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Results of operational verification of vertical ground heat exchangers

Daniel Adamovskýa [a,*], Pavel Neuberger [b], Radomír Adamovský [b]

[a] Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Trinecka 1024, Bustehrad, 273 43, Czech Republic
[b] Czech University of Life Sciences Prague, Faculty of Engineering, Kamycka 129, 165 21 Praha 6, Czech Republic

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ABSTRACT

This article is devoted to verification of VGHEs (Vertical Ground Heat Exchangers) used as a low-temperature energy source for heat pumps. The aim and objective of the study was to obtain practical knowledge of temperatures of rock mass and heat transfer fluids which affect the life cycle of the low temperature sources and the effectiveness of heat pump systems. The objective was also to gain knowledge of specific thermal energy and power extracted by these exchangers which are relevant to the evaluation of frequently used configurations of VGHEs. The results of the operational tests of two active boreholes with different arrangements, namely a single U exchanger (A), a double U exchanger (B) – and the reference (inactive) borehole (R). The tests were performed in the years 2012–2014 and involved 2 heating seasons and 2 exchanger stagnation periods. Results of the tests showed that exchanger B is more effective than exchanger A in terms of temperatures and particularly specific heat power and energies. The average specific thermal power in the heating periods were 23.11 W m^{-1} and 26.57 W m^{-1} for exchanger B and 16.88 W m^{-1} and 20.66 W m^{-1} for exchanger A. Total specific energies transferred from the massif during the heating periods were higher by 6.05 kWh m^{-1} and 6.94 kWh m^{-1} at exchanger B than at exchanger A.

1. Introduction

VGHEs are important elements of power systems, enabling geothermal energy to be utilized for the heating of buildings by means of heat pumps. These exchangers, which in Europe are mostly installed at depths of 50–150 m, warm the heat transfer fluid, which then transfers the desired energy of a low energy potential to the evaporator of the heat exchanger. Trends of development, configuration and types of vertical rock exchangers are addressed in literature [1–3]. In Central Europe, only VGHEs with one or two U-shaped loops are mostly used. An important factor of effective use of VGHE at low operating costs is the efficiency of heat transfer from the rock massif into heat transfer fluid in the primary circuit of the heat pump [1,2].

Banks [3] described two types of thermal resistance in connection with the transfer of heat from the rock massif to the heat transfer fluid: the thermal resistance of the rock massif and the thermal resistance of the borehole. The boundary between both thermal resistance types is the wall of the borehole.

The value of the thermal resistance of the rock massif depends primarily on its thermal characteristics, the coefficient of thermal conductivity λ [W m^{-1} K^{-1}], volumetric heat capacity C [J m^{-3} K^{-1}], and the temperature diffusivity factor a [m^2 s^{-1}]. These quantities influence not only the power of the vertical heat exchanger, but also the distribution of temperatures in the massif and the period of utilization of the heat pump systems. Both experimental [4,5] and theoretical studies [6,7] have proved the significant influence of groundwater flow on the thermal resistance of the massif.

The thermal resistance of the borehole depends on the size, configuration, and material of the heat exchanger, the distance between the pipes, the diameter of the borehole, the material of the grouting, and the type of flow of the heat transfer fluid. The material of the grouting of the borehole plays an important role in the heat transfer between the rock massif and the heat transfer fluid. The issues of thermal, hydraulic, and mechanical properties of grouting materials are dealt with by Selçuk and Bertrand [8], who focused on improving the thermal properties of grouting material by adding graphite powder. Huang et al. analyzed the basic parameters of vertical U exchangers from the point of view of the configuration, operation, CAPEX, and OPEX [9]. Sanner and Mands [10] considered thermal resistance below 0.11 K m W^{-1} acceptable and thermal resistance above 0.14 K m W^{-1} unacceptable.

The parallel pipes of the U loop constitute a countercurrent heat exchanger, in which heat is transferred between the pipe leading from the evaporator and the pipe leading to the evaporator. The heat transfer occurs especially in the upper part of the

* Corresponding author.
E-mail address: daniel.adamovsky@fsv.cvut.cz (D. Adamovskýa).

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Nomenclature

A	Single U exchanger
B	Double U exchanger
C	Volumetric thermal capacity (J m^{-3} K^{-1})
I^2_{yx}	Coefficient of determination (–)
R	Reference (inactive) borehole
Re	Reynolds number (–)
VGHE	Vertical ground heat exchanger
a	Temperature diffusivity factor (m^2 s^{-1})
q	Specific energy (Wh m^{-1} day)
q_Σ	Total specific energy (kWh m^{-1})
q_τ	Specific thermal power (W m^{-1})
m_τ	Mass flow of the heat transfer fluid (kg s^{-1})
t	Temperature (°C)
w	Flow velocity of the heat transfer fluid (m s^{-1})
Δt	Temperature difference (K)
Ω	Angular velocity (2·π/365 rad day^{-1})
α	Heat transfer coefficient (W m^{-2} K^{-1})
λ	Coefficient of thermal conductivity (W m^{-1} K^{-1})
τ	Number of days from the start of measurement (day)
ϕ	Initial phase of oscillation (rad)
9	Depth of the borehole 9 m
100	Depth of the borehole 100 m

