Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Analysis of Borehole Heat Exchangers Design in View of Stream of Heat Exchanged Maximization with the Rock Mass

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Keywords: borehole heat exchanger designs, heat transfer factor, BHE heat resistance, heat pump, low temperature geothermal energy

ABSTRACT

Five borehole heat exchangers of different design were made at the Faculty of Drilling, Oil and Gas AGH University of Science and Technology in Cracow (Poland). These are a coaxial system, a single and double U-pipes. Different grouts of various heat conductivity were used for sealing. The effective heat transfer value (λ_{eff}) of the drilled profile and the heat resistance (R_b) of the heat exchanger were compared on the basis of thermal response tests (TRT) performed at various heat carrier streams. As a result various efficiency values were obtained for different technological solutions of borehole heat exchangers.

1. INTRODUCTION

Borehole heat exchangers (BHE) are more and more frequently applied for heating, cooling and heating-and-cooling systems with heat pumps. Five such heat exchangers were worked out at AGH University of Science and Technology. Each of them was 78 m deep. They are used for experimental purposes and also for heating and air-conditioning an auditory hall for 140 persons.

The experimental aspect concentrates on determining energy and economic efficiency of borehole heat exchangers of various designs. BHE could be directly compared at AGH UST owing to the fact that the same lithological profile was present in all analyzed boreholes (Table 1). Table 2 lists the most important factors affecting the economic and energy profitability of BHEs.

Table 1: The most important thermal parameters of rocks in a lithological profile of borehole heat exchangers at AGH UST.

Lithology	Top, m	Bottom, m	Thickness of layer, m	Heat transfer coef. ($W\cdot m^{-1}\cdot K^{-1}$)	Specific heat, ($MJ\cdot m^{-3}\cdot K^{-1}$)
Clays	1.8	2.2	0.4	1.5	2
Aggradate mud	2.2	2.6	0.4	1.5	2.2
Fine and dusty sand	2.6	4.0	1.4	2	2
Fine sand	4.0	6.0	2	2.2	2.5
All-in aggregate and gravel	6.0	15.0	9	1.8	2.4
Grey silt	15.0	30.0	15	2	2.3
Grey shale clay	30.0	78.0	48	2.1	2.3
Weighted average				**2.039**	**2.309**

Table: 2: Factors influencing energy and economic efficiency of BHE, being part of heating, cooling and heating-and-cooling systems

Geological factors (natural)	Design parameters	Exploitation parameters
- geothermal gradient, - natural stream of Earth's heat, - heat transfer of drilled rocks, - anisotropy of heat transfer of rocks, - density of rocks, - specific heat of rocks, - porosity and saturation of rocks, - type of medium filling the porous space, - hydrogeodynamic conditions, - depth of periodic penetration of heat and temperature of neutral surface, - local climatic conditions.	- depth of installation, - borehole diameter, - diameter of pipes making up BHE, - thickness of BHE wall, - distance between BHE pipes, - heat resistance of pipes and filling material, - trajectory of borehole axis, - distance between BHEs, - type of design, - coaxiality of pipes in the borehole, - kind of heat carrier, - distance from the heat consumer.	- yearly heat production, - peak demand, - duration of peak demand, - bulk stream of heat carrier, - duration of heat resources regeneration in the rock mass, - ways of regeneration of heat resources in the rock mass, - temperature of heat carrier, - kind of heat/cold receiver (required temperature of heat carrier).

Table 2 reveals that one of the factors shaping the energy parameters of heat sources is the BHE design. Rock mass with borehole heat exchangers, as low-temperature energy sources, can be characterized be the quantity of exploitable energy and its stream defined as momentous heating power. The energy quantity is determined by thermal parameters of rocks (specific heat), geothermal and hydrogeological conditions of the profile, and also temperature of rock mass cooling/heating. These parameters do not depend on the borehole design.

