

## Research and Teaching Capacities of the Geoenetics Laboratory at Drilling, Oil and Gas Faculty AGH University of Science and Technology in Kraków (Poland)

Tomasz Sliwa, Dariusz Knez, Andrzej Gonet, Aneta Sapinska-Sliwa, Bartłomiej Szłapa

AGH University of Science and Technology in Kraków, Drilling, Oil and Gas Faculty, al. Mickiewicza 30; 30-059 Kraków, Poland

sliwa@agh.edu.pl; gonet@agh.edu.pl; ans@agh.edu.pl; bartlomiejszlapa@gmail.com

**Keywords:** Geoenetics laboratory, borehole heat exchangers (BHEs), heat pumps, thermal response test (TRT), geoenetics, geothermal energy, geothermal research, underground thermal energy storages (UTESs)

### ABSTRACT

The dynamic development of renewable energy recovery systems and also rationalization of heat management gave spur to the construction of the Geoenetics Laboratory at Drilling, Oil and Gas Faculty AGH University of Science and Technology (DOGF AGH-UST) in Kraków. One of the important factors deciding about the build are previous works on adapting depleted and negative wells. Research carried out at the Laboratory up today and its usability functions are described in the paper.

The laboratory is based on various types of borehole heat exchangers. They were investigated in view of their design for their effective thermal conductivity  $\lambda_{eff}$  and thermal resistance  $R_b$ . The thermal response tests were used for elaborating BHE thermal conductivity test. It can be used for optimizing the structure and technology of exploitation of large underground heat storages with borehole heat exchangers.

This system can co-operate with various types of solar collectors which in an appropriate climate zone may be a perfect source to be used for charging underground heat storage.

### 1. INTRODUCTION

At the end of 1990's the idea of borehole heat exchangers (BHE) started to be in focus at the Faculty of Drilling, Oil and Gas AGH-UST, coinciding with the opening of a PhD procedure on the application of existing, old boreholes for heat recovery from the rock mass (Sliwa 2002). The first works on underground heat stores were realized in 2006. As the use of the rock mass for heating/cooling purposes covers many disciplines, a dedicated laboratory was worked out, where BHE design, performance and exploitation, underground heat storages performance and modelling, as well as renewal of energy resources in underground storages could be analyzed.

Rock mass can be a source of heat and cold energy for heating and heating/cooling installations making use of heat pumps. This type of installations is more frequently realized in developed countries. Such systems rely not so much on recovering renewable heat, as on rational managing of heat in objects. It lies in using heat of the rock for heating in the heating season, and making use of cold of the rock to air-condition the interior space of buildings. Air conditioning is a reverse process to heating. Having borehole heat exchangers, one may cyclically use the rock mass as a source of heat or cold. Instead of going up to the atmosphere, energy flows are circulated between the receiver (building) and the rock mass. This process can be passive to some extent, i.e. without heat pumps, which adjust energy (temperature) to the reception conditions.

As far as environmental protection and energy aspects are concerned, the driver-energy of heat pumps is very important. In the Polish conditions, electrical energy mainly comes from coal combustion. The thermal capacity of heat pump as referred to the primary energy of coal is slightly above 100 %. Heat pumps substitute electrical energy heating, hence are favorable energetically and ecologically. If a local, traditional source of heat (coal, gas, oil) is replaced with a heat pump, the energy and environmental effect will be less distinct. In the case of electrical energy production from renewable sources, e.g. in Scandinavia, the use of heat pumps is unquestionably purposeful.

To enable designing and exploiting borehole heat exchangers, a specialist Laboratory of Geoenetics was established at the Faculty of Drilling, Oil and Gas AGH-UST. It is part of Interfaculty Field Station for Environmental Surveys. The Laboratory's works were inaugurated in 2007, when the first in Poland commercial Thermal Response Test (TRT) was performed (Gonet and Sliwa 2008).

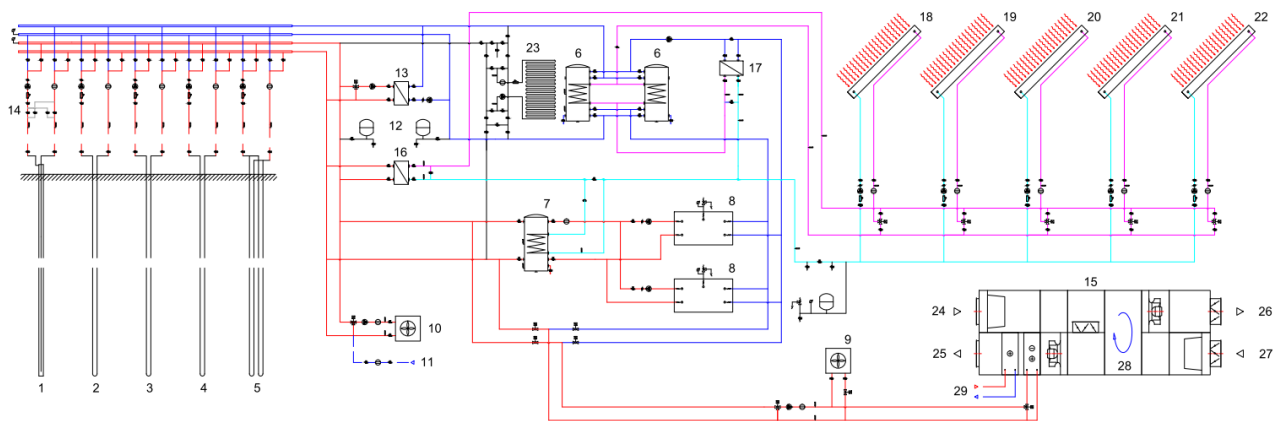
The Laboratory is based on borehole heat exchangers of various design. The schematic of the laboratory, which was completed in 2012 is presented in fig. 1. The marked elements denote: 1 – borehole heat exchanger (concentric, coaxial), 2 – borehole heat exchanger (single U-tube) sealed with an ordinary grout (cement), 3 – borehole heat exchanger (single U-tube) sealed with increased thermal conductivity cement (grout), 4 – borehole heat exchanger (single U-tube) filled out with gravel and sealed with compactonite in the permeable interval, 5 – borehole heat exchanger (double U-tube), 6 – buffering tank of heat carrier on the cold side (cold supply), 7 – buffering tank of heat carrier on the heat side (heat supply), 8 – heat pump units, 9 – fan coil unit for heating/cooling the laboratory space, 10 – water heating coil (for discharging potential excess of power), 11 – network water supplied to fill out the installation, 12 – diaphragm pressure expansion vessel, 13 – plate heat exchanger for transferring heat between cold and heat supply tanks, 14 – set of valves for redirecting fluid flow in a concentric heat exchanger, 15 – heat carrier supplied to the ventilation central of the FDOG Auditory, to provide heating/air conditioning, 16 – heat exchanger between solar collectors and BHE carrier, 17 – additional heat exchanger, from 18 to 22 – solar energy collectors (different kinds), 23 – installation of heating tubes in the parking place. 24-25 – air inlet and outlet in the Auditorium, 26-27 – air inlet probe and air launcher from ventilartion system, 28 – rotary heat exchanger (recuperator), 29 – inlet and outlet of the heat from the municipal

district heating. At this stage various types of BHEs were analyzed for their energy efficiency, and the results are presented in a monograph (Gonet et al. 2011).

