Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Deep Borehole Heat Exchangers – A Conceptual Review

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Keywords: Borehole heat exchanger, geoenergetics, geothermal heat, abandoned wells, exploited wells

ABSTRACT

Borehole heat exchangers are used for transforming a rock mass into an underground heat storage. Usually, their depth does not exceed 200 m, but some extend to a depth of almost 3000 m. Underground heat storages can operate as part of heating and cooling systems, often economically. In winter they extract heat from the rock mass for space heating, while in summer the cooled rock mass is used for air conditioning. The heat extracted from buildings via air conditioning is transferred into the rock mass, thereby regenerating its condition for winter time. Deep borehole exchangers also may operate only in the heating mode. Then, the rock resource conditions are regenerated via heat transfer through neighboring rocks. If a groundwater flow is present, the heat can also be removed and the source conditions regenerated through convection.

Here, an overview is provided of the use and operation of deep borehole heat exchangers around the world. Special emphasis is placed on the Carpathians, where numerous analyses of geothermal heat use have been performed since 1999. Examples of calculations for old oil and gas wells as well as negative exploration boreholes are given. Such analyses have been performed for boreholes in Poland and the Ukraine. However little research has been published on this subject to date, for reasons described herein.

1. INTRODUCTION

Increasing energy prices often foster development of alternative energy sources. Important sources of energy are waste energy streams. Some installations can also become alternative energy sources, especially when their infrastructure is decommissioned. This idea relates particularly to mining excavations, existing or intended for closure, e.g., underground minings, pencast minings and boreholes.

During mining activity, additional or incidental activities are possible. Also, during the elimination of excavations, it is possible to introduce alternative activities in some instances (Ostaficzuk, 2000). One such activity is the acquisition and utilization of the Earth's heat. Heat can be acquired from existing, decommissioned or partially decommissioned mine workings (mines and wells) in several ways. One category of methods involves open systems, such as the following:

- For operating underground mines, heat can be extracted from ventilation air.
- For operating underground or open pit mines, heat can be extracted from water during mine dewatering (Solik-Heliasz, 2002). For example, a total of about 416 m^3/min of water is used for dewatering in hard coal mines in the Upper Silesian Basin, and the total heat rate potentially available is estimated at more than 220 MW (Solik-Heliasz, 2007, 2009).
- For closed coal mines, the underground water pumped out to protect neighboring mines can be used as a thermal energy source for heating purposes (Mutke, 2008).
- For closed underground mines, water from one shaft can be extracted and returned to another shaft. This water serves as a heat carrier, which can be used for heating. Underground flooded mines and pits/ excavations contain a reservoir of water that is heated from the surrounding rocks and also is usable for heating. Example installations exist in Heerlen (The Netherlands), Edinburgh (Scotland) and Springhill (Nova Scotia, Canada), and are described elsewhere (Verhoeven et al., 2014; Burke, 2002; Jessop, 1995).

The second category of methods for extracting and exploiting the heat from underground mines involves the use closed systems. Such systems utilize heat exchangers (Hopkirk and Rybach, 1994), often in the form of closed helical pipes filled with a working fluid. Such systems can be installed in excavations before completing the backfill (before closing), and in excavations connected by vertical insulated pipes to heat consumers on the surface (Borkiewicz, 2002). Some other examples follow:

- For partially closed underground mines, heat carrier pipes can be installed in closed excavations before filling flooring material. This heat can be used in other working parts of the mine (Gonet et al., 2015).
- For boreholes made for exploration for oil and gas and evaluation, geothermal water can be extracted for heating (Barbacki et al., 2000). The boreholes can be also used as injection wells, to disposal of spent geothermal waters.
- Boreholes that are scheduled for closing can be adapted to be borehole heat exchangers after partial closure. This can be accomplished by either sealing exhausted intervals using cement plugs, as described by Sliwa (2002), and Pająk and Bujakowski (2000), or restoring holes previously closed, as described by Sliwa and Gonet (2006).

In this paper, an overview is provided of deep borehole heat exchangers around the world, with emphasis on the Carpathian region for which numerous analyses of geothermal energy systems have been reported over the last 15 years. Evaluation methods are provided for old oil and gas wells and exploration boreholes. Little research has been reported on these subjects, so the objective of this paper is to improve understanding of deep borehole heat exchangers and their potential applications.

The authors feel that the ideas discussed in this article provide an interesting and potentially beneficial use for oil and gas wells that are old, abandoned or being prepared for closure. In some cases, that total costs of adapting worn out oil wells, with surface connections and heat pump installation, can be lower than the costs of full decommissioning of the well (Sliwa, 2002). Some modeling has been undertaken for wells in one of the oldest oil region in the world, the Carpathians, for which wells often are located within urban areas. A particular aim of this paper is to show examples of the adaptability of the old holes. One basic problem when using old wells in this manner is reducing complications, which can be technical, economic, environmental or regulatory/legal. Sometimes such complications lead to cancellations of plans for such BHE systems using of the old holes.

2. BOREHOLE HEAT EXCHANGERS

An increasingly popular technology for maintaining thermal comfort in residential and commercial buildings is underground thermal energy storage (UTES). Most UTES are based on borehole heat exchangers (BHEs), which can be used for heating and air-conditioning building interiors. The largest existing installations have over 1000 BHEs. One such example is the system at Ball State University, Indiana, U.S. (Lund et al., 2010), for which the arrangement of the BHE field is shown in fig. 1. That installation has BHE depths ranging from 122 to 152 m.

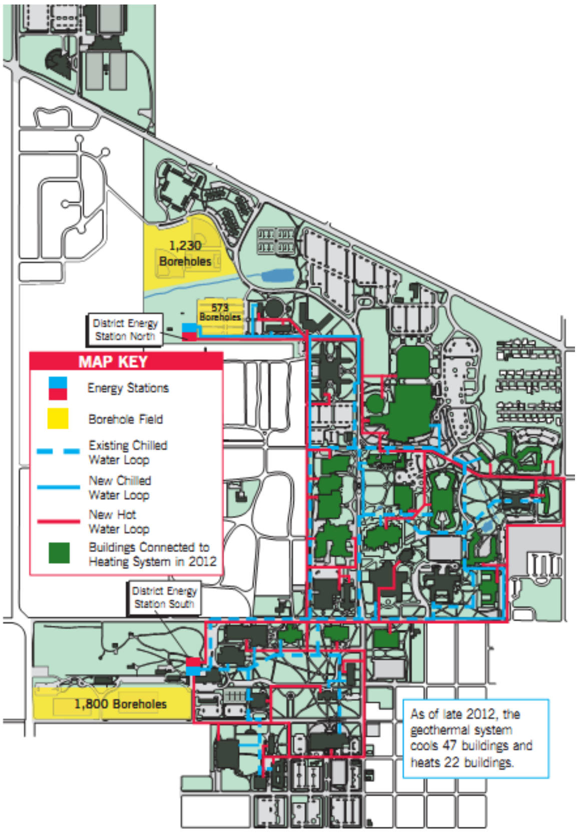

Figure 1: Illustration of UTES at Ball State University, Indiana, U.S., showing BHE field and piping map (cms.bsu.edu).

