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ANALYSIS OF DRILLING AND WELL COMPLETION TECHNOLOGY FOR GEOTHERMAL WELLS IN POLAND AS A RESULT OF A EEA INTERNATIONAL PROJECT IN COOPERATION WITH ICELAND

ABSTRACT

Iceland is known to be a one of the leading countries in geothermal energy research, mainly due to its unique geological location and active volcanism. Around 90% of heating and hot water requirements in Icelandic households are provided by geothermal energy sources. Process of drilling a geothermal well is not an easy procedure as it involves consideration of many different aspects prior to drilling in order to avoid unexpected accidents and ensure safe drilling operations. Recent case studies from Iceland have shown that use of low enthalpy geothermal resources with heat pumps might be even more efficient than risky and expensive deep high-temperature drilling escapades. The geothermal drilling technology currently being in use in Iceland for low and high temperature geothermal wells and previous successful case scenarios are thought to be undeniably helpful for growing interests in low enthalpy geothermal resources in Poland.

In following work, many aspects related to drilling of geothermal wells in Lądek-Zdrój, Sochaczew and Konstantynów Łódzki are presented. Positive outcome of these drilling escapades will have a major impact on development of geothermal systems in Poland. Additionally, most important matters of well testing of mentioned wells are described.

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KEYWORDS

Geothermal drilling, geothermal boreholes, geothermal wells, design of geothermal boreholes

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INTRODUCTION

Iceland lies astride Mid-Atlantic range, boundary between Eurasian and North American tectonic plates, moving apart approximately 2 cm each year. As a result of such location, it is one of the most tectonically active countries in the world with perfect conditions for research and development of geothermal energy resources. Active rifting provides naturally high permeability, whereas volcanism, a major heat source for local geothermal industry (Sapińska-Śliwa et al. 2017).

In Iceland, high temperature areas are connected with active volcanic zones (e.g. Krafla, Reykjanes or Hengill) with well temperatures above 200°C at 1000 m, whereas medium temperature areas correspond to wells with temperatures lower than 200°C at 1000 m. Low temperature areas are present around the volcanic zones with well temperatures ranged between 70 and 100°C at 1000 m (Thorhallsson 2008). There are at least 250 low temperature and 26 high temperature geothermal areas registered in Iceland (Fig. 1).

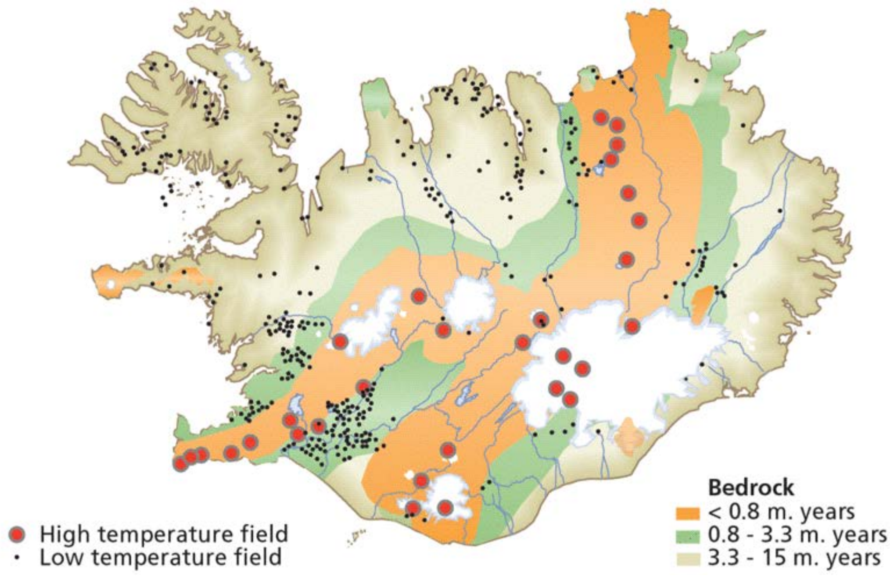

Fig. 1. Low and high temperature geothermal fields in Iceland (http://www.nea.is/geothermal/the-resource/)

Rys. 1. Nisko i wysokotemperaturowe obszary geotermalne na Islandii (http://www.nea.is/geothermal/the-resource/)

1. GEOTHERMAL DRILLING IN ICELAND

Geothermal drilling in Iceland uses drilling rigs derived mainly from oil and gas industry with hook load capacity varied between 5 and 350 t. The older type, kelly driven rigs and newer type, top drive drilling rigs are applied. Top drive, which rotates the drill string during drilling, can be powered by either electrical or hydraulic motor. Modern drilling rigs are equipped with automatic pipe handling system, which significantly reduces manual labour and associated risks. Old type rotary table and kelly drilling rigs are still being used in Iceland, due to proven performance, robust design and much lower costs (Thorhallsson 2008). Geothermal wells in Iceland are usually drilled with one, two or even three drill rigs (i.e. IDDP-1 and IDDP-2[1]). The first rig is used for pre-drilling (i.e. drilling the hole for conductor pipe in order to prevent hole collapsing). This operation can be performed with either truck mounted drilling rig, auger rig or cable tool rigs (last two much less popular). Iceland Drilling (icelandic drilling contractor) operates currently seven different rig types:

- Bentec Euro Rig 350 with theoretical depth of 6.0 km (used for IDDP-2),
- Drillmec HH-300 with theoretical depth of 5.5 km (used for IDDP-1),
- Drillmec HH-220 with theoretical depth of 4.0 km,
- Drillmec HH-200S with theoretical depth of 4.0 km,
- Gardner Denver 700E with theoretical depth of 3.5 km,
- Drillmec G-102 with theoretical depth of 1.8 km,
- Drillmec G-55 with theoretical depth of 1.3 km.