The task of the collectors (18-22) is to regenerate heat resources in the rock mass. Thank to solar collectors heat can be introduced in the rock mass along with heat generated when air conditioning the Auditory (Sliwa 2012).

After winter season, the rock mass is cooled down as the energy used for heating has been already recuperated. This creates possibilities for passive air conditioning. Upon reaching maximum temperature by the rock mass in the passive mode, the active air conditioning mode making use of heat pumps is activated. The heat resources for the next heating season start being regenerated with heat coming from solar collectors. Collectors are additionally investigated for their energy efficiency, and the dependence on the design and way in which heat is transferred (to heat and/or cold supply tank). Each of the five collectors has a different design and is assembled differently (mobile and stable). The results of the investigations is a monograph by Sliwa (2012).

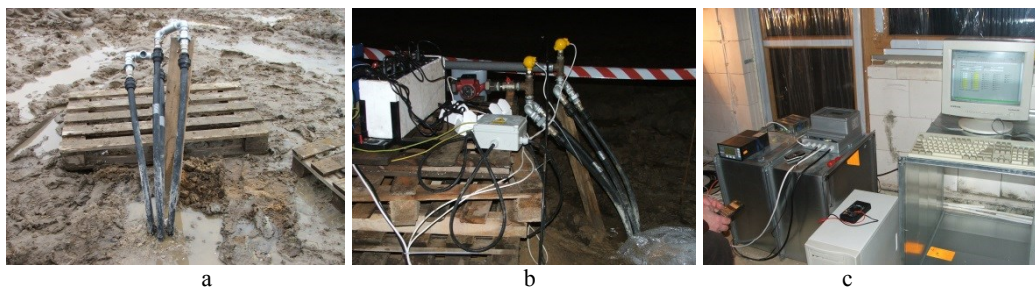
At the end of 2011, the Laboratory was also equipped with a system for snow melting and defrosting of the parking. The system was so incorporated in the hydraulic system of the Laboratory as to enable analyses of heat recovery from the parking surface before the Laboratory (23) to regenerate heat resources in the rock mass.



**Figure 1: Schematic of heat transfer installation in the Laboratory of Geoenergetics, Faculty of Drilling, Oil and Gas AGH-UST (Sliwa and Gonet 2011).**

**2. THE BEGINNING OF THE LABORATORY OF GEOENERGETICS**

The Laboratory of Geoenergetics started its activity with the first two commercial Thermal Response Tests in Poland (fig. 2) for two borehole heat exchangers in Ossa (Rawa Mazowiecka County in Łódź Province). The tests were performed based on a project design in early 2007 (Sliwa 2007).



**Figure 2: First in Poland commercial Thermal Response Test performed in 2007; a – BHE double U-tubes, b – tubes connected with the heating-measuring system, c – control-recording system.**

The idea of making borehole heat exchangers at AGH-UST came into being thanks to the funds from an R&D grant. The Laboratory was located in an object between buildings A3 and A4 within AGH-UST premises, whereas mining works were performed in the green area. The boreholes were drilled with two URB 2A rigs.

The lithological-stratigraphic profile is presented in table 1. The thermal conductivity of rocks and specific volume heat were also accounted for. The borehole heat exchanger 'begins' at 1.8 m of depth, which is connected with the depth of measuring manholes.

To satisfy the needs of the study, five different borehole heat exchangers were performed: centric, with single U-tubes and with a double U-tube. Then single U-tube heat exchangers were sealed with materials of different thermal conductivity. The design and sealing methods were assumed as variables. The description of the boreholes heat exchangers is presented in table 2.

According to the plan of geological works, the Quaternary strata were drilled with a cogged bit 216 mm and clayey drilling mud 'bentopol' to 19.80 m b.s. The casing 7" (177.8 mm) was tripped at 18.80 m b.s. and seated in grey Miocene clays, thus insulating the lower deposited Miocene and Upper Jurassic beds from the influence of the Quaternary water. A cement plug was installed; then the Tertiary strata were drilled with a cogged bit 143 mm and drilling mud, which was naturally formed by water and the

washed rock mass. A core barrel was used twice in the well AGH BHE-2 at the end depth, i.e. 84 m in intervals 60-63 m and 81-84 m. The top of Jurassic limestone strata was found in the lower interval.

**Table 1. Lithological-stratigraphic profile of well AGH LG-2 (Pawlikowski 2008) with thermal parameters of rocks (Gonet et al. 2011).**

No.	Top, m	Bottom, m	Thickness, m	Lithology	Stratigraphy	Thermal conductivity, $\lambda$ , $W \cdot m^{-1} K^{-1}$	Volumetric specific heat, $c_v$ , $MJ \cdot m^{-3} K^{-1}$
1	1.8	2.2	0.4	Anthropogenic ground (dark grey fill with debris)	Quaternary (Pleistocene, Holocene)	1.600	2.000
2	2.2	2.6	0.4	Aggregate mud (grey ground)		1.600	2.200
3	2.6	4.0	1.4	Fine, dusty and slightly clayey sand		1.000	2.000
4	4.0	6.0	2.0	Fine sand		1.200	2.500
5	6.0	15.0	9.0	Sand and slag mix, slag		1.800	2.400
6	15.0	30.0	15.0	Grey clay	Tertiary (Miocene)	2.200	2.300
7	30.0	78.0	48.0	Gray clay slate	(Miocene)	2.100	2.300
Weighted average						<b>2.039</b>	<b>2.309</b>

Hence, a clayey plug 6 m long was performed on the well's bottom (Pawlikowski 2008). Then a U-tube was introduced under pressure (with heat carrier) and the borehole was cemented through the string, from the bottom to the top. The remaining four boreholes were performed to 78 m of depth.

For determining the actual velocity of water flowing in the aquifer, the location of water table in the nearby hydrogeological node (well and 2 piezometers) owned by the Interfaculty Field Station for Environmental Surveys was analyzed. On this basis the hydraulic gradient  $I = 0.005$  was calculated.

On the basis of results of research carried out *in situ*, the average filtration of analyzed layer  $k = 150$  m/d was defined with the test pumping method in the hydronode. Such values are typical of porous, highly permeable rocks, where water flows quickly.

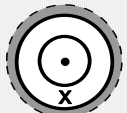
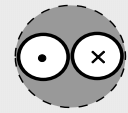
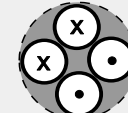
Having assumed the active porosity coefficient at 30%, the actual velocity of water flowing in the analyzed aquifer was calculated:  $v_{rz} = 2.67$ ; m/d = 975 m/year. The obtained value determines the groundwater motion as very quick. It can be assumed that water flowed to the south and east-south. The flow covered the entire interval from 3 to 15 m b.s., but differed in intensity. The best conditions were encountered between ca. 8 and 15 m b.s. Rock fragments at 9 and 10 m of depth are presented in fig. 3.