Another BHE parameter is available heating power. This parameter greatly influences the depth, number and distribution of borehole heat exchangers. More about BHE was written by: Kohl et al. 2000, Kohl et al. 2002, Kujawa and Szaflik 2000, Kujawa and Nowak 2000a, Kujawa and Nowak 2000b, Nowak 2004, Czekalski 2004, Lee and Lam 2008, Śliwa and Gonet 2005, Spitler et al. 2000 and others.

2. BHE DESIGNS

The BHE design influences the size of the system in the aspect of peak loads. The most frequently applied are designs presented in Fig. 1.

In the case presented in Fig. 1a a single artificial (mostly polyethylene) U-pipe is introduced to the borehole. A similar system is presented in Fig. 1b and 1c, where two and three U-pipes are tripped to the boreholes. A coaxial BHE system is depicted in Fig. 1d. The qualitative listing of parameters characteristic of the described designs are given in Table 3 (Gonet and Śliwa, 2008). The cost of enhanced circulation of heat carrier should be treated as exploitation cost. The energy demand was described in the literature, e.g. (Gonet et al. 2005).

3. THERMAL PARAMETERS OF BHE

Ground thermal conductivity and borehole thermal resistance cannot be measured directly. Heat flow in the rock mass can be described by the following equation (Śliwa and Gonet 2004):

$$\overline{\rho_u c_u}\frac{\partial T_u}{\partial t} + \Phi \rho_{fu} c_{fu} v_{fux}(z)\frac{\partial T_u}{\partial x} = \overline{\lambda_{ux}(z)}\frac{\partial^2 T_u}{\partial x^2} + \overline{\lambda_{uy}(z)}\frac{\partial^2 T_u}{\partial y^2} + \frac{\partial}{\partial z}\left(\overline{\lambda_{uz}(z)}\frac{\partial T_u}{\partial z}\right) \quad (1)$$

In a coaxial BHE (Figs. 1d and 2), which may bed used for deep boreholes, the heat flow inside the inner pipe is described by the formula:

$$\rho_f c_f \cdot A_w\left(\frac{\partial T_{fw}}{\partial t} - v_{fw}\frac{\partial T_{fw}}{\partial z}\right) = A_w \lambda_f \frac{\partial^2 T_{fw}}{\partial z^2} - \pi d_w K_r \left(T_w - T_v\right) \quad (2)$$

In the annular space between the well casing and insulating string, the following equation holds:

$$\rho_f c_f \cdot A_v\left(\frac{\partial T_{fv}}{\partial t} - v_{fv}\frac{\partial T_{fv}}{\partial z}\right) = A_v \lambda_f \frac{\partial^2 T_{fv}}{\partial z^2} + \pi d_w K_r \left(T_w - T_v\right) + \pi D_o K_{so}\left(T_{uk} - T_v\right) \quad (3)$$

Table 3: Qualitative characteristic of BHE according to designs presented in Fig. 2, 1 – 4 denote "from the least to the highest" (after Gonet and Śliwa, 2008).

Type of BHE design	**a**	**b**	**c**	**d**
Capital costs	1	2	3	4
Exploitation costs	4	3	2	1
Heating power	1	2	3	4

