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DETERMINING THE ACTUAL TEMPERATURE
OF THE SIDE OF A BOREHOLE HEAT EXCHANGER**

1. INTRODUCTION

The modernization of the electricity sector realized in compliance with international agreements obliges countries to also make use of other sources of energy production than conventional ones. A strong emphasis is also put on the dispersion of the heat and electrical energy generation structure. The ecological aspect makes producers reduce atmospheric emissions of greenhouse gases. All these requirements can be met when heat pumps (HP) are used for heating households and other objects [2, 3, 10].

Installations using heat generated by a HP are characterized by a working temperature of 30–40°C. Such a temperature is sufficient for domestic hot water (DHW), but requires a large surface heating system inside the building. The best solution to take advantage of a large area is to use of an under floor heating system. Another advantage of this type of installation is the low temperature of heating factor, which further lowers the cost of electricity consumed by HP. Another solution for lowering the working temperature on the HP condenser side is warm-air heating which, through forced convection, will more efficiently supply energy to the premises. HP-based installation is not recommended for use in buildings without thermal insulation and fitted with a traditional heat supply system [1, 4, 5].

HP operation is based on low-temperature energy conversion abstracted from the air, groundwater, rock mass or waste heat. The compressor system with an evaporator and a condenser filled with refrigerant, mounted on a HP can increase the low temperature energy value needed for space heating. The drive of the heat pump compressor is usually implemented by means of an electric motor. The ratio of the amount of heat energy generated and delivered for heating purposes to the amount of electric energy can be expressed by the coefficient of heating performance (COP).

Typical COP values are in the range of 2.5 to 5. This means in a very simple way that the COP = 4 consumes 1 kWh of electricity (3.6 MJ) is produced 4 kWh of heat (14.4 MJ).

The intention of each user installation is to keep operating costs as low as possible, which can be achieved by increasing the COP. COP value increases if the temperature of the upper source (temperature supplied to buildings) decreases or if the temperature of the lower source (rock mass, air, groundwater, waste heat) increases according to formula (1):

$$\phi = \eta_{HP} \cdot \frac{T_{z1}}{T_{z1} - T_{z2}} \tag{1}$$

In addition, the real COP value depends on the construction of thermodynamic cycle, the type of installed compressor and kind of refrigerant used in HP.

The high temperature delivered to the HP evaporators depends to a large extent on the temperature of the energy reservoir and heat exchanger design. The use of waste heat from industrial processes has the highest temperature of all low-temperature sources, but its availability is limited to sites where industry production is realized. The heat from atmospheric air is the least expensive heat storage option and the acquisition of energy from it is also relatively uncomplicated and inexpensive. However, it has a flaw, i.e. large temperature fluctuations; the increased energy demand in winter drastically reduces the COP. The use of groundwater requires a production well from which water is drawn and another one to receive water. The use of such circulation is legally regulated and suitable water permits are needed (collection area. 5 m³/24 h, at 5°C temperature difference gives approx. 105 MJ possible to receive daily, low temperature energy). Therefore, Borehole Heat Exchangers remain the most popular HP designs for low temperature energy supplies [8, 9].

The BHE technology assumes the drilling of a hole into which U-tube pipes are plunged. Usually the cheapest type of heat exchanger, equipped with a single U-tube, or sometimes a double U-tube, is performed. A typical diameter of the BHE hole is 143 mm and diameters of borehole pipe (high density polyethylene (HDPE)) 40 mm. The distance between the borehole pipe axes in the heat exchanger with a single U-tube is from 20 mm to 60 mm. The bigger the distance, the lower is the amount of heat transmitted between borehole pipes. Cement slurry consolidates the installation with the rock mass. BHE should be cemented by an additional borehole pipe from the bottom of the exchanger. The injected cement slurry must extrude mud used during the drilling of the hole. Cement slurries characterized by a higher heat transfer coefficient are recommended. Distancers for single and double U-pipes in BHE are shown in Figure 1.