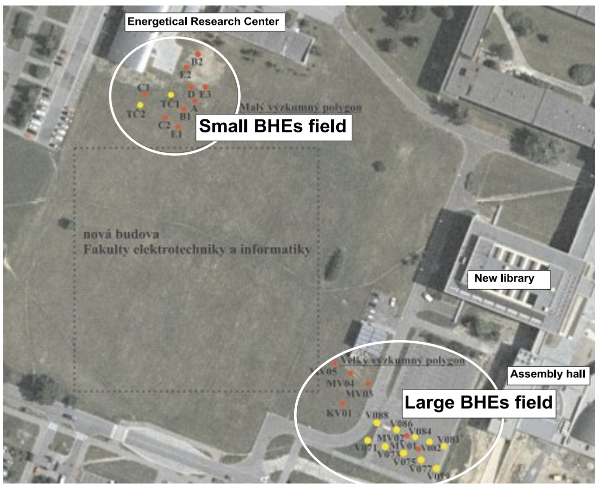

Figure 2: Borehole heat exchangers and test holes at Technical University of Ostrava (VSB) (Bujok et al., 2012). Yellow dots denote BHEs collectors and red dots test holes.

The increasing interest in BHEs has fostered increased research in the area and to the development of advanced systems. Some BHE systems for heating or heating and cooling are being installed at universities and government facilities, for operation, demonstration and research purposes. These include the Ball State University system as well as the following:

- Luleå University of Technology, Luleå (Sweden). Has the first large-scale borehole heat store, constructed in 1982-83 (Nordell, 1994).
- Technical University of Ostrava (VSB) (Czech Republic). The BHEs arrangement on this university campus are shown in fig. 2 and described by Bujok et al. (2012).
- University of Ontario Institute of Technology, Oshawa (Canada). This system is shown in fig. 3 and described by Koohi-Fayegh and Rosen (2012).
- AGH University of Science and Technology, Drilling, Oil and Gas Faculty, Drilling and Geoengineering Dept., Cracow (Poland). The BHE arrangement for this system is shown in fig. 4 and described by Sliwa and Gonet (2011).

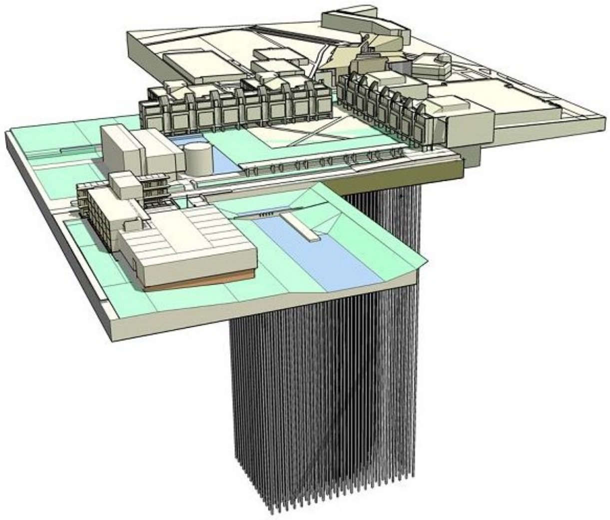

Figure 3: Borehole thermal energy storage system below university buildings of University of Ontario Institute of Technology (engineering.uoit.ca).

Whereas single or multiple shallow BHEs (<200 m depth) are often used for heating (and/or cooling) in conjunction with a heat pump, deep BHEs (up to several kilometers deep) produce temperatures high enough for direct use, heating several buildings and sometimes districts, depending on the depth, diameter and flow rate (Mottaghy and Dijkshoorn, 2012).

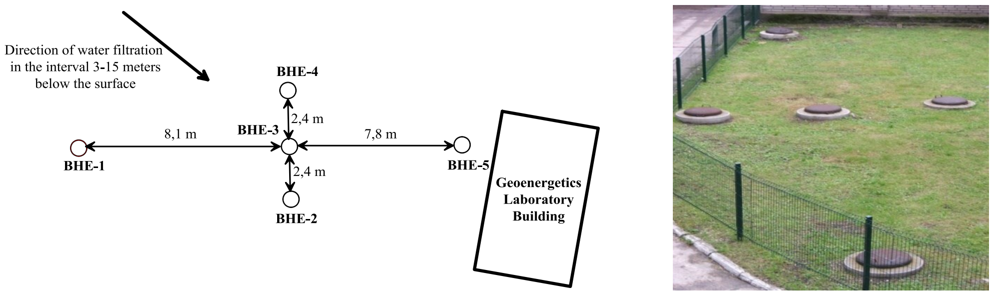

Figure 4: Borehole heat exchanger field arrangement at the geothermal laboratory of the Drilling, Oil and Gas Faculty, AGH University of Science and Technology in Cracow. BHE-1 is a coaxial system, BHE-2, BHE-3 and BHE-4 are holes with single U-tube construction and different grouts, and BHE-5 has a double U-tube construction (Sliwa and Gonet, 2011).

3. PAST AND PRESENT DEEP BOREHOLE HEAT EXCHANGERS

Based on reports in the literature, deep borehole heat exchangers can be divided as follows:

- deep borehole heat exchangers drilled specifically for this purpose,
- deep borehole heat exchangers created in exploration holes, and
- deep borehole heat exchangers created in negative geothermal holes.

Descriptions of the deep BHEs are provided, as well as their operation in heating systems, including some that only operated for short periods or only for experiments.

3.1. Prenzlau (Germany)

The town of Penzlau is situated in an area with a positive geothermal anomaly, and the borehole heat exchanger in Penzlau is described by Schneider et al. (1996). In the heating installation, the existing geothermal borehole was used. It did not achieve the expected flows of geothermal water so, to convert it into a borehole heat exchanger, the hole was deepened to 2786 m. At the bottom the rock temperature is 108°C. The internal diameter of the column for the heat exchangers pipes is 9 $^{6}/_{8}$" to a depth of 950 m, and then 6 $^{5}/_{8}$" to the bottom.