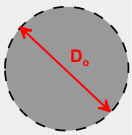
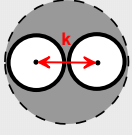
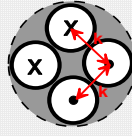
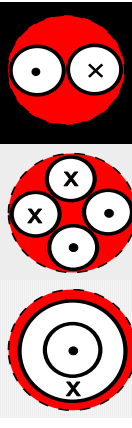
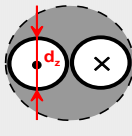
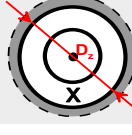
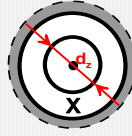
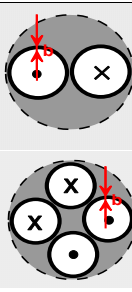
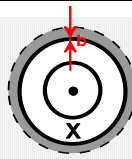


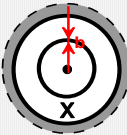
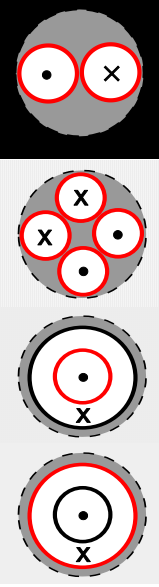
**Figure 3: Rock mass samples collected during drilling at 9.0 and 10.0 m.**

Owing to its removable inner tube, centric borehole heat exchanger BHE-1 can be used for further surveys. The applied polyethylene tube of 40 mm nominal diameter, equipped with centralizers (fig. 4c) is removable. It is disposed inside a tube of 90 mm nominal diameter (fig. 4d), which was also centralized prior to cementing. The effective conductivity in a borehole heat exchanger is being defined for other tubes, different diameters and other materials.

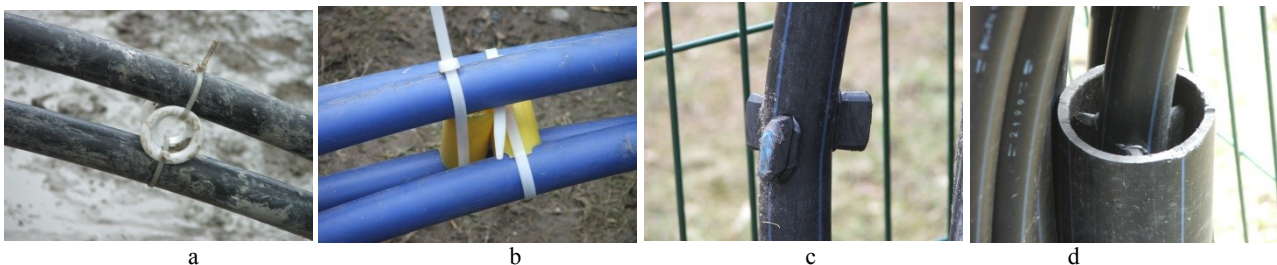
**Table 2. Detailed parameters of borehole heat exchangers (Gonet et al. 2011).**

No.	Parameter	Picture	Value					
			LG 1 (BHE 1)	LG 2 (BHE 2)	LG 3 (BHE 3)	LG 4 (BHE 4)	LG 5 (BHE 5)	
1	Depth of borehole	-	78 m	82 m	78 m	78 m	78 m	
2	Depth at which exchanger's tubes are seated	78 m						
3	Design of borehole heat exchanger	-				centric	single U-tube	double U-tube

4	Borehole diameter $D_o$ (drill tool diameter)		143 mm				
5	Distance between tubes in heat exchanger, k		n/a	80 mm		n/a	
5'	Distance between tubes in heat exchanger, k		n/a	n/a		70 mm	
6	Material used for sealing heat exchanger		cement, $\lambda=1.2 \text{ Wm}^{-1}\text{K}^{-1}$	cement, $\lambda=1.2 \text{ Wm}^{-1}\text{K}^{-1}$	Thermocem, increased thermal conductivity cement (grout), $\lambda=2.0 \text{ Wm}^{-1}\text{K}^{-1}$	Gravel 8-16 mm of grain and clayey plugs, $\lambda=1.8 \text{ Wm}^{-1}\text{K}^{-1}$	cement, $\lambda=1.2 \text{ Wm}^{-1}\text{K}^{-1}$
7	Outer diameter of tubes in heat exchanger		n/a	40 mm		32 mm	
7'	Outer diameter of outer tubes in heat exchanger		90 mm	n/a			
7''	Outer diameter of inner tubes in heat exchanger		40 mm	n/a			
8	Thickness of tube wall in heat exchanger		n/a	2.4 mm		2.4 mm	
8'	Thickness of outer tube wall in heat exchanger		5.4 mm	n/a			

8	Thickness of inner tube wall in heat		2.4 mm	n/a
9	Material of tubes in heat exchanger		Polyethylene, $\lambda = 0.42 \text{ Wm}^{-1}\text{K}^{-1}$	

Single and double U-tubes (fig. 4a, 4b) are equipped with bottom heads. They have metal guides for tubular members aiding the tripping of U-tubes inside the holes. The guide is also used for anchoring the U-tube in the borehole and is important in view of buoyancy, especially during cementing.



**Figure 4: Various configurations of tubes, a - space fitting of tubes in a single U-tube; b - space fitting of tubes in a double U-tube, c - inner tube of centric borehole heat exchanger with a centralizer, d - inner and outer tube of centric borehole heat exchanger.**

In June 2008 the borehole heat exchangers were connected with the Laboratory. The conductors were led from particular borehole outlets to the laboratory, thanks to which borehole heat exchangers could be turned on selectively.

In the second half of 2008, the following installations were made inside the laboratory: heat and cold energy receivers, circulation pumps, manual and automatic valves, pressure meters, vents, fan for heating and/or cooling the laboratory interior, heating coil for discharging excess heat power, heat exchanger for transferring heat between receivers and two heat pump units of summatic heating power 26 kW (fig. 5).

Once the inner installation at the Laboratory was finished, the works on measuring, control and recording system could commence. Among the registered parameters were temperatures, heat carrier volume flows (and so indirectly heating power), voltage and current in heat pumps (and so indirectly electrical power), coefficient of performance (COP) of heat pumps, pressures and also states of specific executive and control elements (e.g. valves).

In 2010 the first installation was connected to the FDOG Auditory located between buildings A3 and A4 (fig. 6a, 6b). The old ventilation central was replaced with a new one (fig. 6c), allowing for heat (and cold) energy recuperation from the ventilation as the first degree change of ventilation air temperature (heating or cooling). Heat is recovered through a rotary heat exchanger.

The second degree change of air temperature is the heating/cooling coil, with circulating glycol from cold receivers (conditioning) or heat (heating) from the Laboratory of Geoenergetics. The third degree change is the heating coil fed with network heat, being peak or emergency source of heat (only heating). The heating season 2010/2011 was the first one when the Auditory makes use of heat of earth for heating atmospheric air. Central heating substation are installed at the Auditory (25 kW), nonetheless most of the heat gets inside with the ventilation air (75 kW).