Subscript

e	Ambient air
min.	Minimal
r.m.	Rock massif
Φ	Average
1	Input to the heat pump evaporator
2	Output from the heat pump evaporator

exchanger because the biggest difference in the temperatures of the heat transfer fluid is located there. Banks [3] stated that up to 75% of the needed heat transfer may take place already between the exchanger pipes. The heat transfer between the branches of the U exchangers causes a reduction in the thermal power brought by the heat transfer fluid to the evaporator of the heat pump. They also established that the active length of the borehole is reduced by 23% in comparison with the length of freely embedded tied pipes when spacers are used between the exchanger pipes.

The service life of vertical ground heat exchangers must be estimated to extend over several decades. After the end of the service life or technology obsolescence, new heat pump machinery can be connected to these low-temperature energy sources. Exchanger configuration, changes in energy potential of the sources, heat transfer fluid temperatures and regeneration ability of energy potential of the sources have major impact on the effectiveness of these heat pump systems and on life cycle of the low-potential source [1,11]. Knowledge of the power and specific energies of the heat exchangers transferred from the massif are particularly important in terms of proposal of type and configuration of the exchangers [12]. Obtaining such information for the most common configurations of VGHEs in Central Europe was the reason and expected benefit of the operational verification, with the aim to:

- Monitor the temperatures and analyze the changes in the rock massif with the VGHEs in dependence on the operation of the exchangers;
- Monitor and analyze the differences in the temperatures of the rock massif with the VGHEs and in the reference borehole;
- Evaluate the regenerative capacity of the energy potential of the rock massif at the time of stagnation of the VGHE operation;
- Determine the specific heat flows and specific energy removed by the VGHEs from the rock massif during the heating season;
- Analyze the differences in the operating parameters of the tested VGHE types.

The following hypotheses were tested:

(a) The temperatures of the rock massif in the area of both VGHEs will only rarely be negative;
(b) The temperatures of the rock massif at the tested VGHEs will not change significantly at the beginning and end of the heating seasons;
(c) The temperatures of the rock massif in the area of the active VGHEs A and B will decrease by a maximum of 10 K (5 K on average) during the heating season, in comparison to the temperatures of the rock massif in the reference inactive borehole;
(d) The temperatures of the rock massif in the area of the double U exchanger (B) will be higher than for the single U exchanger (A);
(e) The values of the specific thermal power and specific energy removed from the rock massif will be higher for exchanger B than for exchanger A;
(f) The operating parameters of exchanger B will be more favourable than those of exchanger A.

The values of specific heat flows removed from the ground massif in various geological environments of Europe were dealt with by Banks [3]. Banks specified the average specific thermal power for Europe to be 62 W m^{-1} and the specific energy removed from the rock massif as 159 kWh m^{-1}. However, he noted that although the values of the specific heat extractions may be a good starting point for the design of the exchanger, a rule this simple is probably too simplifying. He emphasized the impact of operating hours, operating temperature of the exchanger, operational heating or cooling energy requirements and thermal interference between nearby boreholes. These aspects make the rules, based on several assumptions, less and less reliable.

The temperatures and heat transfer for single and double U exchanger in a rock massif were analyzed by Carli et al. [13]. They analyzed the temperatures of the heat transfer fluid, the types of flow, and the temperatures of the rock massif at various depths and distances from the exchanger. Marcotte and Pasquier [14] monitored the influence of borehole inclination on temperature distribution and heat transfer in the rock massif. They proved the positive influence of slight inclination on the heat exchanger power.

2. Materials and methods

The tested vertical ground heat exchangers are energy sources for the heat pumps 1x IVT PremiumLine EQ E13 (thermal power 13.3 kW at 0/35 °C) a 2× GreenLine HT Plus E 17 (thermal power 2 × 16.2 kW at 0/35 °C) (Industriell Värme Teknik, Tnanas, Sweden). The heat pumps, together with another three, are used for heating the office building and operating halls of VESKOM s.r.o., based in Dolní Měcholupy in Prague.

The measurements were performed on 2 types of exchangers located in boreholes A and B and in the reference unequipped borehole R, all of the same depth of 113 m. Borehole A is a single U exchanger made of polyethylene piping PE 100RC 2 × 40 × 3.7 mm (LUNA PLAST a.s., Hořín, Czech Republic) resistant to point load and formation of cracks. The outer surface area per unit length of the borehole was 0.2512 m^2 m^{-1} while the inner surface area was 0.2047 m^2 m^{-1}. Borehole B is a double U exchanger made of polyethylene piping PE 100RC 4 × 32 × 2.9 mm of the same material. The outer surface area per unit length of the borehole B was