The vertical underground heat exchanger is in the form of concentric pipes. The active heat exchange surface in contact with the rock mass is 1463 m^2. An internal column for heat carrier transport to the top used insulated pipes (double steel pipes). The flow rate of the carrier could vary from 5 to 65 $m \cdot min^{-1}$. A single complete circulation of the heat carrier in the borehole took from 4 to 10 hours depending on flow rate.

The heating plant linked to the deep BHE had a heating capacity 9.6 MW. This power was made up of two parts:

- a geothermal part, with a capacity of 0.6 MW, and
- a peak part with gas and oil boilers, with a capacity of 9 MW.

The geothermal part had plate heat exchanger for direct heat exchange and also a heat pump (with a refrigerant/working medium of NH_3). The heat transfer rate during direct heat exchange was 150 kW and the heating rate of the heat pump was 350–500 kW. In the evaporator, the temperature of water from the borehole was cooled to 15°C. The receiving installation parameters (T_{in}/T_{out}) were 70/35°C. The heating plant could satisfy the needs for space heating and hot water, the latter requiring 6% of the total power.

For many years there was a lack of information on the BHE in Penzlau. Only in 2011–2012 was a connection made of the deep BHE to a retirement home, for the space heating and sanitary hot water (en.gtn-online.de). In this new retirement home in Prenzlau, space heating and sanitary hot water are supplied to the maximum 112 inhabitants via the already existing deep BHE, which is coaxial. A heat transfer station was constructed to transfer the thermal energy recovered from the subsoil to the heating and drinking water system of the retirement home.

Heating water is prepared in a heat exchanger having a transfer capacity of 120 kW. Sanitary hot water – SHW (65°C) is produced via a 26 kW high-temperature heat pump. Peak demands are covered by a buffer store with a holding capacity of 2 m^3. The cost of reconstruction of the installation was 200,000 Euro. The commissioning the installation included (en.gtn-online.de):

- numerical simulation of the BHE thermal operation and output,
- design, call for bids and construction supervision of the equipment of the heat transfer station and the buried pipelines, and
- development of a control concept for the automated operation of the system.

The temperature of the BHE feed flow is about 60°C at 6 $m^3 \cdot h^{-1}$. The temperature on the consumer side is 50-40°C for heating and 65°C for sanitary hot water. The thermal output rates on the BHE side is 120 kW for heating and 18.5 kW for SHW (en.gtn-online.de).

3.2. Aachen (Germany)

The borehole RWTH-1 is 2500 m deep and was drilled in spring 2004 in the urban center of Aachen, at a distance of about 500 m from the “Imperial Cathedral” (Dijkshoorn et al., 2013). The installation can be used for space heating and cooling the buildings of the RWTH-Aachen University. Direct heating of the building in winter requires temperatures of 40°C. In summer, cooling the university buildings uses a climatic control adsorption unit, which requires a minimum temperature of 55°C.

The drilled rocks of the 2500 m deep borehole have extremely low permeabilities, and porosities less than 1%. Their thermal conductivity varies between 2.2 and 8.9 $W \cdot m^{-1} \cdot K^{-1}$. These values are relatively high, and are due to the presence of quartzite sandstones. The maximum temperature in the borehole is 85°C, at a 2500 m depth, which corresponds to a mean specific heat flow of 85–90 $mW \cdot m^{-2}$.

During an initial period of operation, the borehole was shown to be able to deliver the required temperature. But after 20-years of operation, the temperatures became too low to drive the adsorption unit for cooling. In winter, however, the borehole heat exchanger can still supply the building with sufficient heat, with temperatures varying between 25 and 55°C and a maximum circulation flow rate of 10 $m^3 \cdot h^{-1}$ (Dijkshoorn et al., 2013).

To simulate the long-term performance of a deep borehole heat exchanger, the thermal conductivity of the rocks is important (Signorelli, 2004). Others important parameters include the rock’s specific heat capacity, porosity, permeability and density. The thermal conductivity of the cuttings was determined using a cuttings-water mixture, and found to vary from 2.2 to 8.9 $W \cdot m^{-1} \cdot K^{-1}$, with a mean of 3.8 $W \cdot m^{-1} \cdot K^{-1}$. These relatively high values can be explained by noting the high percentage of quartz present. Quartz cemented clean sandstones are frequently observed in the deeper part of the borehole below 1895 m (Dijkshoorn et al., 2013).

The thermal conductivities of the cores vary between 2.3 to 4.9 $W \cdot m^{-1} \cdot K^{-1}$, with minimum and maximum values of 2.0 $W \cdot m^{-1} \cdot K^{-1}$ and 5.9 $W \cdot m^{-1} \cdot K^{-1}$, respectively.

A finite difference numerical simulation tool SHEMAT (Simulator for HEat and MAss Transport) (Clauser, 2003) was used to examine the effects of various operating and design parameters on the outlet temperature and the thermal power of the borehole heat exchanger.

The borehole has four casings of different lengths. The inner pipe, dividing the cool water flowing down from the hot water flowing up, needs to be insulated and has a thermal conductivity of about 0.1 $W \cdot m^{-1} \cdot K^{-1}$. The steel outer pipe has a thermal conductivity of 50 $W \cdot m^{-1} \cdot K^{-1}$, while the values for the cement are 0.52 $W \cdot m^{-1} \cdot K^{-1}$ for the insulating cement, 2.02 $W \cdot m^{-1} \cdot K^{-1}$ for the heat conducting cement, and 1.21 $W \cdot m^{-1} \cdot K^{-1}$ for the normal one. Based on the logging data of the effectiveness of cementation, perfect backfilling can be assumed (Dijkshoorn et al., 2013).

The heat generation is smaller than 3 $\mu W \cdot m^{-3}$ and average only 0.5 $\mu W \cdot m^{-3}$ and is therefore neglected in the model.

The temperature of the injected water in the model was set to 40°C, according to the expected design parameters of the climate control system.

3.3. Sucha Beskidzka (Poland)

The well Jachówka 2K was drilled in 1996-1997 in Sucha Beskidzka (Carpathians, south Poland) for oil exploration, as a directional hole to a depth 4281 m, true vertical depth (TVD) 4098.5 m. To a depth of 2040 m, the hole is vertical, and below its deviation from the vertical is a maximum of 38° (Sliwa and Kotyza, 2000). Small tributaries of natural gas were discovered in the borehole, so geothermal research was started. The goal was to test the possibility of using the hole as a BHE and the possibility to obtain a flow of geothermal waters after perforation at appropriate intervals.