Figure 5: Two Stiebel Eltron heat pumps, a – heat pumps with switchboard and electrical energy counter, b – heat pumps with heat receivers on the left, and cold receivers on the right.

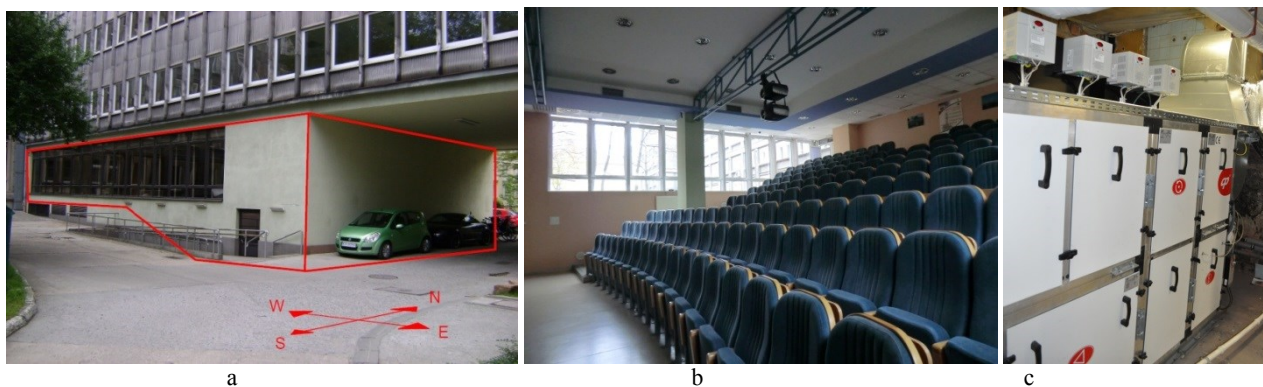


Figure 6: FDOG Auditory, a – southern wall with windows, b – interior, c -new ventilation central with a rotary heat exchanger.

The distribution of borehole heat exchangers is visualized in a schematic and on photo fig. 7. At the beginning of 2011 the solar energy collectors started to be installed. Five solar energy collectors operate within the Laboratory of Geoenergetics: two (flat-face and evacuated tube collectors are mobile and their position can be modified depending on the Sun position (fig. 8a) with servomotors (fig. 8b). Three collectors are stationary: flat-face, evacuated tubes and hot pipe (fig. 8c). Each of the solar collectors has an independent circulation system (individual circulation pumps) and measuring system, thanks to which their energy efficiency can be investigated and compared. Collectors are localized at the Interfaculty Field Station for Environmental Surveys for teaching purposes; this placement, however, does not allow for their full use as the neighboring buildings and trees limit the access of sunlight.

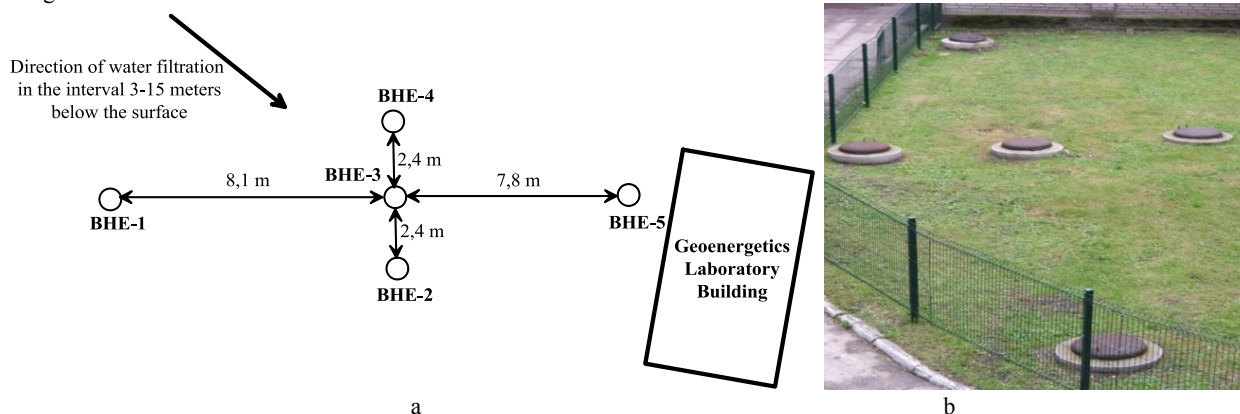
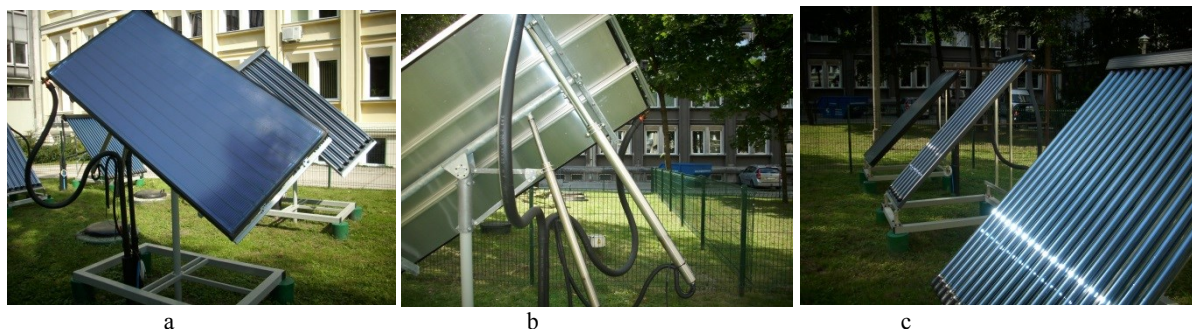


Figure 7: Distribution of borehole exchangers owned by the Laboratory of Geoenergetics FDOG AGH-UST, a – dimensioned schematic of distribution, measurement manholes.



**Figure 8: Mobile and stationary solar collectors, a – flat-face collector in the foreground and evacuated tube collector behind it, b – servo-motors controlling the position of collectors, c – stationary float, vacuum and heat pipe collectors.**

For the purpose of efficiency analysis of heat recovery from solar energy collectors of various design and mode of fixing, a stand for measuring the intensity of solar radiation and wind direction was made. The temperature of atmospheric air is also measured. The stand is connected with the computer registering all measurements through the control box.

The next stage of development of the Laboratory of Geoenenergetics was broadening research and utilization possibilities by installing snow melting and defrosting systems under the parking area before the Laboratory. Works started during the exchange of the surface between buildings A3 and A4. The tubes were disposed under the brick surface in the form of numerous loops (fig. 9a, 9b, 9c). This allows for their selective operation in the in-series, parallel and Tichelman systems thanks to the valve system inside the Laboratory (fig. 9d).



**Figure 9: Tube loops in sand under the bricks, a,b,c - views at various stages of work, d - distribution installation of heating loops in the parking.**

In 2012 the inner installations inside the Laboratory covered three heating/cooling systems. Black tubes correspond to the basic installation made of heat pumps, borehole heat exchangers and heat/cold receivers. Silver tubes belong to the solar collector installation, red ones are the parking tubes installation, and the blue ones are the Auditory installation.