Bit program as well as final well diameter is selected in accordance with previous bit records from offset wells, investment costs as well as expected lithology (if available). Sizes of drill bits used are dependent on casing diameters and on cement wall thickness, which should be at least 1½” to ensure proper cementing operation and good cement bondage. It is popular drilling practice to use older drill bits for shallower and softer well parts. In Iceland it is common that the same bit and casing diameter scheme is applied. Similar situation occurs with depths for casing shoe.

Most common bit type while drilling geothermal wells in Iceland is conventional tri-cone roller-cone drill bit. Upper section might be sometimes drilled with milled tooth tri-cone bits or under-reamer (e.g. in IDDP-1), whereas deeper section with Tungsten Carbide Insert (TCI) tri-cone drill bits. If temperatures in reservoir are expected to be extremely high, bits with sealed bearings will be utilized (e.g. IADC 627). When well temperatures are lower, drilling fluid might be used as a lubricant and cooling agent for drill bit, thus no seals are required. The tri-cone type drill bits have proved performance while drilling geothermal wells in various geothermal fields in Iceland in different formation types. These bits are the most versatile and can be utilized in many conditions i.e. from softer to harder formation rocks. The bit life of TCI bits might be up to 1000 m without replacement. Polycrystalline Diamond Compact (PDC) bits, popularly used in oil and gas industry, are not as common in

[1] IDDP – Iceland Deep Drilling Project (www.iddp.is).

geothermal industry and are mostly utilized while drilling in softer, sedimentary formations. New bit technologies, such as hybrid bits, are being slowly introduced into geothermal industry, mainly due to high costs and lack of experience.

It was proven by previous researchers (Thorhallsson 2008) that actual time spent on making a geothermal well is between 30 and 40% of total project duration. The rest of time is spent on rig mobilization, demobilization, logging, cementing, well completion etc.

2. FUTURE DRILLING OF GEOTHERMAL WELLS IN POLAND

In section below, results from analysis of three planned geothermal wells in Poland has been presented. Two of them (Sochaczew and Lądek-Zdrój) have been already given a confirmation of financial backing from the National Fund for Environmental Protection and Water Management in Warsaw.

2.1. Well Sochaczew GT-1

In order to design a drilling program, data from offset wells has to be considered and thoroughly analysed. Based on previously applied drilling tools and achieved penetration rates, selection of the most suitable drill bits and Bottom Hole Assembly (BHA) is carried out. From well reports, information about well problems during drilling such as circulation loss zones, well stability issues or loose formations and cave-ins can be achieved. During drilling formations from Lower Cretaceous to final depth, interlayered quartz sandstone and mudstones might be particularly hard to penetrate. In such circumstances, it is crucial to apply drill bits and stabilizers for hard and not easily drillable rock formations. BHA should allow for applying appropriate weight on bit (WOB) in accordance with bit manufacturer's specifications. Once PDC bits are applied, mainly for hard and abrasive formations, down hole mud motor with MWD (Measurement While Drilling) system, allowing for continuous inclination and azimuth measurements is advised. Depending on the project's needs, LWD (Logging While Drilling) system, allowing for logging some of lithological parameters (e.g. gamma ray or resistivity) in continuous matter is advised. Additional drill bit selection, particularly for drilling production parts of the well should be performed, which exception of PDC bit type, might include conventional TCI tri-cone bits (e.g. IADC 517 or 537). Using MWD and LWD systems during drilling a geothermal well will enable to gain more control over drilling process and allow for continuous measurement of formation changes as well as saturation of formation rocks with geothermal waters. For vertical wells, proper BHA should be selected to ensure that an increase of deviation (dog leg) is kept not higher than 1°/30 m, whereas maximum inclination angle amounts to 1–4°. When necessity for well verticality occurs, RSS (Rotary Steerable System) system, that allow for control of well inclination with drilling parameters allowing for highest penetration rates, can be applied. The only disadvantage of RSS systems is the high market price.