The depth of the inner pipe column reaches 2864.5 m. Due to the fact that steel pipes without insulation were used, the results were not satisfactory. Within the framework, self-circulation measurements were carried out. In 1 h it was possible to obtain a self-flow of 0.36 $m^3 \cdot h^{-1}$ related to the heat recovery on the surface and the difference of the heat carrier density.

The project was conducted to analyze the performance of internal heat concentric exchanger pipes. The analysis also included a column of double steel tubes with nitrogen between them. The thermal expansion of these two tubes was calculated for the medium selection.

The primary factor in the selection of the internal pipe diameters should be the sum of the hydraulic resistance that occurs during the circulation of the heat carrier. For a constant thickness of the column (insulating layer) there is an area (or diameter) at which the flow resistance in the circulation system is lowest. As the volumetric flow rate of the heat carrier increases, the area decreases to an optimum (minimum), and then increases. The influence of flow character on energy efficiency was investigated by Sliwa and Gałuszka (2013).

3.4. Weissbad (Switzerland)

Deep BHEs can be installed in abandoned boreholes, provided that consumers are nearby (Rybach et al., 2000). Some examples exist in Switzerland.

Kohl et al. (2000) investigated over two consecutive years (1996-1998) the operation of a 1.2 km deep BHE in Weissbad. A borehole of 1.6 km depth was deepened in 1993 with the aim of finding a porous/fractured aquifer at depth. A directly adjacent spa was envisaged as the heat consumer. The borehole encountered only tight formations and therefore it was decided to equip the well as a deep BHE. For this purpose the well was cemented down to 1213.3 m and a centralized steel pipe was inserted. A temperature log shows a temperature of 45°C at 1200 m depth. The completion of the 1213 m deep BHE in Weissbad was described by Kohl et al. (2000).

Pure water is circulated in the deep BHE as a heat carrier. The circulation flow rate is 10.5 $m^3 \cdot h^{-1}$ (3 $dm^3 \cdot s^{-1}$). The original design was expected to achieve a BHE delivery temperature of about 15°C in the long term. The extrapolated thermal power was 80 kW (Kohl and Rybach, 2003). The quantity of energy produced in 2006 was 0.33 GWh (Signorelli et al., 2007). The system operates at a seasonal performance factor of 3.42 and a coefficient of performance of 3.91 (Kohl et al., 2000).

It became evident from the measured data that the BHE output temperatures were significantly lower than expected, only 10.6°C on yearly average. The temperature varied between 14 and 9°C over the total period. The reason for this situation is likely the fact that, during installation of the casing, good contact to the surrounding medium was not achieved nor initially intended. Another reason is the existence of voids due to the drilling at greater depths. The increasing magnitudes of the stress field create borehole breakouts which remain present after the installation of the casing.

The total system performance could be improved using different types of central pipes. In this case, a steel casing was used, which potentially enables high heat transfer from the downgoing to the upcoming fluid. By isolating especially the upper parts of this installation, the energy output of the system can be improved (Kohl et al., 2000).

3.5. Weggis (Switzerland)

The 2.3 km deep BHE at Weggis has proven a success (Rybach and Eugster, 1998). In the center of Weggis, a private investor commissioned a 2.3 km deep geothermal borehole. Since the productivity of the envisaged formation was uncertain, the installation of a deep BHE was planned from the beginning. The water yield of the well was negligible. So it was completed with the following BHE construction: a 7" (0 to 1902 m deep) diameter casing, inside of which is a double, vacuum-isolated production tube (0 to 1780 m), followed by an uninsulated pipe (1780-2281 m) in a 5 ½" hanger-liner (1781-2295 m) with a prefabricated bottom seal. The corrected bottom hole temperature was 78°C (Rybach and Hopkirk, 1995).

For long-term system behaviour, the modelling assumes heat extraction over 30 years. Two load scenarios have been investigated: houses with a peak load of 100 or 250 kW. For each additional year, a corresponding load profile was inserted. Rybach and Hopkirk (1995) show the calculated injection and source temperatures, and the 31st year is shown in detail. A load of 250 kW yields input/output temperatures of 9/28°C. When the load is 100 kW, the corresponding temperatures are 32/40°C.

Kohl and Rybach (2003) determine the energy production of the Weggis BHE to be 0.37 GWh in 2000 and 0.42 GWh in 2001. In 2007 Signorelli et al. evaluated the indicative installed power to be 100 kW and the BHE's heat production to be 0.41 GWh. More extensive analysis of deep BHE in Weggis is presented by Kohl et al. (2002).

3.6. Hawaii (USA)

For February 22 to March 1, 1991, an experiment was conducted on the borehole HGP-A in Hawaii, in the Kapoho (Puna), in order to verify the concept of a coaxial borehole heat exchanger CBHE. The total depth of the bore was 1962 m, and the bottom of inner pipe CBHE was at a depth of 876.5 m. Over the entire length of the hole were basaltic formations. The undisturbed temperature at the bottom of the test section was 110°C. The heat exchanger was installed in casing pipes with a diameter of 7". The inner tube heat exchanger was made of 74 segments (double vacuum tubes) with a diameter of 3.5 in.

In the construction of the heat exchanger, an innovative approach was applied to the construction of the inner pipes. It was attempted to increase the possibility of isolation through the use of a dual vacuum tube. The space between the walls of the inner tube was filled with powder, which provided support for the thinner wall of the inner pipe transporting a heat fluid to the surface. Its presence was intended to enhance the stability of the vacuum by producing a low vacuum. As a result of these modifications, the equivalent thermal conductivity of the obtained tube was approximately 0.02 $W \cdot m^{-1} \cdot K^{-1}$ (Morita et al., 1985, 1992).

A water temperature of 30°C was injected into the borehole at a flow rate of 80 $dm^3 \cdot min^{-1}$. The highest temperature of heat carrier obtained during the experiment was 98°C, and there was a maximum heat power of about 370 kW. The experiment confirmed previously conducted numerical simulations for this area.

4. MATHEMATICAL MODELING OF BOREHOLE HEAT EXCHANGERS

Analyses of operating borehole heat exchangers are presented in this section. Possible methods for such mathematical modeling have been described by many authors, including models for BHEs. Many examples have been published (Eskilson, 1987; Kohl et al., 2002; Sliwa and Gonet, 2005; Al-Khoury et al., 2010; Al-Khoury, 2010). Much modeling has been described recently (Beier et al., 2014). Also use of simulators such as SHEMAT and ANSYS CFX have been described (Dijkshoorn et al., 2013; Sliwa et al., 2012).