### 3. LABORATORY – RESEARCH UNITS

The Laboratory of Geoenenergetics is equipped with 17 survey stands:

- 1) heating-cooling system of the FDOG Auditory,
- 2) apparatus for thermal response test (TRT),
- 3) heat pumps with bi-directional heat flow in the rock mass (heating and cooling),
- 4) borehole heat exchangers of various designs, each 78 m deep,
- 5) laboratory model of coaxial heat exchanger (Sliwa and Gałuszka 2013),
- 6) didactic apparatus for measuring thermal power,
- 7)  $\lambda$ -meter for measuring thermal conductivity of rocks and materials (hardened sealing slurries),
- 8) apparatus NIMO-T for temperature logging in borehole heat exchangers,
- 9) meteo mini-station for measuring external temperature, speed and direction of wind and intensity of solar radiation,
- 10) five solar collectors for regeneration of heat in the rock mass with individual measurement,
- 11) heating/cooling system for snow melting of the parking before the Laboratory,
- 12) pressure meter for measuring location of the water table in the borehole,

and computer stands for calculations:

- 13) numerical simulator BoHEX for predicting exploitation in borehole heat exchangers in heating, cooling and heating/cooling systems,
- 14) RETScreen® International package for technical and economic analyses of renewable energy sources and determining their environmental impact,
- 15) TOUGH2.0 numerical simulator for modelling exploitation in geothermal reservoirs with PetraSim pre- and postprocessor package,
- 16) BIES (Buildings' Integrated Evaluation System) computer program for analyzing the environmental impact of buildings,
- 17) AUDYTOR OZC program for determining buildings' heat demand.

#### 2.1. Apparatus for thermal response tests

The apparatus for thermal response test (TRT) consists of sensors of flow and temperature, circulation pump, electrical furnace and a computer with specialist software (fig. 10). This system allows for determining effective thermal conductivity of rocks and thermal resistance of borehole heat exchangers. Knowing these parameters one can design the amount and distribution of borehole

heat exchangers for specific thermal power of an object or determine temperature characteristic of heat exchange with the rock mass and predict further exploitation.



Figure 10: Setup for thermal response tests.

### 2.2. Geothermal Source Heat Pumps unit

The heat pumps stand can be used for long measurements of the rock mass as a source of heat and cold. The condensing and evaporator coils of heat pumps are connected to the heat/cold storages, which in turn, are connected to all borehole heat exchangers. In this way the heat can be recovered from the rock mass when borehole heat exchangers are connected to the storage of cold energy. The evaporator coil recuperates the heat, which is then used for warming up the energy carrier in the heat storage. The heat storage is connected to the ventilation air heating system. In the reverse configuration (cooling mode) the borehole heat exchangers may be connected with the heat storage, where the heat from the cold storage is directed. The cold storage recuperates the heat when the ventilation air in the Auditory is being cooled.

### 2.3. Borehole heat exchangers

Borehole heat exchangers of various designs (table 2) can be used for: analyzing the heat exchange efficiency and influence of the BHE type on the efficiency, and also exploitation parameters (carrier flow, pumping temperature, type of heat carrier). A centric borehole heat exchanger may also operate for two opposite flow directions of the heat carrier (position 14 in fig. 1). The internal column is replaceable. For the reason of analyzing such an exchanger, a laboratory model was construed.

### 2.4. Laboratory model of coaxial borehole heat exchanger

The laboratory is equipped with a model for analyzing the energy efficiency of centric borehole exchangers. It allows for making tests related to the heat recovery form the rock mass simulated by electric heaters, and quantity of heat transported to the surface at various insulation parameters of the internal column. The investigations were performed for various volumes of heat carrier with the use of temperature and flow sensors.

### 2.5. Apparatus for measuring thermal power of heat source

The apparatus for measuring heat power is used for determining how the heat carrier flow and its type influence the thermal flow parameters. The apparatus bases on a heater in the prototype TRT setup. It is equipped with five electrical heaters and a flow meter. Used generally for teaching.

### 2.6. The $\lambda$ -meter

The  $\lambda$ -meter is mainly used for analyzing sealing slurries applied to heat exchangers (fig. 11), the influence of recipes, time of bonding and humidity on thermal conductivity of the grout. The thermal power is measured with TT-TCP-01 apparatus produced by ThermTest Inc. in Canada.



Figure 11: Setup with TT-TCP-01  $\lambda$ -meter

### 2.7. Non-wired Immersible Measuring Object for Temperature

The Swiss NIMO-T (Non-wired Immersible Measuring Object for Temperature) can be used for temperature logging in a borehole heat exchanger (fig. 12). The object automatically falls down to the bottom of the exchanger making current measurements of



temperature and pressure or storing them in internal memory every 2 s, or more rarely. With the density of fluid in the borehole U-pipe known, the pressure corresponds to the depth at which temperature was logged. The measurements are performed with very high precision. The relative accuracy of temperature measurement is 0.0015 K, whereas the absolute accuracy equals to 0.1 K. The accuracy data for the device are listed in table 3. After reaching the bottom, the object gets back to the surface after the heat carrier circulation in the U-tube has been activated (Rohner et al. 2005).

**Table 3: Scope of measurement and accuracy of NIMO-T.**

Temperature	-5 to +50	°C
Pressure	0 to 40	bar
Maximum depth of measurement	400	m
Maximum test pressure	110	bar
Accuracy of temperature log (+5° to +25°C)	+/- 0.0015 +/- 0.1	°C relative temperature °C absolute temperature
Accuracy of pressure log	+/-0.02 +/-0.1	bar relative pressure bar absolute pressure



**Figure 12: Pressure and temperature logger NIMO-T, and setup for precise temperature logging.**

## 2.8. Heating/cooling system

Measurement elements in the heating/cooling system can be used for analyzing the heat exchange with the rock mass through the borehole heat exchangers, and also the efficiency of heat/cold energy storing in the rock mass. The logging and recording system play an important role in the installation. It is based on a central unit providing full communication with sensors and executive elements (switching on/off of pumps and fans, valve control, etc.) At the same time this is a source of historical data thanks to which information currently presented in the Internet can be visualized.