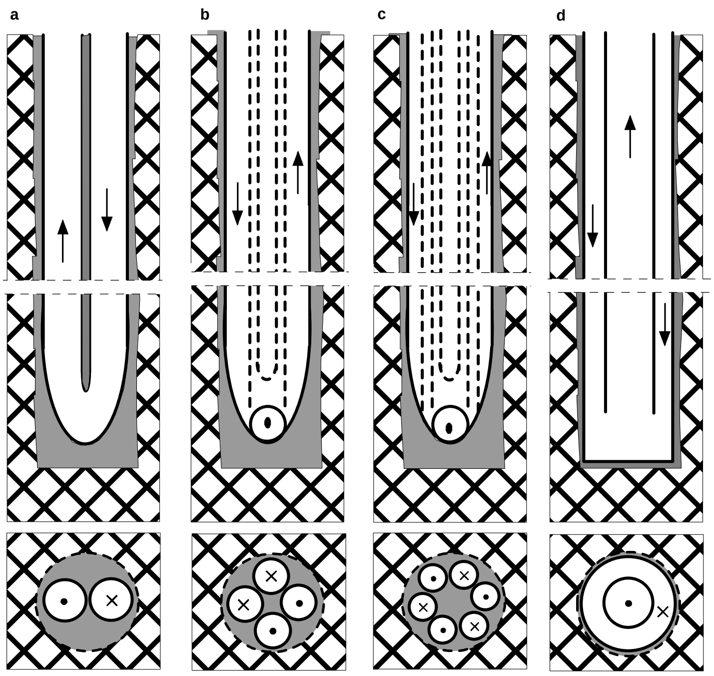

Figure 1: BHE designs, a – with a single U-pipe, b – with a double u-pipe, c – with a tipple U-pipe, d –coaxial system (after Gonet and Śliwa, 2008).

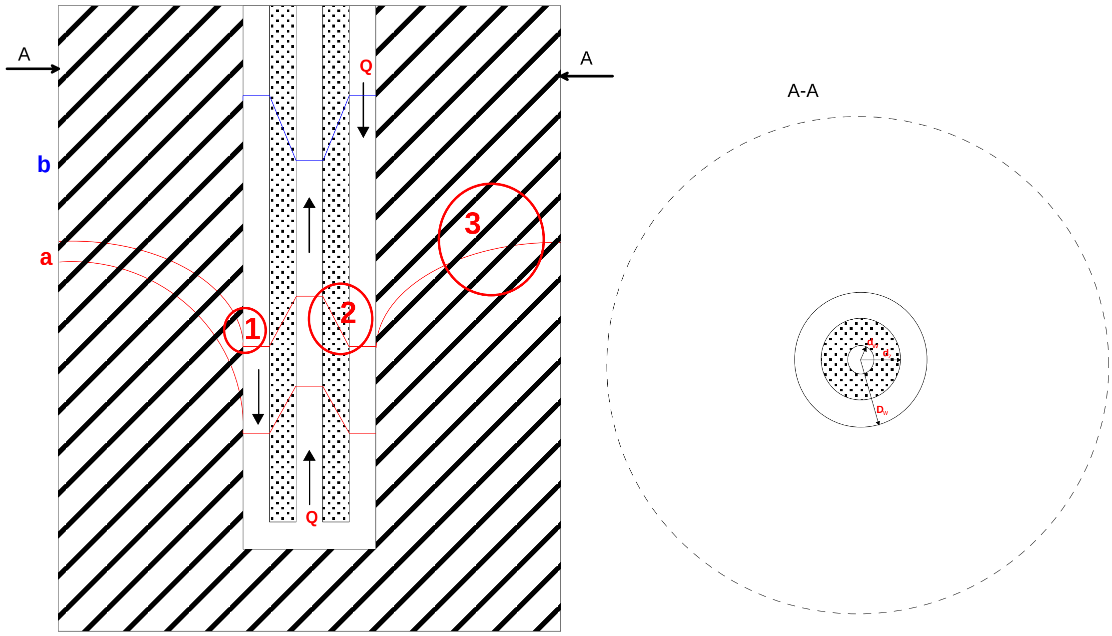

Figure 2: Section through a coaxial BHE with a distribution of isotherms during exploitation with reverse circulation of heat carrier and during heat storing.

