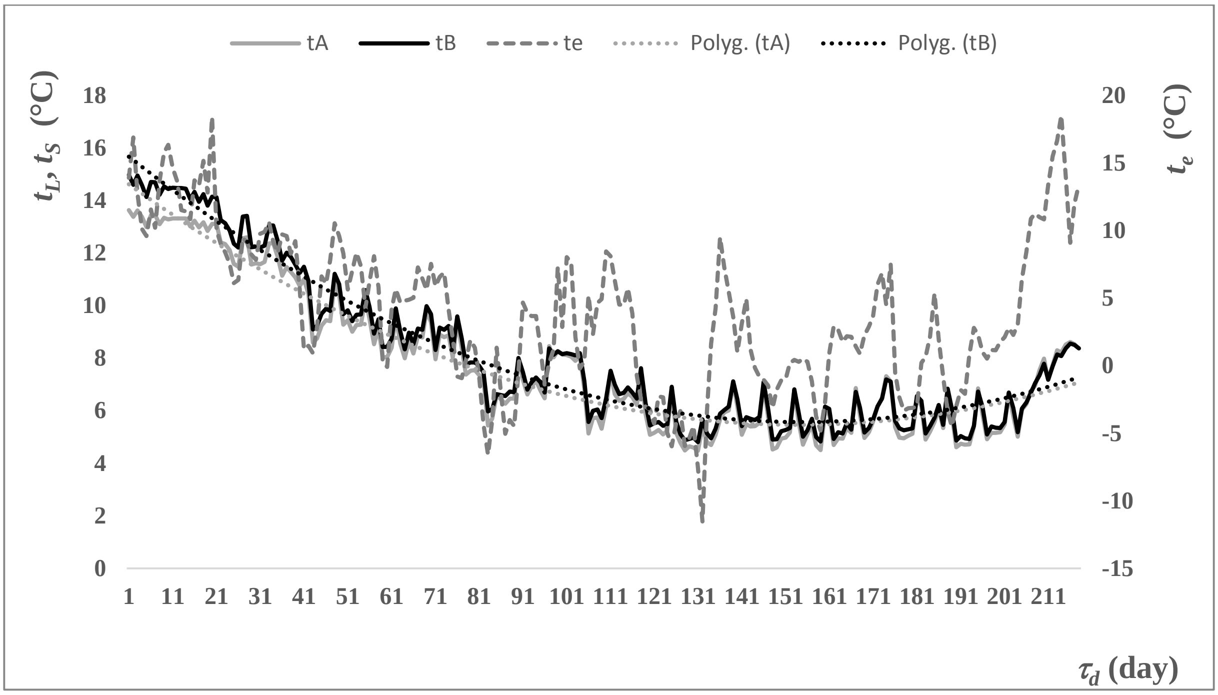
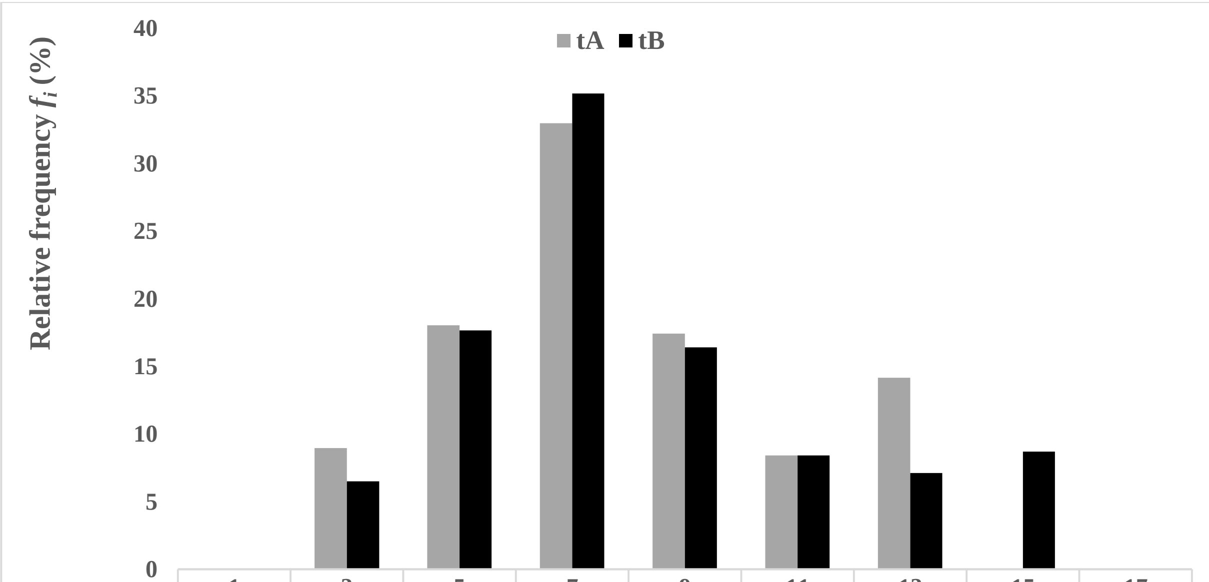


Fig. 1 Average daily temperatures of VGHEs heat carrier fluids t_A, t_B and ambient air temperatures t_e.