Drilling of 12½″ well section to final depth might be time-consuming as a result of multiple bit runs and long tripping operations. Drilling of upper well sections, through Upper Cretaceous (240–1200 m), might require additional wiper trips, in intervals of 200 m, in order to control well stability. Afterwards, core runs may be performed. Subsequently, during drilling to final depth, previously used conventional or especially designed for drilling through hard quartz sandstone BHA might be implemented. After final depth is achieved, additional bit run with hole opener with diameter of 438 mm is advised. Penetration rates during drilling with hole opener are expected to be not higher than during conventional drilling due to expected hard formation rocks. Cementing operation of $9^5/_8$″ casing will require running caliper log, as casing strings are cemented with overlap. It is crucial to monitor fluid losses during drilling, as it might have significant influence on primary cementation job. Due to pumping chamber in upper well section, it is essential to lower $9^5/_8$″ casing strings as a liner. System of lowering casing strings should allow for locating liner hanger inside of $13^3/_8$″ casing section and simultaneously sealing annular space $9^5/_8$″ x $13^3/_8$″. It is essential to install appropriate equipment to accommodate liner on liner hanger and then free the drill string on which the whole casing section will be lowered and then cemented. Cheaper option will be to lower $9^5/_8$″ casing string and cut the upper section after it is cemented. This procedure is however much more dangerous, mainly due to possible leakage in the cement sheaths. During drilling production section, drilling fluid that does not deteriorate properties of the reservoir (i.e. permeability) and water quality should be used. Due to this phenomenon, weighting agents, such as barite, that might impair production zones and are difficult to remove during well cleaning operations, should be avoided. Well design should include drilling fluid that is the least invasive. Use of loss circulation materials (LCM) might have negative impact on future geothermal fluid production. Potential circulation loss zones should be sealed by cemented casing strings. Design of geothermal well in Sochaczew is presented in Fig. 2.

The Geological Works Design made for the Town of Sochaczew is very general, which is not necessarily its drawback. On the basis of the design it would be difficult to make a detailed Technical Drilling project, e.g. due to the lack of expected reservoir gradients and fracturing. This relates, first of all, to the way in which a borehole is secured during drilling, i.e. a set of preventers and an exploitation head. In case of a geothermal borehole, which may intake geothermal waters for the Town of Sochaczew, in specific geological conditions, a variety of high-pressure blowout preventer is not required. However it is recommended to have technical possibility of shutting the well in case of any unexpected water flow from the well. It is enough to install a standard simple head with a hanger for production pipes, with a downhole pump as a well completion. It does not stem from a Geological Works Design whether preventers are required or not. On the basis of the above-mentioned document, an Operations Plan for a given company is created, so a number of technical issues have to be made precise with persons involved in geology and drilling at the stage of preparing a bidding procedure. Based on the proposed mud density (1.05–1.25 g/dm^3), pressure gradients should be known, although they do not seem to be very high. There is no information about potential mud loss zones.

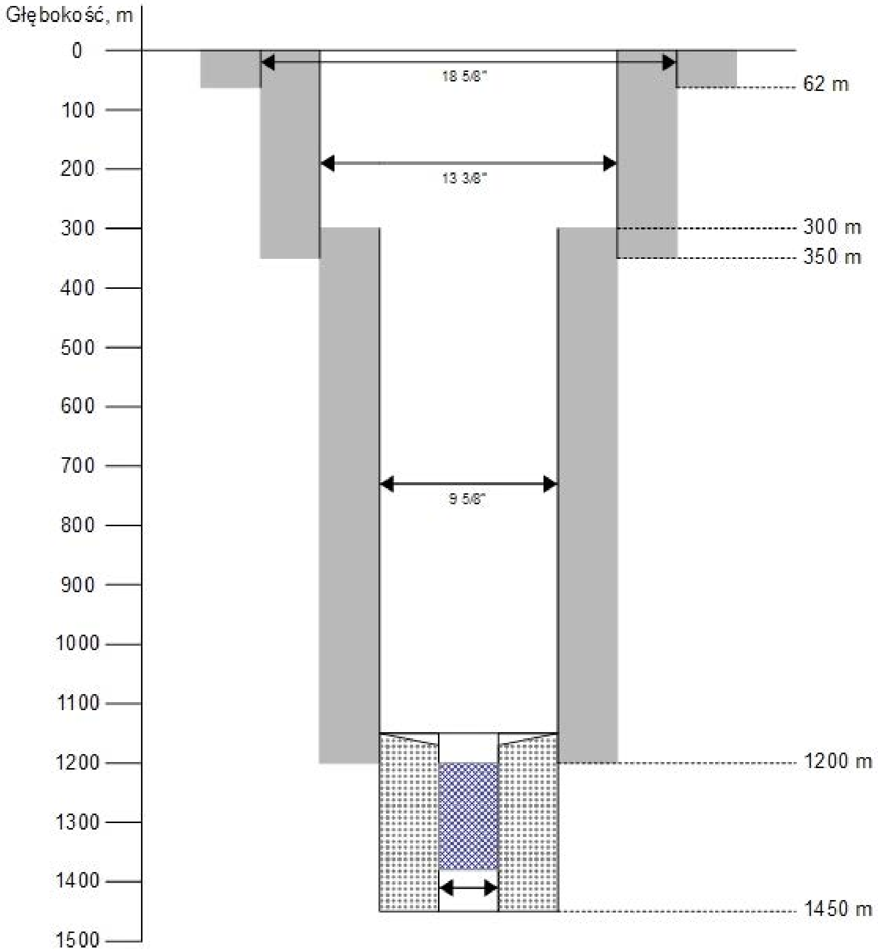

Fig. 2. Sochaczew GT-1 well design

Rys. 2. Konstrukcja zaprojektowanego otworu Sochaczew GT-1

At given mud densities, the use of carbonate blocker, building weight up to 1.25 g/dm^3, should be enough. Yet, additional blockers should be prepared during drilling, which is a standard anyway.