The industrial computer can be used for reading out data and continuous recording of:

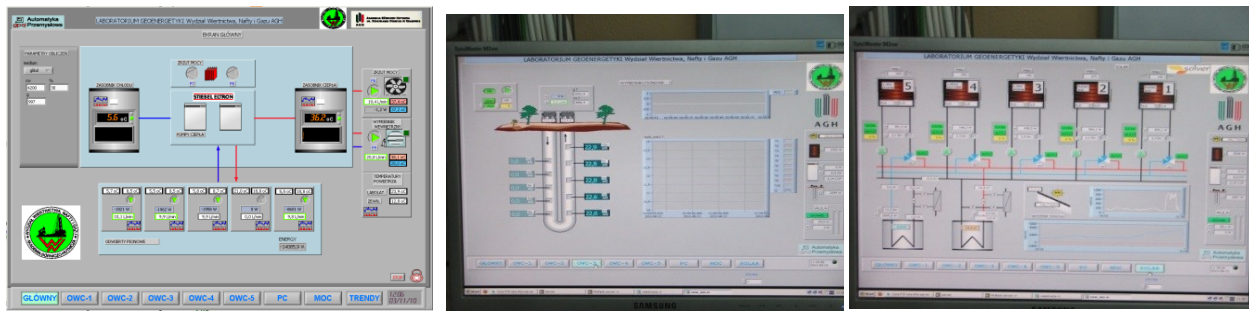
- temperatures from each of the heat meters,
- volumetric flow of heat carrier in each borehole heat exchanger,
- thermal power (at each borehole heat exchanger and from heat meters in the reception system),
- electrical power supplied to the heat pumps,
- total supplied heating and electrical energy,
- temperature of atmospheric air,
- temperature inside the laboratory and four characteristic temperatures of ventilation center unit of the AGH-UST Auditory,
- data from the snow melting and de-icing system used at the parking.

It also allows for fluent regulation of:

- volumetric flow of heat carrier in each of the borehole heat exchangers,
- temperature in cold/heat storage,
- temperature in the Auditory and Laboratory.

Current parameters and historical data are visualized, and the communication can be done remotely through the Internet. The control system reports the errors, therefore the constant volume flow of heat carrier can be maintained in the borehole heat exchangers, regardless the network voltage and difference pressure. In this way the operation of heat pumps can be provided (emergency shutdown after admissible threshold temperature values were obtained in condensing and evaporator coils).

A number of computer programs were worked out for the laboratory purposes (fig. 13). The most important one is used for controlling and recording the operation of: heat pumps, particular borehole heat exchangers, solar collectors, ventilation system of the Auditory, heating coils and de-snowing system.



**Figure 13: The main screen of the program controlling the operation of heating/cooling system based on borehole heat exchangers at the Laboratory of Geenergetics FDOG AGH-UST.**

**2.9. Meteorological mini-station**

The devices for measuring speed and direction of wind and solar radiation intensity are installed. These measurements are used for analyzing the energy efficiency of solar collectors of various designs and various fixing modes. Wind measurements are made for determining boundary conditions and calibration of BoHEX simulator, used for modelling the operation of various types of borehole heat exchangers.

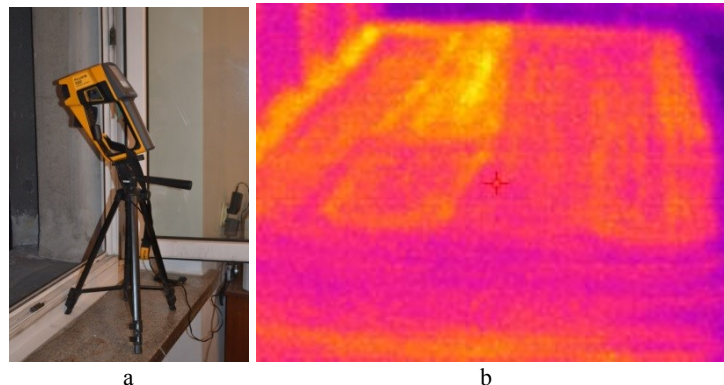
**2.10. Solar collectors**

Five solar collectors are used at the Laboratory of Geenergetics for renewing heat resources in the rock mass. Each collector has a different design or is mounted in a different mode, has individual software and pumps with fluent regulation of heat carrier flow.

**2.11. Heating system for snow melting of the parking**

A yard and a parking are located in front of the Laboratory. Under the surface of this area, a system of tubes was disposed (fig. 9). They can be fed by the heat pumps or directly from the borehole heat exchangers. The tube system is now investigated for the recoverability of solar radiation on this surface in summer.

The efficiency of snow melting of surface with the use of heat of the rock mass has been already proved several times. The thermovision cameras showed higher temperature in the places where tubular heating loops were disposed under the surface (fig. 14).



**Figure 14: Measurement with a thermovision camera showing the distribution of heating tubes under the parking surface, a) thermovision camera, b) picture showing distribution of heating tubes under the parking surface.**

**2.12. Pressure meter for locating water level in the borehole**

Pressure meter is mounted on a carrying line which enables tripping of the device to the borehole. The carrying line is equipped with a capillary, which transmits the atmospheric pressure value to the immersed pressure meter. The main task of such a pressure meter is locating the water table in a borehole during the test pumping operations.

**2.13. Numerical simulator BoHEX**

Numerical simulator BoHEX is used for predicting exploitation of borehole heat exchangers in the heating, cooling and heating/cooling systems. Its application principle was described by Jaszczur et al. (2010), Sliwa et al. (2010) and Gonet et al. (2011).

**2.14. RETScreen® International Package**

The RETScreen® International package is used for technical and economic analyses oriented to energy saving and use of the renewable energy sources. This international internet e-platform (retscreen.net) is a universal and standardized tool for evaluating technical and economic investments as far as generation and saving of energy based on economic combustion and renewable energy sources are concerned. It also enables one to determine and compare ecological effects of the analyzed undertakings. The RETScreen® Platform was worked out by the Ministry of Natural Resources of Canada, and CANMET Energy Technology Center, Varennes (Canada) in cooperation with the UN Environmental Program (UNEP), Global Environment Facility (GEF), and NASA in USA (Zimny 2010).

The advanced didactic, instruction materials and high standard software are free and available to everyone who registers and accepts the license conditions. The user of the e-platform has to be equipped with Microsoft Excel, where RETScreen® operates with its modules: Start, System Model, Cost Analysis, Emission Analysis, Financial Analysis, Risk Analysis and Tools (Zimny 2010).

### 2.15. Numerical simulator TOUGH2.0

Numerical simulator TOUGH2.0 is used for modelling exploitation of geothermal reservoirs. Together with the PetraSim pre- and postprocessor PetraSim it constitutes the World's best known tool for predicting exploitation and injection of geothermal waters. This program was elaborated at the Lawrence Berkeley National Laboratory and purchased by the Department of Energy U.S.

The numerical simulator TOUGH2.0 is well known software, frequently used for modelling of the heat exchange processes and fluid flows within porous and fractured reservoirs. It is particularly popular for modelling effects related to the geothermal energy use. The simulator is equipped with own generator of PetraSim mesh grids. It enables one to create a 3D mesh grid in a radially symmetrical system. The nodes of the grid are ascribed coordinates, and the simulator itself does not make use of nodal coordinates; this information is helpful at the stage of result data processing (Gonet et al. 2011).

The TOUGH2.0 code is the main simulator, based on which additional capabilities have been built. The most current version (V2.1) is released by the Berkeley Lab Software Center. This version is an upgrade from TOUGH2 V2.0, released by the Department of Energy's Energy Science and Technology Software Center since 1999. The most current version differs from the previous version in that:

- all known bugs have been fixed,
- the core has been restructured to fully integrate the TMVOC and ECO2N modules,
- the new fluid property module ECO2M has been added to the suite, to analyze the use of CO<sub>2</sub> as working fluid in enhanced geothermal systems – EGS (esd.lbl.gov).