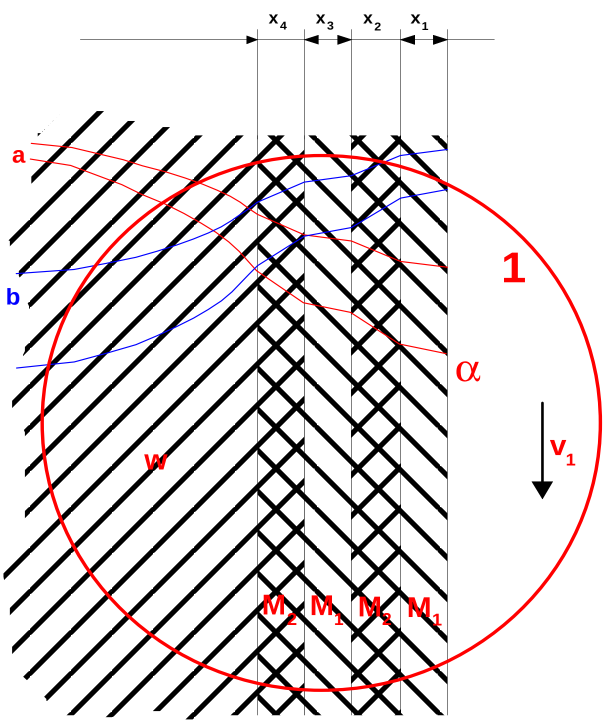

Figure 3: Heat penetration and conductivity through the wall of a borehole with two casing strings.

The distribution of temperatures during heat production (a) and heat storing (b) with the reverse circulation of heat carrier is presented in Fig. 3 (item 1 from Fig. 2). The casing and its influence on heat propagation is accounted for. Owing to good heat transfer values, steel casing causes a reduction of radial temperature gradient (x_1 and x_3).

The isotherms in the inner casing string during heat exploitation (a) and heat storing (b) with the reverse circulation of heat carrier are presented in Fig. 4 (item 2 from Fig. 2). A case of a three-layer inner column was analyzed. For insulation layer m_2 a higher temperature gradient was observed.

Rock mass isotherms are presented in Fig. 5.No heat convection resulting from the mass movement the aquifer was assumed. This corresponds to the assumption that the second component at the left side of equation (1) equals to zero. Heat flows towards the BHE (isotherm a) during heat exploitation, and off the borehole (isotherm b) during heat injection.

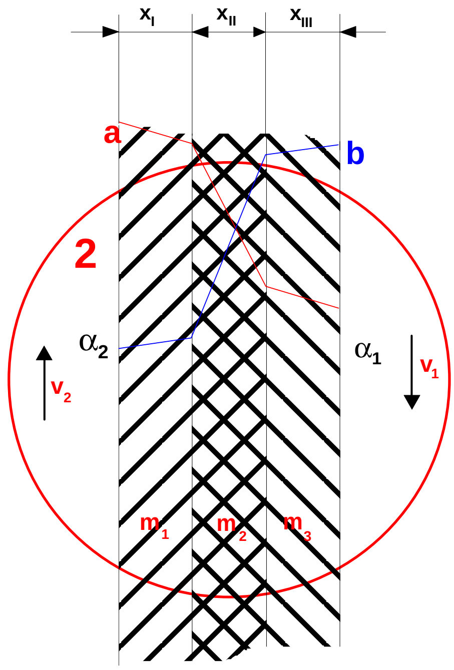

Figure 4: Scheme of heat penetration between cold heat carrier in annular space (penetration α_1) and heated carrier (a) inside the inner string (penetration α_2) made of two steel or plastic strings (x_I and x_{III}) and an insulating layer (x_{II} – air or nitrogen); b – isotherms for reverse direction of heat flow (during heat storing).

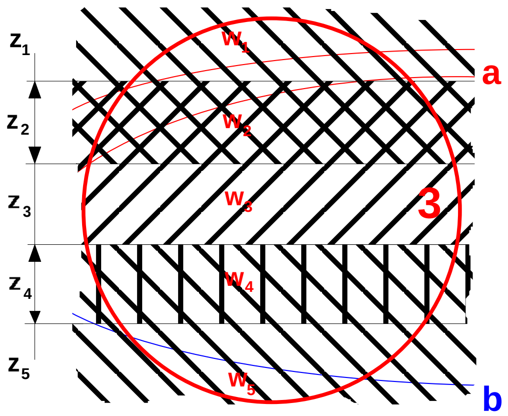

Figure 5: Distribution of isotherms in the rock mass without mass flow, a – during heat exploitation, b – during heat injection.