Fig. 1. The distancers for single and double U-pipes in BHE

2. BHE OPERATION

Energy transport between the rock mass and the HP is realized through BHE. Parameters characterizing BHE are determined by a Thermal Response Test (TRT), with an output in the form of the heat transfer coefficient (2) and the thermal resistance of the borehole heat exchanger (3).

$$\lambda = \frac{P_{TRT} \cdot \ln\left(\frac{t_2}{t_1}\right)}{4 \cdot \pi \cdot H_{wo} \cdot (T_{BHE2} - T_{BHE1})} \tag{2}$$

$$R_b = \frac{H_{wo}}{P_{TRT}} \cdot (T_{BHE2} - T_{og}) - \frac{1}{4 \cdot \pi \cdot \lambda} \cdot \left[\ln(t_2) + \ln\left(\frac{4 \cdot \lambda}{r_{wo}^2 \cdot \rho_g \cdot Cp_g}\right) - 0.5772 \right] \tag{3}$$

The mathematical description of the results of TRT assumes that the temperature of whole the borehole heat exchanger is equal to the average temperature of the fluid entering and leaving the BHE borehole pipes (4).

$$T_{BHE}(t) = \frac{T_{in}(t) + T_{out}(t)}{2} \tag{4}$$

It was assumed that the temperature across the cross-section of the heat exchanger and the entire length was identical. In fact, it varied both along the heat exchanger and in its cross-section. The temperature corresponding to the value of the liquid within the borehole pipe influences the inner wall of the borehole pipe and transfers through it. Heat transfer through the wall of the HDPE with a thickness of approx. 3 mm and a heat transfer coefficient approx. 0.45 W/(m·K) is reduced and then transferred to hardened cement slurry. The distance from the borehole pipe of the heat exchanger to the side wall of the exchanger is variable. Therefore, the temperature value transferring from the heat exchanger to the rock also varies. In addition, the temperature value changes during the operation of the exchanger. Assuming that the amount of energy transferred from the borehole pipes to the heat exchanger and from the heat exchanger to the surrounding rocks is a constant value, after working time semi-steady state can be obtained, when the temperature in the cross-section of the exchanger stops changing. Then, the temperature on the surface side of BHE is determined and its value is a function of the radius function angle of the cross-sectional exchanger relative to the horizontal reference plane [3, 6, 7].

3. THE COURSE OF THE TEST

For performing measurements aimed at establishing the temperature of the side surface of the BHE, a model BHE 0.3 m long, construed with a single U-tube was worked out (Fig. 2). In the interior of borehole pipes, electrical heaters with stabilized working
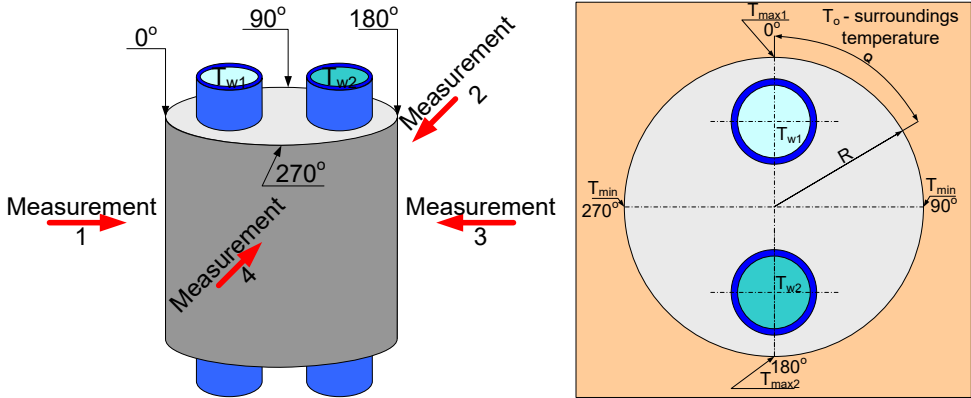
temperature were placed. The borehole pipes are filled with fluid and the temperature in the borehole pipes of the BHE model is maintained at 32°C and 30°C (±0.2°C). The temperature of the side surface of the heat exchanger and the front was measured with a FLIR E60 thermal imaging camera for temperature measurement resolution 0.05°C and accuracy 0.1°C. The images of temperature of BHE model (Fig 3) were performed at 4 min intervals at power heaters until the temperature stabilized on the side surface of the model. Measuring the temperature of the side surface was performed with four-fold shift angle of 90° (Fig 4). Temperatures of the intermediate angles (30° and 60°) were read out from the temperature scale of a thermal imaging camera. The initial temperature of the BHE model was fixed at a constant value and amounted to 20°C (±0.2°C). Hardened cement slurry was in an air – dry state and the heat thermal conductivity was set at 0.8 W/(m·K). The ambient temperature during the measurement was 20°C (±0.2°C). The measurement results are summarized in Table 1 and plots (Fig. 5 and 6). The principle of determining the value of adopted angles θ is explained in Figure 7.