TOUGH2.0 offers the flexibility to handle different fluid mixtures, the properties of which are described in separate Equation-of-State (EOS) modules. TOUGH2.0 uses an integral finite difference method for space discretization, and first-order fully implicit time differencing. A choice of a sparse direct solver or various preconditioned conjugate gradient algorithms is available for linear equation solution. Thermophysical properties of water are represented, within experimental accuracy, by steam table equations. The program provides options for specifying injection or withdrawal of heat and fluids. Double-porosity, dual-permeability, and multiple interacting continua (MINC) methods are available for modeling flow in fractured porous media (esd.lbl.gov).

Although primarily designed for geothermal reservoir studies and high-level nuclear waste isolation, TOUGH2.0 can be applied to a wider range of problems in heat and moisture transfer, and in the drying of porous materials. The TOUGH2.0 simulator was developed for problems involving strongly heat-driven flow. To describe these phenomena a multi-phase approach to fluid and heat flow is used, which fully accounts for the movement of gaseous and liquid phases, their transport of latent and sensible heat, and phase transitions between liquid and vapor. TOUGH2.0 takes account of fluid flow in both liquid and gaseous phases occurring under pressure, viscous, and gravity forces according to Darcy's law. Interference between the phases is represented by means of relative permeability functions. The code includes Klinkenberg effects and binary diffusion in the gas phase, and capillary and phase adsorption effects for the liquid phase. Heat transport occurs by means of conduction (with thermal conductivity dependent on water saturation), convection, and binary diffusion, which includes both sensible and latent heat (esd.lbl.gov).

### 2.16. Computer program for analyzing environmental impact of buildings

The computer program BIES (Buildings' Integrated Evaluation System) for analyzing the environmental impact of buildings (Sapinska-Sliwa 2014) is similar to the British BREEM method. The Laboratory's works concentrated on sustained development in view of geothermal and solar energy use and heat storing in the rock mass. The methods of buildings certification were analyzed at the Faculty of Drilling, Oil and Gas. The most important programs of environmental impact of buildings were compared with special emphasis on their energy certifications. Moreover, a model of building's evaluation in view of sustained development criteria was created. Its sample templates are presented in literature (Sapinska-Sliwa 2014). This methodics is partly based on a few already existing systems. The solutions of E-Audit and BREEM programs were used, introducing also solutions employed in other systems. This model operates in MS Excel environment.

The buildings in this model were assessed similarly as in BREEM program, in 10 sections, each of them being ascribed its weight to be later used for calculating the final weight. The evaluation covered:

- 1) managing the process of planning, realization and exploitation of the investment,
- 2) impact on health and well-being of users,
- 3) waste management,
- 4) rational energy management,
- 5) transport and logistics,
- 6) useful and waste water management,
- 7) used construction materials,
- 8) ecology and environmental impact,
- 9) emission of pollutions,
- 10) use of modern solutions.

### 2.17. The AUDYTOR OZC program

The AUDYTOR OZC program is an aid to be used for calculating designed heat load and determining seasonal demand for thermal energy for heating of buildings. This program can be used for calculating heat objects in compliance with the relevant regulations.

Despite complicated calculation methods and considerable amount of data to be introduced, the time in which the project is performed is not excessively long. The software was purchased by the Faculty at the National Energy Conservation Agency.

The following parameters can be calculated with the use of this program:

- heat transfer coefficient for walls, floors, roofs and flat roofs,
- thermal power demand of particular rooms,
- thermal power demand of entire building,
- seasonal heat demand (heating of residential buildings),
- seasonal heat demand (Wereszczyński 1999).

#### **4. FUNCTIONS OF THE LABORATORY**

The basic function of the laboratories is conducting analyses with the use of available laboratory stands and setups for the needs of grants and contracts with industry. Such laboratories also play a didactic function or, as it is in the case of the Laboratory of Geoenergetics, have a utility aspect, i.e. are used for heating and air conditioning of rooms.

##### **3.1. Scientific research**

The most important function of the Laboratory is geothermal research. The research stands can be used for investigating borehole heat exchangers *in situ* and in the field. Apart from it, the Laboratory is also used for analyzing heat flows in the rock mass: absorption of heat for heating of the Auditory room in winter, and introduction of heat during passive and active air conditioning. The recuperation of heat and cold is realized through a rotary exchanger. The threshold difference of temperatures at which heat/cold recuperation is activated is 3 K.

The energy efficiency beyond the laboratory system and economics of such solutions was a subject of realized research grant. For this reason a numerical simulator was construed thanks to which the exploitation of systems with a large number of borehole heat exchangers could be predicted. Presently the calibration works are on-going.

Besides these functions, the Laboratory is used for working out simple installations with controllers. The software controlling such systems is optimized in view of economic (maximization of NPV) and/or energy criterion (minimization of yearly consumption of primary energy).

Apart from borehole heat exchangers, the Laboratory is also used for analyzing heat flows in the rock mass. Heat flows are connected with the consumption of heat in winter for heating of the Auditory of the FDOG and introduction of heat during its passive and active air conditioning.

The tubes installed under the surface of the parking are investigated and used for snow melting and de-icing of the surface. Works continue on determining the usability of this installment for renewal of heat in the rock mass. The surface of parking can work in summer as flat solar collector.

##### **3.2. Teaching and promotion (demo function)**

The second function of the Laboratory is didactics, i.e. familiarizing geologists and miners with heating issues, and getting heating specialists known with geology and mining. Presently the Laboratory is open for the 2<sup>nd</sup> year part- and full-time MSc students of Mining and Geology, specialization Drilling and Geoengineering, and postgraduate students of Geoenergetics and Geoengineering. The solar collectors were so located as to match the didactic goals and make the place directly available for the students. As a result of research conducted in the laboratory, a few M.Sc. theses and research papers, three monographs have been written.

Works ordered by industry are also realized at the Laboratory. The borehole heat exchangers are analyzed and their operation mathematically modelled. Geoenergetical analyses and predictions of underground heat storage exploitation are also made. Two research grants have been realized at the Laboratory so far. Apart from it, the Laboratory is used for demonstrating the use of rock mass for energy purposes.

##### **3.3. Heating and air conditioning**

The third target of the Laboratory is supplying heat/cold to the Auditory room of the FDOG, and the Laboratory itself. The demand for heat considerably exceeds that for the cold, especially that during summer season there are no classes, lectures or conferences and the place is closed. Therefore the balance between heat consumed and heat introduced to the rock mass is disturbed. This situation (especially in the case of bigger installations) leads to lowering of the temperature of the rock mass over the years of exploitation due to insufficient regeneration of heat reserves during air conditioning periods. Accordingly, an additional source of heat was introduced, which would regenerate the heat reserves in the rock mass. These are solar collectors of various designs. Thanks to this solution an additional possibility of research on recuperation of solar heat became available. The collectors and the laboratory are located in a place surrounded with high buildings therefore the thermal effects from only diffused radiation can be additionally investigated.