Thermal parameters of a BHE are determined from the analysis of thermal response test data. This lies in heating up or cooling off the BHE at a stable heating (cooling) power and measuring the temperature of the heat carrier. The inclination of the straight line in a coordinates system is determined, and the temperature variability is presented as a logarithm of time of test performance *T=f(ln t)*.

The temperature of the rock mass (T_u), as a function of time (t) and radius (r) with constant heating power (q), was described in the literature. For instance, Eklöf & Gehlin (1996) and Austin (1998) give a formula for a *line source model* in the form:

$$T(r,t) = T_{kb} + \frac{q}{4\cdot\pi\cdot\lambda_u}\int_{\frac{r^2}{4\alpha_u t}}^{\infty}\frac{e^{-u}}{u}du \cong T_{kb} + \frac{q}{4\cdot\pi\cdot\lambda_u}\left[\ln\left(\frac{4\alpha_u\cdot t}{r_b^2}\right)-\gamma\right] \quad (4)$$

where:

$$q = \frac{\dot{Q}}{H} \quad (5)$$

$$\alpha_u = \frac{\lambda_u}{\rho_u\cdot c_u} \quad (6)$$

and

$$u = \frac{r_b^2}{4\alpha_u\cdot t} \quad (7)$$

The maximum error of solution of eq. (4) is 2.5% for $t \geq \frac{20\cdot r_b^2}{\alpha_u}$ and 10% for $t \geq \frac{5\cdot r_b^2}{\alpha_u}$.

The results of temperature measurements during the thermal response test are influenced by a number of parameters, e.g. air temperature, natural and/or enhanced water flow in water-bearing horizons.

According to Table 2, gravel and all-in aggregate mix constitutes a potential water-bearing bed in the AGH UST borehole. The BHE parameters may be also influenced by the neighboring well. In the thermal response tests the existence of a water-bearing bed was neglected as its thickness was only 11.5% total depth of BHE. Besides, the existing well was not used during the tests.

Thermal resistances R_b of the borehole could be calculated on the basis of known depth H_b and borehole diameter d_b, thermal characteristic pf the rocks (heat transfer coefficient λ, specific heat c and mass density of rocks ρ). The temperature measurements give the average value of undisturbed temperature T_{kb} in BHE (it may be also determined during the thermal response test), and then the temperature of inlet T_α and outlet T_ω as well as time of the test t are obtained from the thermal response test at a constant assumed power $\dot{Q}$. For such conditions the thermal resistance can be calculated from the following formula:

$$R_b = \frac{1}{q}(T_{km} - T_{kb}) - \frac{1}{4 \cdot \pi \cdot \lambda_u}\left[\ln(t) + \ln\left(\frac{4\alpha_u}{r_b^{\ 2}}\right) - \gamma\right] \tag{8}$$

where:

$$T_{km} = \frac{T_{\alpha f} + T_{\omega f}}{2} \tag{9}$$

In a semi logarithmic system, the variability of fluid temperature becomes linear as compared to ln(t), and the inclination of curve k may be used for assessing the effective thermal conductivity:

$$\lambda_e = \frac{q}{4 \cdot \pi \cdot k} \tag{10}$$

The coefficient of inclination k can be calculated from mean inlet and outlet temperature T_f for the time interval from:

$$t_m = \frac{5 \cdot r_b^2}{\alpha_u} \tag{11}$$

to the end of heating phase of the test.

The description of BHE designs, for which thermal response tests were made, is listed in Table 4. There was made a cost analysis of rotary drilling of BHEs 143 mm of drilling diameter, having a collector filled with 30% propylene glycol solution. For a BHE in the form of a polyethylene U-pipe DN 40 2.4 mm wall filled with gravel the 100% cost was assumed (cost of drilling the borehole, materials, assembly operations).