Many modeling studies on the use of existing oil wells intended for closure have been carried out for boreholes in the Carpathian mountains in Poland. Exploited Carpathian oil fields are often considered to be the cradle of the oil industry. Thousands of excavations have been closed and many of them are now in urban areas, often near schools, offices, and residences (Sliwa and Kotyza, 2003).

The boreholes of Iwonicz Zdrój's deposit are located in a health resort. An analysis of the operation of two holes intended for closure were described in 2002 (Sliwa, 2002; Sliwa and Gonet, 2003). On the basis of the borehole Elin-3 it was possible to develop a BHE with a depth of 470 m and borehole Elin-10 BHE with a depth of 870 m. These holes were located in the vicinity of the sanatorium building. The potential heat rate from both exchangers based on the simulations of long–term operation amounts to 105 kW. However, due to low temperature of the obtained heat, it was necessary to use a heat pump. The boreholes, however, were mainly closed due to legal regulations. The current operator had to close them because their exploitation had ended, and at the same time he was not interested in adapting them into BHE and selling heat. The health resort and the municipality wanted to use the holes for heating purposes, but they were not interested in a total takeover, partly because owning boreholes necessitates their maintenance. This can be onerous, especially in situations where the heat loss is caused by the onset of leaks attributable to thermal tension. Legal regulations impose a requirement on the borehole's owner to liquidate them at the end of their use. Since the health resort and municipality did not take over the boreholes, they were liquidated by filling the holes with cement.

In Krosno there is old deposit named Turaszówka, where several closed boreholes are located next to municipal indoor swimming pool. There was outdated heating installation of low efficiency in the building. The idea of developing the closed boreholes was proposed, since restoration did not involve high costs (just enough to drill sealing plugs on the surface and replace the scrubber with a heat carrier). There was no need to use heavy equipment because the scrubber could be replaced with the heat carrier after plunging internal pipes inside the restored borehole. Five holes were analyzed with depths from 150 to 230 m. The system permits a heat power of 65 kW (annually about 2000 GJ of low-temperature heat) over a long time (Sliwa and Gonet, 2006). As before, it was necessary to use heat pumps, but, in this case, the idea was not realized due to the fact that closed boreholes were located on private plots. The Geological and Mining Law in such cases gives the entrepreneur some privileges if a mine is developed. However, the law did not anticipate that the holes could be used by the city, and inaccurate interpretations of regulations and problems with entrance onto private property ensued. The necessity to do excavations on connections with private properties also led to legal complications. As a result, new gas boiler was installed in the pool.

In 2007, Sliwa and Jezuit described the concept of using the Kryg reservoir's holes for heating tap water in a primary school building, where water is otherwise heated with electrical flow heaters. Other designs and analyses of the use of the well Lipa 80 (388.7 m depth) in Lipinki community are described by Sliwa et al. (2006) and Sliwa and Jezuit (2007).

The Kryg–Libusza–Lipinki reservoir, discovered in 1860, had over 1000 operational excavations. The area is heavily inhabited, and the holes are located near residential and public utility buildings. Polish Oil and Gas Company closed the wells, following Polish geological and mining law, because the reservoir's exploitation had ended. The borehole depths reach more than 1000 m. However, as before, legal issues connected with the borehole's ownership after adaptation to borehole heat exchangers, has caused no installations to be realized.

In 2013, the use of the hole in the Carpathian reservoir Nadvirna for heating the communal office and kindergarten was described (Sapinska-Sliwa et al., 2013). Borehole No. 470 in Pasiczna was used to analyze the use of an oil well as a borehole heat exchanger. Details on the current structure of the casing in the hole are given in Table 1. The wall thickness of the casing is 12 mm.

All casing is cemented to the top. Sections of casing pipes at intervals of 0-2 m and 2550-2706 m have cement plugs. The original depth of the internal columns was 2540 m.

Table 1. Piping in the borehole Pasiczna 470 (archival data from Ukrnafta).

Casing diameter, in	Longest/deepest casing, m
18	0 - 5
12	0 - 70
8	0 - 2301
5	0 - 2706

The thermal parameters (thermal conductivity and volumetric heat capacity) of rocks were adopted to predict the exploitation of the hole as heat exchanger. These parameters were determined on the basis of the lithological data for Carpathian Flysch. The same values of thermal conductivity and thermal capacity of rocks are assumed throughout the entire profile, which has been justified on the basis of other analyses (Jaszczur et al., 2010).

Table 2. Assumptions and results of simulation.

Simulation variant	No. of construction internal column	Volumetric flow rate of heat carrier, $dm^3 \cdot min^{-1}$	Heating load, kW	Temperature of input media, °C	Temperature of output media, °C	Average temperature, °C
1	1	50	40	21.1	32.5	26.8
2	2	50	40	9.3	20.7	15.0
3	1	50	50	16.6	30.9	23.8
4	2	50	50	3.7	17.9	10.8
5	1	70	50	22.7	32.9	27.8
6	2	70	50	13.2	23.4	18.3
7	1	70	80	12.6	18.8	20.7
8	2	70	80	0.55	16.8	8.7
9	1	70	100	5.8	26.1	16.0
10	2	70	100	-7.9	12.5	2.3
11	2	100	100	2.9	17.1	10.0
12	2	150	150	-3.7	10.5	3.4
13	1	70	120	-1.0	23.5	11.2
14	1	100	100	12.3	26.6	19.5
15	1	150	100	15.7	25.2	20.5
16	2	200	200	-11.7	2.5	-4.6
17	2	200	150	-0.1	10.6	5.3
18	2	100	110	-0.4	15.3	7.4

The values of the thermal conductivity are λ=2.65 W $m^{-1} \cdot K^{-1}$ and the specific heat is c_V = 2.33 MJ $m^{-1} \cdot K^{-1}$, based on weighted averages of these parameters for different layers of Flysch (Plewa, 1994). Along with the analysis of available materials, the following thermal parameters are utilized in calculations:

- temperature of the hole bottom (at a depth of 2680 m): 69°C,
- surface temperature: 4°C,
- earth's natural heat flow: 60 $mW \cdot m^{-2}$, and
- the average value of the initial hole temperature in the range of depth 0-2,540 m (i.e., the average static temperature in the borehole heat exchanger): 34.4°C.