##### **3.4. Snow melting and de-icing**

Another additional side-effect of the Laboratory's operation is snow melting of the parking in front of the buildings between blds. A3 and A4 at AGH-UST. In this way the mechanical removal of snow, emission of pollutions and/or use of chemical (salt) are reduced.

##### **3.5. Regeneration of resources of an underground heat storage**

The function of the Laboratory, which is connected with all the remaining tasks, is introduction of heat to the rock mass. The solar heat (from air-conditioning system, solar collectors and snow melting installation) with natural water flow in the geological layer 3-15 m under surface constitutes heat regeneration source for UTES (artificial and natural).

#### 4. CONCLUSIONS

1. Underground thermal energy storages (UTESs) become more and more popular in assuring suitable heat comfort in residential and commercial buildings. Most of them are running based on borehole heat exchangers (BHEs).
2. BHEs give the opportunity to heat and air condition the indoors. The largest of this installations consist of more than 1000 BHEs, e.g. at Ball State University, Indiana (Lund et al. 2010). Because of the growing interest in BHEs more and more research works are being conducted. They aim at developing technical solutions. Installations formed at technical universities are intended for heating or heating and cooling, demonstration and research works. Besides the Ball University w USA (cms.bsu.edu), BHEs with depths in the range of 122-152 m run at Luleå University of Technology. The very first large-scale borehole heat store was constructed in Luleå (Sweden) during 1982-83 (Nordell 1994); at VSB – Technical University of Ostrava (Czech Republic); at University of Ontario Institute of Technology (Oshawa/Canada) (Koochi-Fayegh and Rosen 2012) and at AGH-UST.
3. The increase in prices of traditional energy carriers, desire for energy independence and the need of environmental protection in terms of reducing emissions of combustion products into the atmosphere are primary arguments for the development of BHEs installations. Systems based on BHEs fulfill two tasks. The first is to gain heat from the environment, which reduces the demand for primary fuels. The second is to rationalize the use of heat, particularly evident in the heating and cooling systems.
4. Drilling, Oil and Gas Faculty at AGH University of Science and Technology is the first, where research works on BHE are being conducted, researches has focused on the optimization and exploitation of BHEs in the aspect of the use of old oil&gas wells. The specific scope of the work is the acquisition of geothermal energy based on existing deep oil&gas wells, which are intended to be liquidated or on the wells being negative.
5. A very important task of geoenergetics systems at universities is a demonstration how those systems work as same as demonstration its effects. These are the energy, environmental and economical effects (especially in the case of reverse heat pump/BHEs systems). The use of local resources contributes to the reduction in export of other energy sources.
6. Another important task of the works being conducted is to develop own (Polish) methodology of designing deep BHEs, what should allow to become technologically independent. A further increase in the prices of traditional energy carriers increases the economic viability of installing deep BHE. Environmental aspects should be also taken into account.

#### ACKNOWLEDGEMENTS

The paper was carried out under the Statutory Research at the Faculty of Drilling, Oil and Gas, AGH University of Science and Technology, financed from the funds of the Polish Ministry of Science and Higher Education.

#### REFERENCES

- Ball State University web page (cms.bsu.edu) – 20 Mar 2014.
- Berkeley Lab Earth Sciences Division web page (esd.lbl.gov) – 2 Mar 2014.
- Gonet A., and Sliwa T.: Thermal response test on the example of borehole heat exchangers in Ecological Park of Education and Amusement “OSSA”, *Transport & Logistics*, **6** (2008) 42–47.
- Gonet A., Sliwa T., Strzycki 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.
- Jaszczur M., Sliwa T., and Gonet A.: Numerical analysis of the coaxial borehole heat exchanger construction parameters effect on the heat transfer with soil, HTRSE 2010, Heat Transfer and Renewable Sources of Energy, *Proceedings* 13<sup>th</sup> International Symposium, ed. A. A. Stachel, D. Mikielwicz, 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.
- Koochi-Fayegh S., and Rosen M.A.: Examination of thermal interaction of multiple vertical ground heat exchangers, *Applied Energy*, **97**, (2012) 962-969.
- Lund J. W., Gawell K., Boyd T. L., and Jennejohn D.: The United States of America Country Update 2010, *Proceedings* World Geothermal 2010, Bali, Indonesia, (2010) 1-18.
- Nordell B.: A Large-scale Borehole Heat Store During Five Years of Operation, *Proceedings* ISRM International Symposium, International Society for Rock Mechanics, Madrid, Spain (1988) 583-587.
- Pawlikowski B.: Dokumentacja geologiczna wierceń dla przyszłej instalacji otworowych wymienników ciepła w celach naukowo-badawczych, Miner-PBG Sp. z o.o., AGH w Krakowie (2008).
- Rohner E., Rybach L., and Schärli U.: A New, Small, Wireless Instrument to Determine Ground Thermal Conductivity In-Situ for Borehole Heat Exchanger Design, *Proceedings* World Geothermal Congress 2005, Antalya, Turkey, (2005) 1-4.
- Sapinska-Sliwa A., Hendel J., Durdziński P., Uruski Ł., Sliwa T., and Gonet A.: Analiza magazynowania ciepła w górotworze na tle systemów oceny oddziaływania obiektu na środowisko (Analysis of underground thermal energy storage on the background of evaluation systems of building influence on the environment), *Energy Policy Journal*, **17/1** (2014) 99-118.
- 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*, (2014) in press
- 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., Jaszczur M., and Gonet A.: Analiza numeryczna wpływu własności górotworu na transport ciepła wokół otworowego wymiennika ciepła (Numerical analysis of the rock properties effect on the heat transport around borehole heat exchanger), *SWCIM – 2010, Proceedings XIV Symposium Wymiany Ciepła i Masy*, Polska Akademia Nauk, Komitet Termodynamiki i Spalania, Zachodniopomorski Uniwersytet Technologiczny w Szczecinie, Katedra Techniki Ciepłej, Wydawnictwo Uczelniane ZUT, Szczecin, (2010) 551–562.
- Sliwa T.: *Badania podziemnego magazynowania ciepła za pomocą kolektorów słonecznych i wymienników otworowych (Research on underground thermal energy storage by use solar collectors and borehole heat exchangers)*, Wydawnictwa AGH, Kraków, (2012) 272.
- Sliwa T.: *Projekt porównawczych testów reakcji cieplnej próbnego wymiennika otworowego do projektu wykonawczego ujęcia i magazynowania ciepła dla obiektu „Ekologiczny Park Edukacji i Rozrywki OSSA” w przedmiocie „Zintegrowany system grzewczo-chłodniczy”*, Kraków (2007).
- 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.
- Wereszczyński P.: *Audytor OZC Wersja 3.0 Podręcznik użytkownika*, Narodowa Agencja Poszanowania Energii S.A., Warszawa (1999) 159.
- Zimny J.: Odnawialne źródła energii w budownictwie niskoenergetycznym (Renewable energy sources in low-energy buildings), Polska Geotermalna Asocjacja, Akademia Górniczo-Hutnicza, *Problemy Ekoenergetyki i Inżynierii Środowiska*, ed. J. Zimny, Warszawa, Kraków, Wydawnictwa Naukowo-Techniczne (2010) 355.