Fig 2. Model of the BHE cross-section with a single U-tube
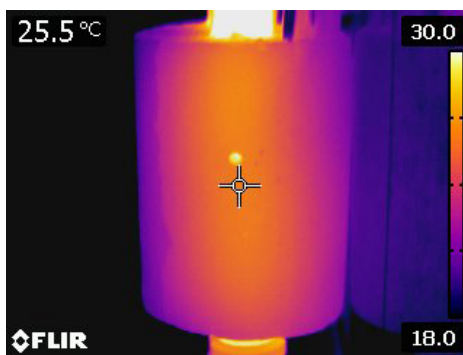
Fig. 3. Example of a temperature measurement of the BHE model with a thermal imaging camera (FLIR E60)

Fig. 4. Conducting measurements of the surface temperature of the BHE model and how to determine the value of the angle θ

Table 1

Values of lateral surface temperature as a function of angle theta, the liquid in the borehole pipes and the environment of BHE model

Time [min]	Value of temperatures for angle θ [°C]								Value of temperatures [°C]		
	0	30	60	90	120	150	180	270	T_{w1}	T_{w2}	T_o
0	20.3	20.2	20.2	20.2	20.2	20.2	20.3	20.2	32.2	30.1	20.0
4	20.4	20.2	20.2	20.2	20.2	20.2	20.4	20.2	32.2	30.1	19.9
8	21.0	20.4	20.2	20.2	20.2	20.3	20.9	20.2	32.1	30.0	19.9
12	23.1	20.8	20.3	20.2	20.2	20.4	21.5	20.2	32.1	30.0	20.0
16	24.2	21.5	20.3	20.2	20.3	20.7	22.4	20.2	32.1	29.9	20.0
20	25.2	22.3	20.4	20.3	20.3	21.1	23.2	20.2	32.1	29.9	20.0