In order to choose the best solution for design and operating parameters of the borehole heat exchanger, some assumptions and computer simulations were made. Sapinska-Sliwa et al. (2013) obtained some important results, while adopting the following assumptions:

- simulated exploitation time: 10 years,
- geothermal heat flows: 0.06 $W \cdot m^{-2}$,
- borehole heat exchanger heat load constant over the entire period of operation.

18 computing variants were carried out with different internal column structures, and the collected heat output (energy flow) and volume flow rate of the heat carrier was determined by Sapińska-Sliwa et al. (2013). To perform the calculations, the numerical simulator BoHEx was used, as described by Sliwa et al. (2010), Jaszczur et al. (2010) and Gonet et al. (2011). The most important results of the projections are summarized in Table 2. Internal column construction no. 1 is double coaxial plastic tubes, and no. 2 is a single plastic tube.

In 2015 Sliwa et al., a simulation for the oil borehole with a depth of 2340 m was carried out, as a deep BHE. The ceiling sealing plug, which closes the lower part of the borehole, located at a depth of 2390 m. The proposed borehole length for use is 2,340 m (where the depth is measured along the axis of the borehole).

The borehole is directional with a horizontal deviation at the hole's bottom of 720.8 m from place where drilling started. The azimuth of the borehole deviation is 72.9°. It is made of 20" diameter pipes to a depth of 10 m. Then 13 $^3/_8$" pipes cemented to the top run to a depth of 306 m. To a depth of 1889 are located 9 $^5/_8$" pipes, which are cemented to 455 m from the top. The last column constitutes 6 $^5/_8$" pipes cemented down to 670 m from the top. For potential exploitation, tubes of 2 $^3/_8$" API (wall thickness 4.83 mm) are located to a depth of 2387 m. However, these are steel pipes, although the use of plastic pipes was planned during adaptation.

Regarding deep BHEs, several other works have been carried out. For example, Geophysica Beratungsgesellschaft mbH (Germany) company on its website (geophysica.de) gives following information on deep BHEs:

- a technical feasibility study (interpretation of well logging data for thermal property prediction) was performed for using the "Bad Urach" deep crystalline wells as deep heat exchangers, see also Kuntz et al. (2011),
- the heating potential of a deep borehole heat exchanger was examined (temperature models and simulation of power characteristic) for the deep BHE at Arnsberg, and
- numerical simulations have been reported for deep BHEs in Düsseldorf, as well as site studies, set-up of steady-state temperature models, modeling, and sensitivity studies of the thermal behavior of deep borehole heat exchanger.

5. CONCLUSIONS

Several conclusions can be drawn from the research reported herein:

Only a few deep BHE installations exist, mainly due to a lack of economic justification. Only a limited number of studies have been performed on a small number of holes.

Costs are incurred when oil and gas holes are closed. In such cases, the investment costs connected with adapting the hole and constructing a BHE installation containing a heat pump may be lower than the total costs of the hole's liquidation (Sliwa 2002). This depends, however, on the manner used for the closing of the hole.

The lack of such installation in the Carpathians, in spite of proven benefits, mainly seems connected with regulatory and legal problems. These involve who has responsibility for an existing hole, which links to ownership. Oil and gas traders are not interested in owning borehole heat exchangers and selling the energy they can produce. In turn, investors interested in selling heat do not want to worry about the holes, and fear there may be high associated costs and potential problems, for example leakage of oil, gas or water, which may occur sometime after the partial liquidation of the hole. The owner of the hole normally bears all costs of repairing the leak, and is also responsible for the decommissioning of the hole at the end of its useful life (although in the case of BHE such times can be very long).

Modeling and investigations of deep BHE performance, techniques and technology appear to be merited, in order to support exploitation. Given the growth in prices of energy resources, deep BHEs may eventually be economically attractive. Experiences in building and exploiting such systems will increase the likelihood of new installations.

Advantages in the use of oil wells and their adaptation to BHEs are observed in instances where land prices are increasing at the hole locations. Such land can be treated as having its own source of heat (Sliwa et al., 2013).

Deep BHEs may be profitable if subsidies are provided. As with other renewable energy installations, the economics can be made more reasonable by various forms of support, often in the form of grants for capital expenditures.

Simplified and straightforward regulatory and legal requirements are needed for the creation of BHEs based on oil and gas holes. Globally, thousands of such holes are being closed, when they could be converted to BHEs. The existence of BHE even in uninhabited areas, where oil fields are liquidated, provides the possibility for creating new infrastructure that can be used for future purposes, by providing the capacity for heating and/or cooling services.

ACKNOWLEDGEMENTS

The paper was founded in statutory research carried at DOGF AGH-UST, funded by the Polish Ministry of Science and Higher Education. The authors thank Agnieszka Pycia and Tomasz Nowosiad from Student Scientific Assoc. GEOWIERT AGH-UST DOGF for help in preparing of publication.

REFERENCES

Al-Khoury R., Kolbel T., and Schramedei R.: Efficient numerical modeling of borehole heat exchangers, *Computers & Geosciences*, **36/10**, (2010), 1301-1315.

Al-Khoury R.: Computational modeling of shallow geothermal systems, Multiphysics modeling, *CRC Press*, (2011).

Ball State University web page (cms.bsu.edu) – (14 May 2014).

Barbacki A. P., Bujakowski W., Graczyk S., Hołojuch G., Kazanowska A., Kępińska B., Pająk L., and Uliasz-Misiak B.: Rekonstrukcja otworu Mszczonów IG-1 na potrzeby eksploatacji złoża geotermalnego do systemu grzewczego, Wybrane problemy wykorzystania geotermii – I, ed. Bujakowski W., *Studia Rozprawy Monografie*, **76**, (2000), 63-107.

Beier R. A., Acuña J., Mogensen P., and Palm B.: Transient heat transfer in a coaxial borehole heat exchanger, *Geothermics*, **51** (2014), 470–482.

Borkiewicz M.: Energia geotermiczna - Ciepło wprost z kopalni, Górnicza Izba Przemysłowo-Handlowa w Katowicach, *Biuletyn Górniczy*, **11-12**, (2002), 89-90.

Bujok P., Klempa M., Koziorek J., Rado R., and Porzer M.: Ocena wpływu warunków klimatycznych na bilans energetyczny górotworu na obszarze poligonu badawczego VSB – TU Ostrava (Evaluation of influence of climate conditions on rock mass energy balance in the research area of VSB – TU Ostrava), *AGH Drilling Oil Gas*, **29/1**, (2012), 97-107.