The documents anticipate a quite broad scope of IADC (International Association of Drilling Contractors) code for bits being proposed. However, it is not certain whether it will be possible to select a tool for fast drilling through Upper and Lower Cretaceous marls, particularly quartz sandstones. A dedicated bit for those sections would be a better solution, especially because drilling progress in such sandstones will not be very fast.

The size of the site for drilling has not been specified. The area of 0.9 ha stipulated in the design is not a large area, even more so that the area does not have a rectangular shape. Drilling rig position with backup equipment should be properly planned.

When applying large weight, it may be difficult to keep verticality, but the requirements regarding curvature cannot be found in the Geological Works Design. In general, it should be 1° per 1000 m. The occurrence of quartzite sandstones in the anticipated geological profile may slow down drilling significantly, in combination with a conventional drill pipe unit. As an option for borehole verticality any available on the market rotary steerable system can be applied, however the cost of the system is high.

2.2. LZT-1 well in Lądek-Zdrój

In Lądek Zdrój, drilling of a geothermal well is planned in order to assess hydrogeochemical properties of underground waters at depths below 1300 m. Additional outcome of planned drilling operation is to decrease carbon dioxide emission related to using coal for district heating purposes in Lądek-Zdrój. As a result of this, it is planned to drill diagonal wells from the inside of houses and tenements. Such boreholes will be equipped with inner pipes and the whole system will be working as a borehole heat exchanger (BHA). It would be beneficial to drill mentioned geothermal well in Lądek-Zdrój using Down-the-Hole (DTH) hammer technology, which will allow for higher penetration rates and enable to gain experience with following technology in Sudetes region. Wells with final depth of 100 m were drilled for heating purposes for nursery school in Lądek-Zdrój using DTH hammer powered by air. Despite water rich formations, it was possible to drill 2 geothermal wells in one day with only one tool. Drilling with DTH is typically easier in harder rocks than in softer and swelling formations. As an example, BHE drilled for Laboratory of Geoenergetics at AGH to final depth of 85 m, where clays and gravel were present, took much more time to drill. One DTH air hammer tool drilled one well with comparable depth in two days' time. Recommended technology for wells in Lądek Zdrój is water powered DTH. Water resources can be obtained from the river, which flows in the vicinity of planned geothermal well (Fig. 3).

Geothermal well in Lądek-Zdrój has been designed in two different variants depending on formation stability. First option is barefoot well (Fig. 4) without liner string, drilled with 8½″ (216 mm) drill bit. Second option is recommended for a geothermal well without good stability of boreholes' walls (possible loose formations) and assumes liner string below 1300 m (Fig. 5).

Drilling by means of a down-the-hole air hammer (DTH) to considerable depths is possible only when there are no aquifers. The application of special boosters enables obtaining very high air pressures. However, in Lądek-Zdrój one should expect groundwater inflow.

In case of water hammers, water inflows can be handled (water pressure in a borehole). Clean water required for a hammer can be obtained from a water course flowing near the planned drilling site. In case of right-hand mud (water) circulation, one can apply a water treatment system, which will remove a solid phase from water. Drilling in formations (gneisses) which are less susceptible to giving clay material to mud (such as clays or shales) would be achievable, due to easier control of the solid phase in water/mud. The hammer also