24	25.5	23.1	20.5	20.4	20.4	21.6	23.5	20.3	32.0	29.9	20.1
28	25.7	23.8	20.7	20.5	20.6	22.1	23.6	20.4	32.0	30.0	20.1
32	25.8	24.3	21.3	20.6	20.8	22.5	23.7	20.5	32.0	30.0	20.1
36	25.8	24.6	21.9	20.7	21.1	22.9	23.7	20.6	32.0	30.1	20.1
40	25.8	24.7	22.4	20.9	21.4	23.0	23.7	20.8	32.1	30.1	20.2
44	25.8	24.7	22.7	21.1	21.6	23.0	23.7	21.0	32.1	30.1	20.2
48	25.8	24.7	22.8	21.3	21.7	23.0	23.7	21.2	32.1	30.0	20.2
52	25.8	24.7	22.8	21.4	21.7	23.0	23.7	21.3	32.1	30.0	20.2
56	25.8	24.7	22.8	21.5	21.7	23.0	23.7	21.4	32.1	29.9	20.2
60	25.8	24.7	22.8	21.5	21.7	23.0	23.7	21.4	32.1	29.9	20.1
64	25.8	24.7	22.8	21.5	21.7	23.0	23.7	21.4	32.1	30.0	20.1
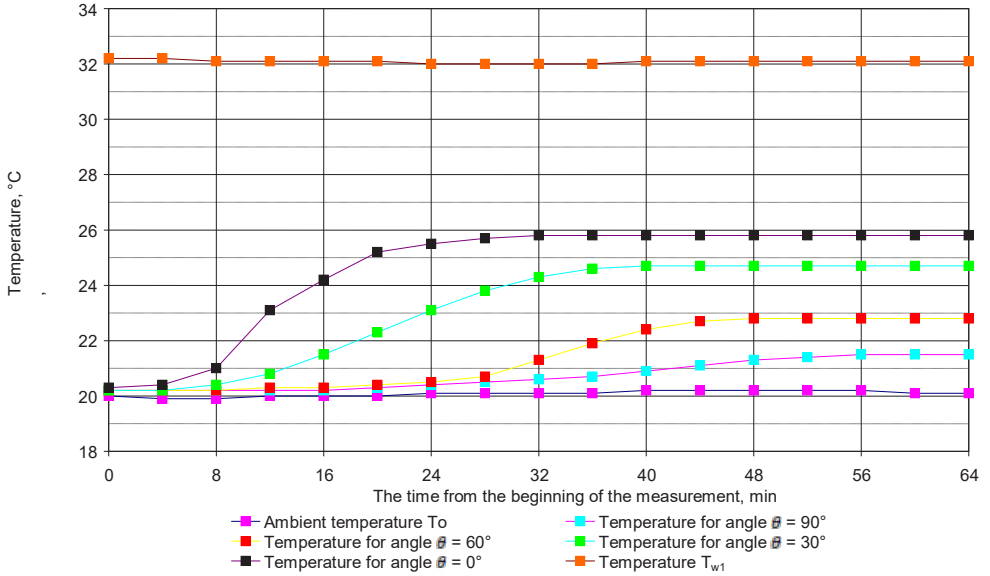
Fig. 5. The values of the surface temperature of the side BHE model as a function of time for the angle theta from 0° to 90°
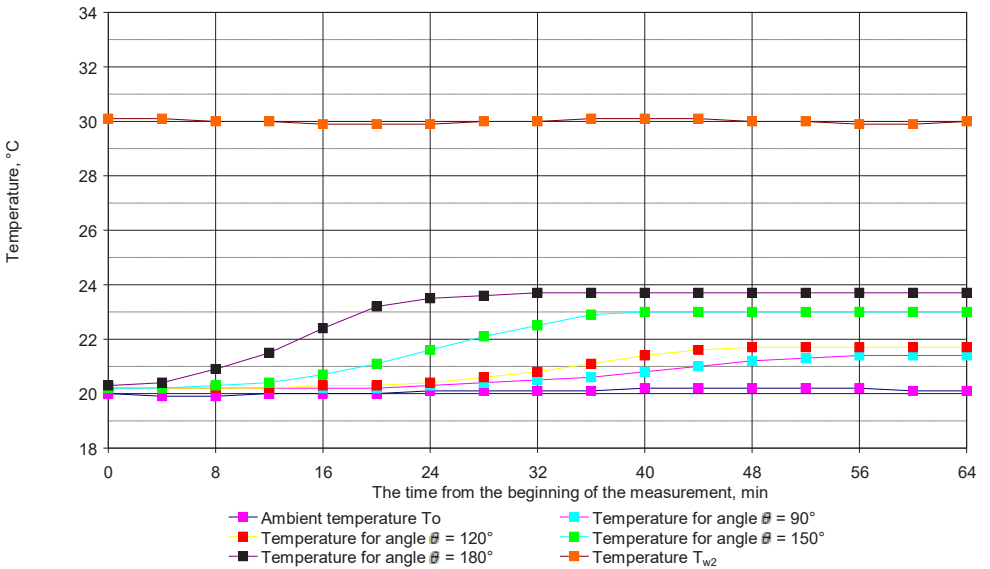
Fig. 6. The temperature values of thte BHE side surface model as a function of time for an angle theta from 90° to 180°