Burke T.: Wykorzystanie zatopionych wyrobisk górniczych w Szkocji jako źródła energii geotermalnej, Energia geotermalna w kopalniach podziemnych, *Prace Wydziału Nauk o Ziemi Uniwersytetu Śląskiego*, **17**, (2002), 191-200.

Clauser C.: Numerical Simulation of Reactive Flowing Hot Aquifers, *Springer*, Berlin, Germany, (2003).

Dijkshoorn L., Speer S., and Pechnig R.: Measurements and Design Calculations for a Deep Coaxial Borehole Heat Exchanger in Aachen, Germany, *International Journal of Geophysics*, **2013**, (2013), 1-14.

Eskilson P.: Thermal Analysis of Heat Extraction Boreholes, *Ph.D. Thesis*, University of Lund, Sweden, (1987).

Geothermie Neubrandenburg GmbH web page (en.gtn-online.de) – http://en.gtn-online.de/Projects/Deepgeothermalenergyuse/Projectexampleinfo/connectionofadeepboreholeheatexchangerbhetoaretirementhomeforthepreperationofheatingandsanitaryhotw, (14 May 2014).

Gonet A., Sliwa T., Stryczek S., Sapinska-Sliwa A., Jaszczur M., Pająk L., and Złotkowski A.: Metodyka identyfikacji potencjału cieplnego górotworu wraz z technologią wykonywania i eksploatacji otworowych wymienników ciepła (Methodology for the identification of potential heat of the rock mass along with technology implementation and operation of the borehole heat exchangers), ed., *Andrzej Gonet,* Wydawnictwa AGH, Krakow, (2011), 439.

Gonet A., Stryczek S., Sliwa T., and Brudnik K.: The Concept of Making Use of Closed Underground Workings for Heat Recovery in Monumental Salt Mine Wieliczka (UNESCO), *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia (2015).

Hopkirk, R.J. and Rybach, L.: Deep borehole heat exchangers, *Proceedings*, 94 In Europe From research to development, Orleans, France, *Document B.R.G.M.*, **230**, (1994), 323-330.

Jaszczur M., Sliwa T., and Gonet A.: Numerical analysis of the coaxial borehole heat exchanger construction parameters effect on the heat transfer with soil, *Proceedings*, XIIIth International Symposium,HTRSE 2010, Heat Transfer and Renewable Sources of Energy, ed., A. A. Stachel, D. Mikielewicz, Polish Academy of Science, Committee of Thermodynamics and Combustion, West Pomeranian University of Technology, Szczecin, Department of Heat Engineering, Dolna Odra Power Plant Complex, Joint Stock Company, Wydawnictwo Uczelniane ZUT w Szczecinie, (2010), 197–206.

Jessop A.: Geothermal Energy from Old Mines at Springhill, Nova Scotia, Canada, *Proceedings*, World Geothermal Congress, (1995), 463-468.

Kohl T., and Rybach L.: Projekt Statistik Geothermische Nutzung der Schweiz für die Jahre 2000 und 2001, (2003).

Kohl T., Brenni R., and Eugster W.: System performance of a deep borehole heat exchanger, *Geothermics*, **31**, (2002), 687-708.

Kohl T., Salton M., and Rybach L.: Data Analysis Of The Deep Borehole Heat Exchanger Plant Weissbad (Switzerland), *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, Japan, (2000), 3459-3464.

Koohi-Fayegh S., and Rosen M.A.: Examination of thermal interaction of multiple vertical ground heat exchangers, *Applied Energy,* **97**, (2012), 962-969.

Kuntz, D., Kübert, M., and Walker-Hertkorn, S.: Einflussfaktoren und Wirtschaftlichkeit tiefer Erdwärmesonden (TEWS) am Beispiel der Bohrungen 3 und 4 Bad Urach, *GeoTHERM Expo & Congress*, Offenburg, (2011).

Lund J. W., Gawell K., Boyd T. L., and Jennejohn D.: The United States of America Country Update 2010, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, (2010), 1-18.

Morita K., Matsubayashi O., and Kusunoki K.: Down-hole coaxial heat exchanger using insulated inner pipe for maximum heat extraction, *GRC Transactions*, **9(I)**, (1985), 17-23.

Morita, K., Bollmeier, W.S. and Mizogami, H.: An experiment to prove the concept of the downhole coaxial heat exchanger (DCHE) in Hawaii, *GRC Transactions*, **16**, (1992), 9-16.

Mottaghya D., and Dijkshoornb L.: Implementing an effective finite difference formulation for borehole heat exchangers into a heat and mass transport code, *Renewable Energy*, **45**, (2012), 59-71.

Mutke G.: Instalacja geotermalna do odbioru ciepła z wód kopalnianych na potrzeby grzewcze nowego Muzeum Śląskiego, Zakład Geologii i Geofizyki Główny Instytut Górnictwa (2008), (cyt. after http://www.portalwiedzy.gig.eu/node/98, - 14.05.2014).

Nordell B.: Borehole heat Store Design Optimization, *Doctoral Thesis*, Division of Water Resources Engineering, Luleå University of Technology, (1994).

Ostaficzuk S.: Ekologiczne możliwości utylizacji zamykanej kopalni węgla - koncepcje restrukturyzacji, *Wydział Nauk o Ziemi Uniwersytetu Śląskiego*, Sosnowiec (Powerpoint presentation), (2000).

Pająk L., and Bujakowski W.: Efektywność wykorzystania istniejących głębokich odwiertów wiertniczych jako wymienników ciepła wykorzystujących energię geotermiczną, Wybrane problemy wykorzystania geotermii – I, ed. Bujakowski W., *Studia Rozprawy Monografie*, **76**, (2000), 5-62.

Plewa S.: Rozkład parametrów geotermalnych na obszarze Polski, *Wydawnictwo CPPGSMiE PAN*, Kraków (1994).

Rybach L., and Eugster W.: Reliable long term performance of BHE systems and market penetration - The Swiss success story, *Procedings*, 2nd Stockton International Geothermal Conference, ed. L. Stiles, (1998), 41-57.

Rybach L., and Hopkirk R.J.: Shallow and Deep Borehole Heat Exchangers - Achievements and Prospects, *Proceedings*, World Geothermal Congress 1995, Italy (1995), 2133-2138.

Rybach L., Brunner M., and Gorhan H.: Swiss Geothermal Update 1995 – 2000, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, Japan (2000), 413-426.