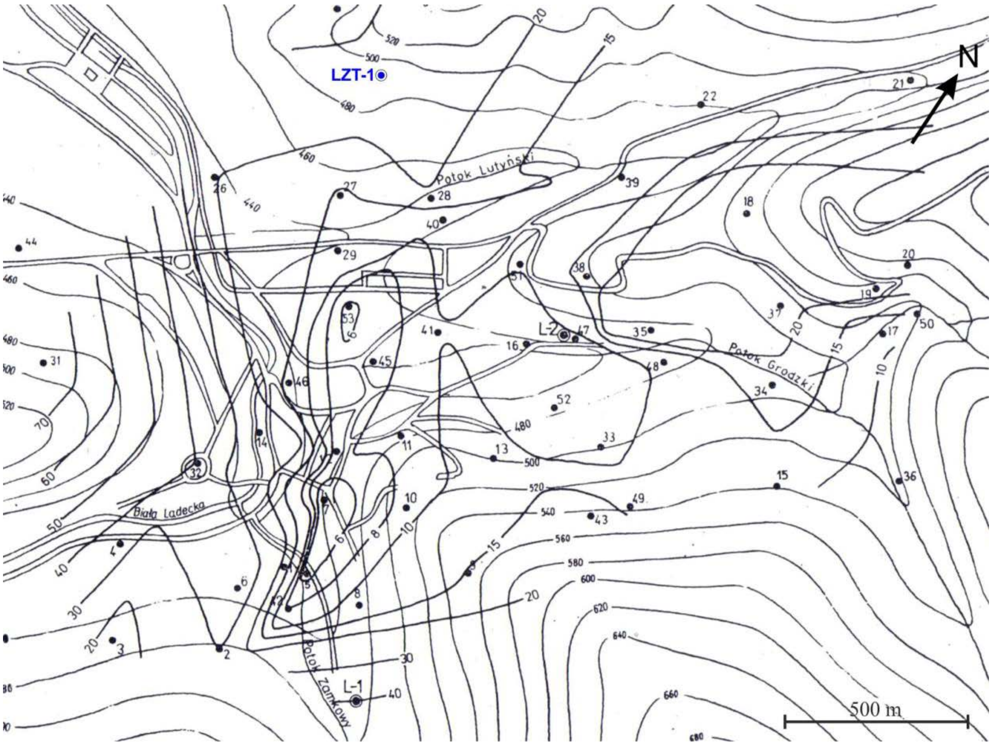

Fig. 3. Well LZT-1 on the map of geothermal anomaly in Lądek-Zdrój region by Szarszewska and Madej (1974a) and Ciężkowski (1980); countour lines of geothermal depth gradient in m/°C (after Ciężkowski et al. 2016)

Rys. 3. Lokalizacja projektowanego otworu LZT-1 na tle anomalii geotermicznej w rejonie Lądka-Zdroju, wg Szarszewskiej i Madej (1974a) i Ciężkowskiego (1980); izolinie wartości stopnia geotermicznego w m/°C (za Ciężkowski i in. 2016)

gives a larger shape of cuttings, which is much simpler to separate in the treatment system. The use of water from a stream seems to be a cheaper solution, but more permits have to be obtained.

The only argument against drilling with a DTH water hammer is only the fact that it is a pioneering project and the question is whether the Investor (municipality) would be willing to invest in experiments. The best solution seems to be bringing a DTH service team, which already has some experience. Employment of conventional equipment and, additionally, an external DHT maintenance team requires checking conventional equipment compatibility with equipment necessary for DHT.

NOV company has a *Fluid Hammer* in its offer, which may be an interesting technical solution. Based on the correspondence exchanged with the company, it seems that standard muds could be applied. Requirements are just as for typical motors (downhole hydraulic motors), i.e. suitable allowed solid phase content (granulation) and there are limitations in using materials for liquidating mud losses.

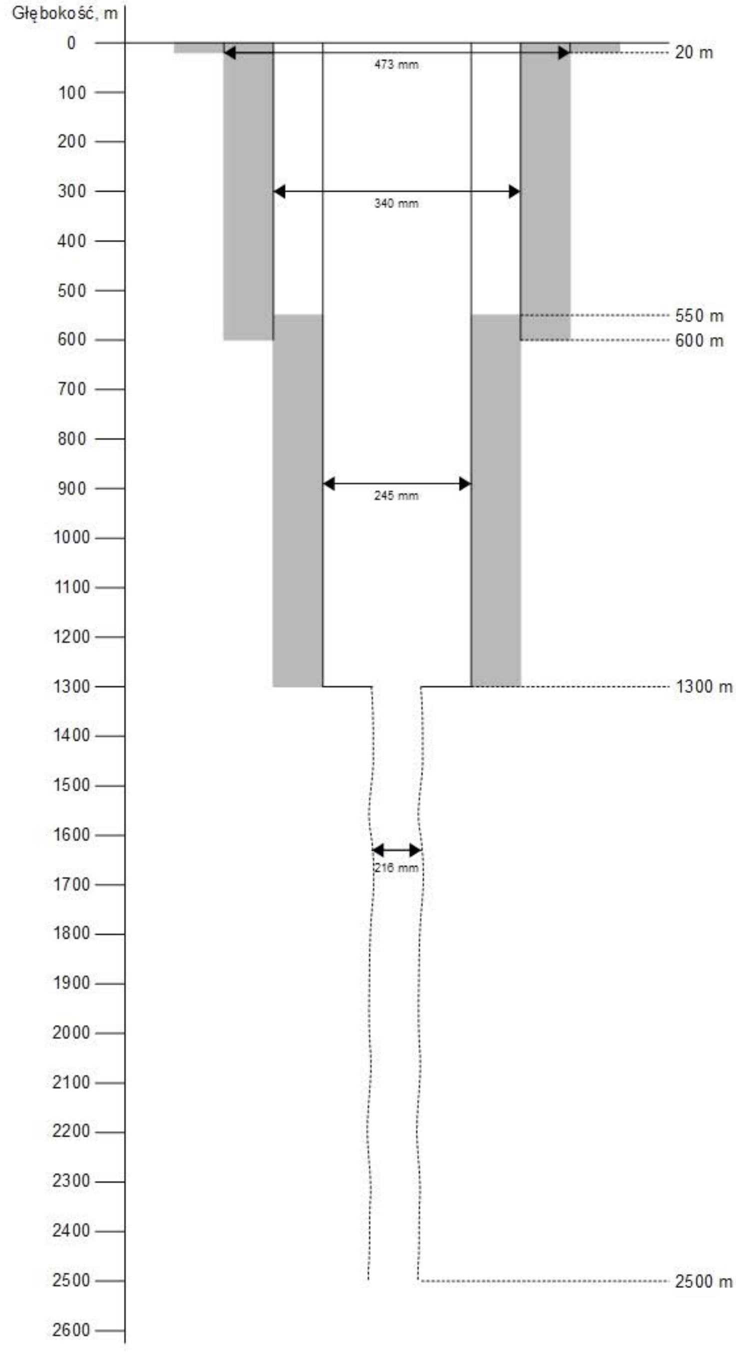

Fig. 4. Design of geothermal well in Lądek-Zdrój with barefoot section between 1300–2500 m