4. ANALYSIS AND INTERPRETATION OF THE RESULTS OF MEASUREMENTS

The surface temperature side during the operation of the BHE tends to ensure a semi-steady state, when the temperature of the side surface BHE is stabilized at a constant source temperature (T_{w1} and T_{w2}). The value of these temperatures in a semi-steady state can be represented as a function of the radius function of angle θ. The temperature of the side surface changes from the highest obtained for the angles θ 0° and 180° to the loweest value for θ = 90°. The temperature at angles θ = 0° and 180° reaches values T_{max1} and T_{max2}. These values vary due to different temperatures in the two borehole pipes of the BHE model (T_{w1} and T_{w2}).

When interpreting the results of measurements, a mathematical formula can be proposed where the side surface temperature of BHE can be described by a function of the radius function of angle θ. This function ranging from 0° to 360° has 2 minima of the same value and 2 maxima of different value. Based on the results of the measurement of surface temperature with a thermal imaging camera, the mathematical function can be derived and its correctness verified. The temperature of the lateral surface can be described by a function (5):

$$T_b = T_{1\max} - \left(\frac{T_{1\max} + T_{2\max} - 2 \cdot T_{\min}}{4} \right) \cdot (1 - \cos 2\theta) - \left(\frac{T_{1\max} - T_{2\max}}{2} \right) \cdot (1 - \cos \theta) \qquad (5)$$

Substituting equation (5) the values obtained for the points of maximum and the minimum temperature in the semi-steady state for a function of the progress shown in Figure 4 is obtained. The measurement points are also marked in the plot.
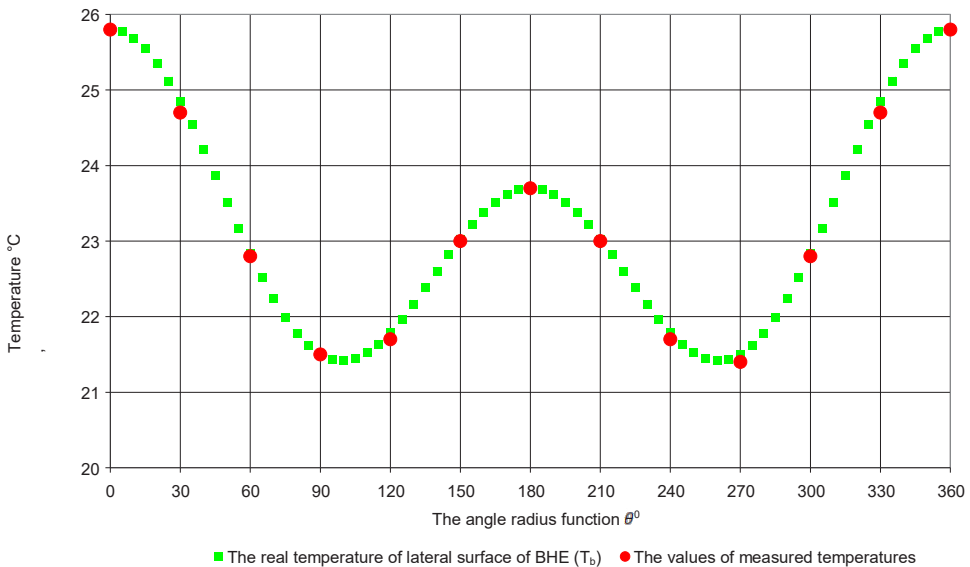
Fig. 7. The values of the lateral surface temperatures of BHE model as a function of the radius function angle θ along with marked measuring points