Sapinska-Sliwa A., Gonet A., Sliwa T., Curyło D., Kondrat O. R., and Vytyaz O. Y.: Rational low-temperature energy management in buildings exemplified by Ivano-Frankivsk Region in Ukraine, ed., Sapinska-Sliwa A., *AGH University of Science and Technology Press*, Krakow (2013), 171.

Schneider D., Strothöffer T., and Broßmann E.: Die 2800 m von Prenzlau oder die tiefste Erdwärmesonde der Welt, *Geothermische Energie*, **16**, (1996), 10-12.

Signorelli S., Wagner R., Kohl T., and Rybach L.: Statistik der geothermischen Nutzung in der Schweiz, *Ausgabe 2006 Überarbeitung der Geothermiestatistik von 1990 bis 2006*, (2007).

Signorelli S.: Geoscientiic investigations for the use of shallow low-enthalpy systems, *Ph.D. thesis*, ETH Zürich University, Zurich, Switzerland, (2004).

Sliwa T., and Gałuszka L.: Study of the effect of medium flow parameters on the heat transfer in the laboratory coaxial model of borehole heat exchanger, *Drilling Oil Gas*, **30/4**, (2013).

Sliwa T., and Gonet A.: Koncepcja wykorzystania likwidowanych odwiertów złoża Turaszówka do pozyskiwania ciepła na ogrzewanie krytej pływalni (Concept of making use of closed wells in field Turaszówka for heat recovery and heating an indoor swimming pool), *Wiertnictwo Nafta Gaz (Drilling Oil Gas)*, **23/1**, (2006), 469-475.

Sliwa T., and Gonet A.: Otworowe wymienniki ciepła jako źródło ciepła lub chłodu na przykładzie Laboratorium Geoenergetyki WWNiG AGH (Borehole heat exchangers as heat or cool source on the basis of Laboratory of Geothermics of Drilling, Oil and Gas Faculty in AGH University of Science and Technology), *Wiertnictwo, Nafta, Gaz* (*Drilling, Oil, Gas*), **28/1–2**, (2011), 419–430.

Sliwa T., and Gonet A.: The idea of utilising old production wells for borehole heat exchangers in the near depleted oil field in Iwonicz Zdrój, *Proceedings*, International Geothermal Conference on “Multiple Integrated Uses of Geothermal Resources”, Reykjavik, Session 13, (2003), 16–22.

Sliwa T., and Gonet A.: Theoretical model of borehole heat exchanger, *Journal of Energy Resources Technology*, **127/2**, (2005), 142–148.

Sliwa T., and Jezuit Z.: Perspectives of use of low enthalpy geothermal energy in Lipinki Community, *Proceedings*, International Conference Geothermal Waters - Their Use and Disposal, ed., Tatiana Simková, Tatralandia, Slovakia, (2007), 138–144.

Sliwa T., and Kotyza J.: Application of existing wells as ground heat source for heat pumps in Poland, *Applied Energy*, **74**, (2003), 3-8.

Sliwa T., and Kotyza J.: Dobór optymalnego otworowego wymiennika ciepła w otworze Jachówka 2K do głębokości 2870 m (Selection of optimal construction of borehole heat exchangers based on Jachówka 2K well to a depth 2870 m), Metodyka i technologia uzyskiwania użytecznej energii geotermicznej z pojedynczego otworu wiertniczego (Methodology and technology of obtaining usable energy from a single geothermal borehole), ed., *Sokołowski J., PGA, Polgeotermia*, PAN Kraków, (2000), 251–284.

Sliwa T., Gołaś A., Wołoszyn J., and Gonet A.: Numerical model of borehole heat exchanger in ANSYS CFX software, *Archives of Mining Sciences*, 57/2, (2012), 375–390.

Sliwa T., Gonet A., and Grasela A.: The wells of the Lipinki oil field in the aspect of borehole heat exchangers retrained, *Acta Montanistica Slovaca*, **11**, (2006), 178–182.

Sliwa T., Gonet A., Sapinska-Sliwa A., and Jezuit Z.: Analysis of Applicability of Borehole R-1 as BHE for Heating of a Gas Well, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia (2015).

Sliwa T., Jaszczur M., and Gonet A.: Analiza numeryczna wpływu własności górotworu na transport ciepła wokół otworowego wymiennik ciepła (Numerical analysis of the rock properties effect on the heat transport around borehole heat exchanger), SWCIM – 2010, *Proceedings*, XIV Sympozjum Wymiany Ciepła i Masy, Polska Akademia Nauk, Komitet Termodynamiki i Spalania, Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Katedra Techniki Cieplnej, Wydawnictwo Uczelniane ZUT, Szczecin, (2010), 551–562.

Sliwa T., Rosen M. A., and Jezuit Z.: Use of Oil Boreholes in the Carpathians in Geoenergetic Systems: Historical and Conceptual Review, *Proceedings*, 8th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia, (2013), 0762-1–0762-12.

Sliwa T.: Techniczno-ekonomiczne problemy adaptacji wykorzystanych odwiertów na otworowe wymienniki ciepła (Technical and economic problems of adaptation used wells into borehole heat exchangers), *Ph.D. thesis*, AGH University of Science and Technology in Krakow, Krakow, (2002), 132.

Solik-Heliasz E. (ed.): Atlas zasobów energii geotermalnej w regionie górnośląskim - utwory neogenu, *karbonu i dewonu*, Katowice, (2009).

Solik-Heliasz E.: Możliwości wykorzystania energii geotermalnej z wód czynnych i zlikwidowanych kopalń w obszarze Górnośląskiego Zagłębia Węglowego, Technika Poszukiwań Geologicznych, *Geotermia, Zrównoważony Rozwój*, **2**, (2007).

Solik-Heliasz E.: Ocena możliwości odzysku ciepła z wód pompowanych z kopalń węgla kamiennego, *Prace naukowe GiG Górnictwo i Środowisko*, **2**, (2002), 17-24.

The Geophysica Beratungsgesellschaft mbH web page (www.geophysica.de) – (11 May 2014).

University of Ontario Institute of Technology, Faculty of Engineering and Applied Science web page (engineering.uoit.ca) – (15 May 2014).

Verhoevena R., Willemsb E., Harcouët-Menouc V., De Boeverc E., Hiddesa L., Op't Veldb P., Demollina E.: Minewater 2.0 Project in Heerlen the Netherlands: Transformation of a Geothermal Mine Water Pilot Project into a Full Scale Hybrid Sustainable Energy Infrastructure for Heating and Cooling, (*Proceedings*, 8th International Renewable Energy Storage Conference and Exhibition - IRES 2013), *Energy Procedia*, **46**, (2014), 58–67.