Rys. 4. Schemat konstrukcji otworu geotermalnego w Lądku-Zdroju z bosym interwałem 1300–500 m

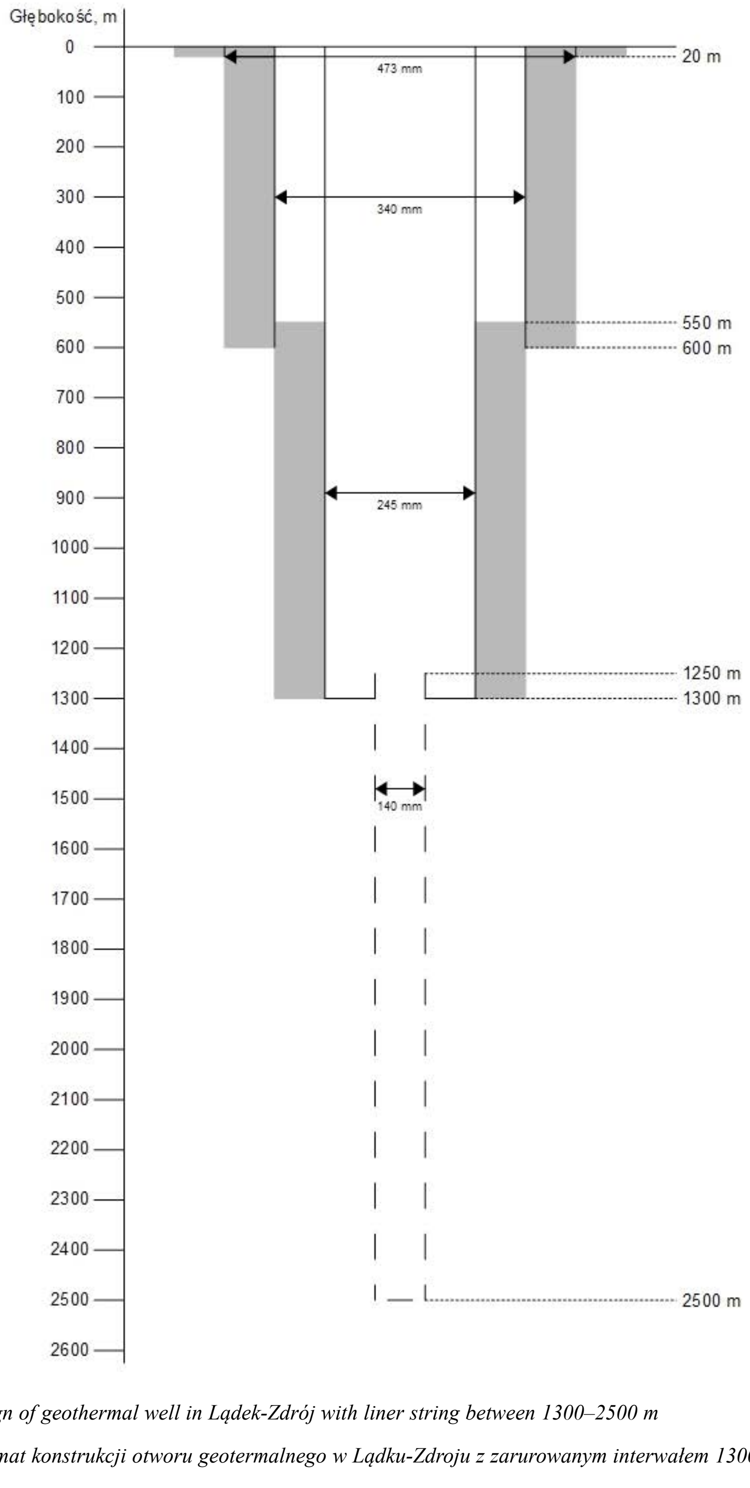

Fig. 5. Design of geothermal well in Lądek-Zdrój with liner string between 1300–2500 m

Rys. 5. Schemat konstrukcji otworu geotermalnego w Lądku-Zdroju z zarurowanym interwałem 1300–2500 m

However, a new technology relates to a higher risk/higher costs. Nonetheless, successful application of a new drilling technology in the geothermal sector in Poland can be very useful in the future, as it may reduce drilling costs considerably.

After the initial analysis, it seems that this tool is compatible with typical bottom equipment, with which a downhole motor works with. In the place of a motor in a bottom unit of a drill pipe, a *Fluid Hammer* is mounted. Elastomers are used to build it, so the operation principle is similar as in the case of a downhole motor, but additionally an impact on bit is generated. It is recommended to use an accelerator (a tool frequently working with drilling jars), which will probably magnify an impact and decrease vibrations transferred upwards by a drill pipe.

Depending on a budget, a 900–1200 KM device should be used for drilling. The unit should include two mud pumps, although one is enough in hydrogeological drilling. However, in case of deeper drilling, where losses are expected or complications relating to borehole stability, two pumps are used. Also, pumping rate is usually high using modern bits, so the application of two pumps working at the same time is a standard.