A different view and more information can be gained from the histogram of temperature distribution of heat carrier fluids during the heating season in Figure 2. This histogram is significant mainly because of the information it gives us on the relative frequency of average hourly temperatures f_i (5.232 values) at 2 K intervals characterized by the so-called class representative *r*, which ranges from 1.0 to 17.0 °C. The temperature mode *Mod(t)*, determining the interval of the most frequently occurring heat carrier fluid temperatures, is especially important variable of the histogram.



	1	3	5	7	9	11	13	15	17
tA	0,00	8,96	18,04	32,99	17,43	8,41	14,16	0,00	0,00
tB	0,00	6,50	17,66	35,19	16,40	8,43	7,11	8,70	0,02

Fig. 2 Relative frequencies of average hourly VGHEs heat carrier fluids temperatures t_A a t_B

As indicated by the results, the temperature mode of the heat carrier fluid *Mod(t)* of both VGHEs occurred in the interval 6.10–8.00 °C (r = 7 °C). However, the relative frequency of occurrence was higher at VGHE B (f_i = 35.19%) than at VGHE A (f_i = 32.99%). At the same time, temperatures of VGHE B occurred in higher ranges (r = 15 °C and r = 17 °C) than that of VGHE A (r = 13 °C). The higher frequency of the heat carrier fluid temperatures at higher temperature intervals indicated the advantage of this low temperature energy source.

2. Heat outputs and extracted energies

The following parameters are presented in Table 1: the average and the maximum flow rates of the heat carrier fluid, $V_{\tau,a}$, and $V_{\tau,max}$ respectively, total volume of the heat carrier fluid that had passed through the exchangers during the heating period, V_{Σ}, specific and maximum heat outputs converted to 1 m of pipe length and 1 m^2 of heat transfer surface of the exchangers, $q_{\tau,a}$ and $q_{\tau,max}$ respectively, average and maximum specific energies transferred from the mass by 1 m^2 of the exchanger during 1 day of the heating season, q_a and q_{max} respectively, the total amount of energy transferred from the mass by the exchanger during the heating season, q_{Σ} and also the total time of energy extraction by exchangers during the heating season, τ_{Σ} .

The specific heat outputs $q_{\tau,a}$, $q_{\tau,max}$ (W/m, W/m^2) as well as the specific energies extracted from the mass q_a, q_{max} (kJ/m^2·K) were higher at VGHE A than at B. The observed specific heat outputs of VGHEs corresponded to the values published by *Banks (2012)*. He defined the specific heat output of a heat pump converted to 1 m length of a borehole with a heating factor of 3.4 within the range of 37–104 W, on average 67 W/m. In the monitored heating period, the average specific outputs of VGHEs related to 1m of a borehole length were 15.07±10.50 W/m for VGHE type A and 19.63±13.70 W/m for type B. Similar values of specific outputs were presented by *Zeng et al. (2003)*.

Tab. 1 Heat carrier fluid flows, heat outputs and extracted energies

Parameter	VGHE A	VGHE B
$V_{\tau,a}$ (m^3/h)	0.52±0.26	0.61±0.31
$V_{\tau,max}$ (m^3/h)	1.03	1.27
V_{Σ} (m^3)	1 435.96	1 787.94
$q_{\tau,a}$ (W/m)	7.53±5.25	4.90±3.42
$q_{\tau,max}$ (W/m)	29.28	14.18
$q_{\tau,a}$ (W/m^2)	59.97±41.80	48.80±34.08
$q_{\tau,max}$ (W/m^2)	233.08	141.05
q_a (kJ/m^2.day)	2 723.40±1 785.58	2 353.59±1 540.89
q_{max} (kJ/m^2.day)	7 495.07	6 564.86
q_{Σ} (MJ/m^2)	593.70	513.08
τ_{Σ} (h)	2 750	2 920

The graph in Figure 3 shows the course of specific energies extracted from the ground mass by VGHEs during the heating season. The specific energies extracted from the ground mass correspond to the trend of specific heat outputs of VGHEs. There is also evident a relationship of the values of extracted specific energies and ambient temperatures, as confirmed by the verification results of *Todoran, Balan (2016)*.