Bearing in mind the research and assuming BHE as a linear heat source, one can draw the conclusion that the value for the calculation of the heat transfer coefficient (fixed during the TRT) should differ from the one represented in formula (4). This value can be taken based on the temperature of the side surface of the BHE. The TRT test requires input values that depend on the temperature rise time. If the temperature of the liquid flowing in borehole pipes is introduced into the equation, the obtained value of the thermal conductivity coefficient will refer to the borehole heat exchanger – the rock mass system. Mathematically, however, exponential functions used for describing heat transfer do not allow for inferring on the heat transfer at the BHE in a radial-axial-integration due to limitations in the applicability. Replacement of input data with temperature at the interface of hardened cement slurry and rock mass will better define the conductivity coefficient of rocks surrounding the BHE.

5. APPLICATIONS

- The use of a thermal imaging camera to conduct a heat transfer test of the BHE model allows for a measurement of temperature distribution with high precision, without the need to install temperature sensors.
- The measurements showed the change of temperature of the side surface of the BHE model in the time and in function of the radius function angle θ.
- The resulting heat transfer of the BHE model with a single U-tube is symmetrical, and the temperatures of the side surface for angles $\theta = 0–180°$ and $180°–360°$ are identical.
- The lateral surface temperatures of the BHE model can be described using the proposed function, which was confirmed by covering up the value of the measurement points obtained during the measurement.
- The fitted function has two maxima of different values due to the temperature difference in the borehole pipes of the exchanger.
- The matched function has two minima distributed symmetrically and of equal value.
- The application of the formula for the heat transfer coefficient TRT, the temperatures of the BHE side surface, allow one to determine the heat transfer coefficient of rocks surrounding the BHE.
- The geometry and arrangement of borehole pipes inside the BHE, the wall thickness of the HDPE, coefficient of cement slurry and the nature of the fluid flow inside the borehole pipes of the exchanger, all influence the temperature of the side surface.

6. THE FOLLOWING NOTATIONS

P_{TRT} – power supplied to the BHE during the test TRT [W]
H_{wo} – BHE lenght [m]
λ – heat transfer coefficient [W/(m·K)]
t_1 – time of beginning of measurement period during TRT [K]
t_2 – working time of borehole heat exchanger (heat time during the TRT) [s]

r_{wo} – radius of BHE [m]

ρ_g – the average rock density [kg/m^3]

$T_{in}(t)$ – the temperature of the liquid entering the heat exchanger as a function of time TRT [K]

$T_{out}(t)$ – the temperature of the fluid flowing out of the heat exchanger as a function of time TRT [K]

$T_{BHE}(t)$ – BHE temperature versus time TRT [K]

T_{BHE1} – BHE temperature at the beginning of measurement period during TRT [K]

T_{BHE2} – BHE maximum temperature during the TRT [K]

T_{og} – the average temperature rock mass before heat transfer [K]

T_{o} – the ambient temperature of the BHE model during the measurement [K]

T_{b} – the temperature of the lateral surface of the BHE model [K]

T_{max1} – the maximum temperature of the lateral surface of the BHE model for $\theta = 0°$ [K]

T_{max2} – the maximum temperature of the lateral surface of the BHE model for $\theta = 180°$ [K]

T_{min} – the minimum temperature of the lateral surface of the BHE model for $\theta = 90°$ and $270°$ [K]

T_{w1} – the temperature inside the borehole pipe of BHE model for $\theta = 0°$ [K]

T_{w2} – the temperature inside the borehole pipe of BHE model for $\theta = 180°$ [K]

R_b – thermal resistance of the BHE [(m·K)/W]

R – the radius function of the BHE model [m]

Cp_g – the average specific heat of rocks [J/(kg^3·K)]

η_{HP} – thermodynamic cycle efficiency of the heat pump ($0.4 < \eta_{PC} < 0.7$),

T_{z1} – the temperature of the upper heat source [K]

T_{z2} – the temperature of the lower heat source [K]

φ – coefficient of heating performance (COP)

θ – angle radius function [°].

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