A more comfortable solution is the use of a Top Drive, and not a kelly. Apart from comfort of drillers' work, more borehole security is assured and trip speed, provided that borehole reaming is required.

Borehole structure is quite typical, so there are no special requirements, compared with devices with similar power, used in oil drilling. The issue of mud and a mud system depends on the applied drilling technique. The selection of mud planned for drilling determines the selection of a treatment system. A standard system is sufficient, such as on a typical device used for rotary drilling (unless a down-the-hole water hammer will be used, with closed water circulation – it is necessary to clear water more precisely). In general, after preparing a Geological Works Design, the investor prepares technical drilling and mud designs. On their basis, one can prepare a bidding procedure precisely.

Drilling techniques in hard and very hard rocks are used commonly in oil drilling. The use of high-speed motors or turbines, in combination with impregnated diamond bits is nothing special. With regard to deep geothermal systems, this issue has to be considered in a complex way. In combination with high temperature, which relates to equipment limitations (elastomers, motor sealing, etc.) and technological limitations (stability of mud parameters, bit cooling), drilling techniques in case of deep geothermal drilling pose a high challenge, especially in economic terms.

IDDP-2 drilling on Iceland shows that it is possible at reasonable costs. Replacement of costly motors and impregnated diamond bits with hammers would certainly be beneficial from the economic point of view. Also, the application of foam, air or water would be cheaper than a mud system with mud cooling. The issue which still has be resolved is cuttings lifting by means of foam, air or water from big depths, while preserving borehole stability. However, in case of hard rocks, such issues should not be a problem. A higher risk is posed by fractured water-bearing intervals. In such case, drilling with the use of water would be a better solution. One could also consider casing drilling, together with control of groundwater inflows or fluid losses.

To this end, it is necessary to obtain as much information as possible from the so-far performed deep drilling (over 4000 m) performed with hammers in South Korea, Australia and Venezuela.

2.3. Well Konstantynów Łódzki GT-1

Deisgn for geothermal well in Konstantynów Łódzki is presented in Fig. 6.

Glass fibre pipes in the designed borehole for Konstantynów Łódzki are designed in order to exploit highly mineralised Eearly Jurassic waters. Their configuration, 16″ x $9^{5}/_{8}$″, is proper provided that 16″ diameters of glass fibre pipes are available. The only thing which might be worrying is a too small cement lap, only 100 m. To obtain higher safety, the length could be larger. In case of ineffective cementing, or cement drop in the space of 16″ x $9^{5}/_{8}$″, it might turn out that there will be too little cement bound in this lap, and thus, the quality of cementing and sealing will be low. Such "precisely" calculated end-pointed cementing, and next, cutting of $9^{5}/_{8}$″ pipes may not give positive results. In case of slurry losses during cementing, it could be difficult to cement full 100 m.

Connection system of 16" fiber glass casing with lower part of wellhead need to be verified. It can be turned down or a slick lock could be used, but then a kind of wedges should be agreed, which are suitable for glass fibre pipes. It is also necessary to analyse resistance of 16″ glass fibre pipes to internal pressure, i.e. maximum expected head pressure. Nonetheless, if glass pipes are to create a pump chamber, their resistance kind should be sufficient. Even more so that the reservoir gradient is low, from 0.095 to 0.105 MPa/10 m and no gassing is anticipated.

$9^{5}/_{8}$″ casing are planned in a borehole in Konstantynów Łódzki at a quite big depth, so weights expected at the hook should be around 150 tonnes (e.g. 1000–1200 HP rig can be utilised). Presently, the requirements for drilling devices are often overstated, mainly due to their age and degree of exploitation. It would be safer to contract a device with a larger weight margin. Boreholes of the same depth as in Konstantynów are often drilled by means of 1200 HP rigs.

In relation to glass fibre pipe selection, it seems necessary to line a pipe ramp, a working platform and a catwalk, (V-door) with non-metal material ensuring pipe passing safe for them. A crane for piping could be also useful. It is recommended to employ specialist maintenance team to supervise making up fiber glass casing, with dedicated tools (hydraulic power tong with torque recording, *spider* slips, elevators and other auxiliary equipment\). When buying such pipes, it is worth requesting a respective specialist to supervise making up the casing; this service should be included in the price.

Fully professional drilling operation (yet costly) requires following services:

— logging unit controlling and recording drilling parameters and the mud system; it should be hired by the investor, independent from the contractor (although in case of turnkey contracts, this item is saved on) – such maintenance team is also responsible for collecting samples from outcrops, it cooperated with a geologist,