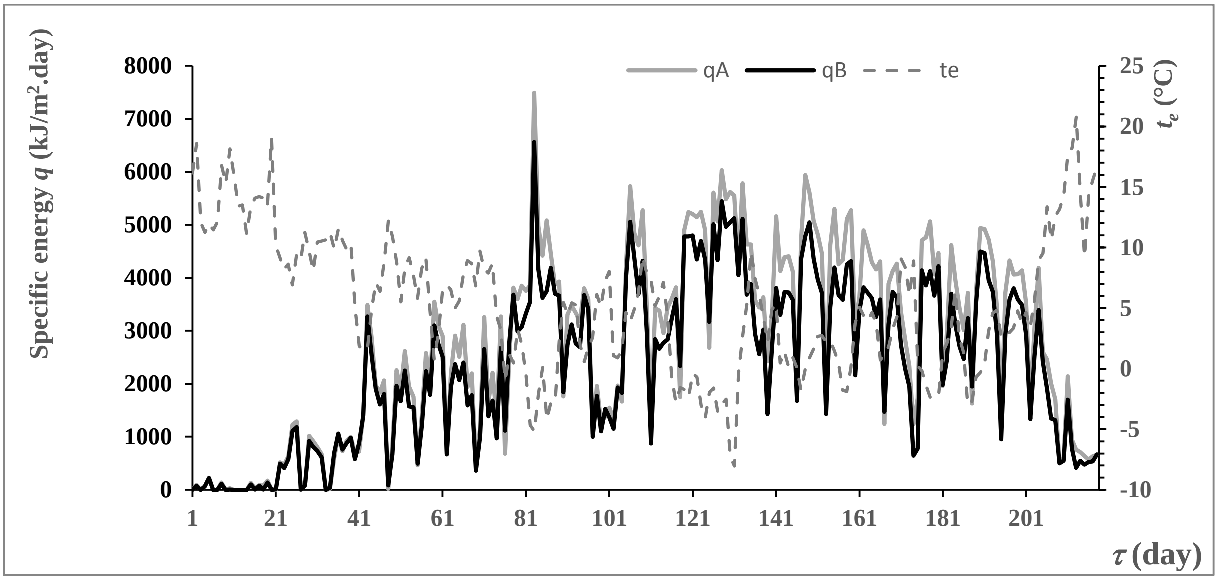


Fig. 3 Specific extracted energies q_A, q_B and ambient temperatures t_e

3. Heat resistances of VGHEs

Zeng et al. (2003) pointed at the dependence of the specific thermal resistances of VGHEs on the pipe diameter and the borehole depth related to 1 m depth of a borehole. They expressed the thermal resistance by relation (3):

$$R = \frac{t_{r.m.} - t_a}{q_\tau} \quad (3)$$

where:

R – specific heat resistance of a borehole (m·K/W);

$t_{r.m.}$ – temperature of reference ground mass (°C);

t_a – temperature of heat carrier fluid;

q_τ – specific heat output converted to 1 m length of a borehole.

They reported that VGHEs thermal resistance decreased as the VGHEs pipe diameter enlarged and increased with a greater depth of a borehole. They also found that the specific thermal resistance was smaller at the double U-tube exchanger than that at the single U-tube VGHE. The results of our verifications confirmed this conclusion. The average specific resistance was 0.36±0,12 m·K/W at VGHE A and 27±0.10 m.K/W at VGHE B.

From the point of view of evaluation and comparison of the heat transfer process between the ground mass and the heat carrier fluid, it seems advantageous to express the specific heat resistance converted to 1 m^2 of the heat transfer surface of VGHE. In this way, the average specific thermal resistance was 0.09±0.03 m^2.K/W at VGHE A and 0.11±0.04 m^2.K/W at VGHE B.

CONCLUSIONS

Higher temperatures of heat carrier fluid, higher relative frequencies in mode of temperature distribution of heat carrier fluid and occurrence of temperatures at higher intervals were more often monitored at VGHE B than at VGHE A. However, graphs in Figures 1 and 2 show that the temperature differences of the heat carrier fluids were not significant.

The average specific heat output calculated per 1 m^2 of heat transfer surface of the exchanger pipes was higher by 22.89% at VGHE A, at a lower average flow rate of the heat carrier fluid by 14.75%. Also, the specific thermal resistance per 1 m^2 of heat exchange surface was lower by 18.18% at VGHE A than at B.

The above analysis indicated that VGHE A can be considered to be more effective than VGHE B in terms of monitored parameters.

The objective of further verifications will be presumably monitoring and analysing the temperatures of the heat carrier fluids in terms of confirming the results in different climatic conditions of the heating seasons.

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