The results of calculation of effective heat transfer (λ_e) and borehole heat resistance (R_b) are listed in Table 5. The BHE parameters used for each of the tests were: heating power P=4 kW, bulk stream of heat carrier 20 dm^3/min.

Identical thermal response tests performed for various BHE designs but in the same geologic conditions reveal that highest values of effective heat transfer were observed for BHE with coaxial pipes array. These values do not depend on the direction of heat carrier circulation during the test. Highest values of heat resistance (R_b) were observed in the borehole.

Table 4: BHE designs and cost of their performing.

BHE type	BHE design	Filling	Cost of BHE vs. cheapest solution, % (US $ per m)[1]
A	single U-pipe PE 100, DN 40 mm, wall 2.4 mm	gravel, 8–16 mm grain size	100.0 (40.5)
B	double U-pipe PE 100 DN 32 mm, wall 2.4 mm	gravel, 8–16 mm grain size	116.7 (46.5)
C	pipe PE DN 90 mm with coaxial pipe DN 40 mm, wall 2.4 mm	gravel, 8–16 mm grain size	150.0 (60)
D	single U-pipe PE 100, DN 40 mm, wall 2.4 mm	cement grout	116.7 (46.5)
E	single U-pipe PE 100, DN 40 mm, wall 2.4 mm	material of increased thermal conductivity	133.3 (54)

1 Assumed 1 $ = 3.0 PLN and without constant costs (like transportation of rig, etc).

Table 5: Effective heat transfer (λ_e) and borehole heat resistance (R_b).

No. of BHE	1[1]	1[2]	2	3	4	5
Effective heat transfer coef., λ_e	2.3849	2.2301	1.9576	2.0552	2.0268	2.1524
Borehole heat resistance, R_b	0.1287	0.1270	0.1142	0.0893	0.0953	0.0774

1 left (reverse) circulation heat carrier (like fig. 1d)
2 right (normal) circulation of heat carrier

4. CONCLUSIONS

1) A number of BHE designs exist for revovering/discharging heat to the rock mass in heating/cooling systems cooperating with heat pumps.

2) The BHE design significantly influences the attainable momentous heat energy stream (heating power) exchanged with the rock mass.

3) At the AGH University of Science and Technology five BHEs of different design were made. This enabled authors to investigate the influence of BHE design on the process of heat exchange with the rock mass.

4) The thermal response test indicated that the BHE with a coaxial pipe system has the highest effective heat transfer and hear resistance values.

Nomenclature

A – area, m^2

D – diameter, m

H – depth, m

K – heat-transfer coefficient, $W \cdot m^{-1} \cdot K^{-1}$

R – thermal resistance, $m \cdot K \cdot W^{-1}$

$\dot{Q}$ *– heat flow, heating power, W*

T – temperature, K

c – specific heat, $J \cdot kg^{-1} \cdot K^{-1}$

d – diameter of inner string, m

k – coefficient, -

q – unit heat flow, $W \cdot m^{-2}$

r – radius, m

t – time, s

v – rate, $m \cdot s^{-1}$

x, y, z – geometrical co-ordinates, m

Φ *– effective porosity, -*

α *– thermal diffusivity coefficient,* $m^2 \cdot s^{-1}$

β *– function*

γ *– Euler constant*

λ *– heat conductivity coefficient,* $W \cdot m^{-1} \cdot K^{-1}$

ρ *– density,* $kg \cdot m^{-3}$

Subscripts

b – borehole

e – effective

f – fluid, heat carrier

k – mean

m – minimum

r – pipe

s – wall

u – rock mass

v – annular space

w – inner

x, y, z – in the direction of x, y, z

z – outer

α *– inlet*

ω *– outlet*

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Realized from the funds of Polish Ministry of Science and Higher Education (grant AGH UST no. 17.17.190.385)