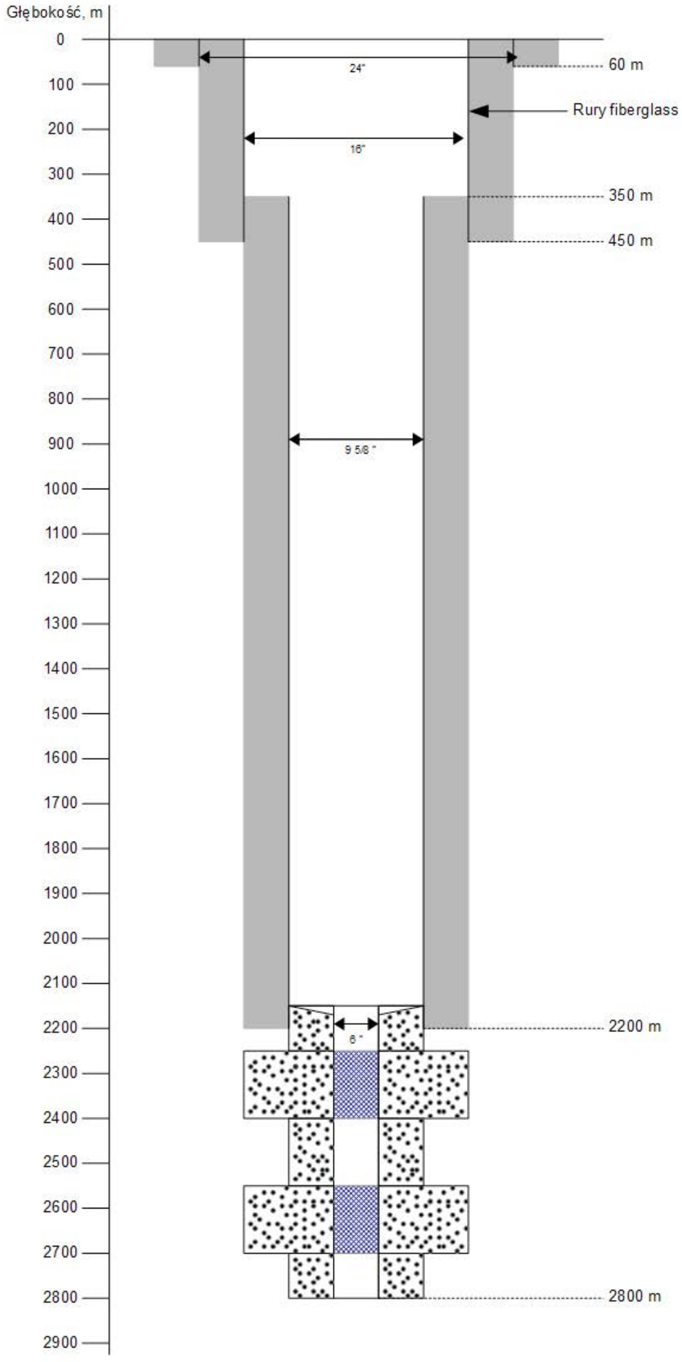

Fig. 6. Design of Konstantynów Łódzki GT-1 geothermal well

Rys. 6. Konstrukcja zaprojektowanego otworu Konstantynów Łódzki GT-1

- mud engineer with laboratory,
- inclinometer with slick line unit,
- servicing of cuttings disposal – vehicles with a container, excavator, a vehicle to dispose of waste mud (liquid waste),
- team for running glass fibre casing with dedicated equipment,
- cementing service,
- wireline well logging unit,
- fishing tools,
- coring services with equipment,
- drill stem testing,
- completion, i.e. a filter and pack,
- wellhead installation team – when buying a wellhead, it is worth to agree with the manufacturer its installation and pressure testing.

The scope of coring stems from the design: When drilling through Lower Cretaceous and Lower Jurassic formations, coring is anticipated in intervals indicated by geological supervision. Coring will be carried out by means of a coring instrument, ϕ 132 mm, whereas:

- within Lower Cretaceous formations – 1 trip,
- within Lower Jurassic formations – at least 5 trip.

It is assumed that the length of 1 trip will be 9 m. Assumed core yield: from 75% to 100%.

Within Lower Jurassic it is to be at least 5 trips. So, it is worth using an apparatus of the section length, i.e. 18 m. Performance 5 core trips, 9 m each, is a very long operation: ca. 10 days of coring and tripping. Therefore, the application of either a longer coring instrument should be considered (but then there is a risk of partial core loss), or the use of a drill pipe fitted for using a retrievable inner core barrel (unfortunately, this option is more expensive). It should be analysed what will be more costly: to use a core barrel or 10-day coring, 9 m each? Retrievable inner core barrel requires using drill pipes with inner diameter suitable for the core barrel diameter.

Coring with a core barrel is more and more often used if several core, 9 m each, have to be collected.

The proposed diameter of a core apparatus is 132 mm. A usually required core diameter is 100 mm. Although 85 mm is also used. In this case, it would be good to use a $8^1/_2''$ x 4″ core bit (4″ – core diameter) with a core apparatus, 18 m. This solution seems to be optimum – 3 trips, 18 m each, can be performed on the same drill pipe, which is used for drilling. Some Polish companies use a $6^5/_8''$ core bit, which would make it necessary to extend the borehole diameter later on.

As per the design, in a 216 mm ($8^1/_2''$) section, reaming to the diameter of 350 mm has been assumed. It is important to use a good quality reamers with cutting structure ensuring reasonable reaming progress, without a risk of losing its elements in a borehole. Operators often use services of foreign companies, which provide good quality tools to minimise the risk of complications in a borehole. Such a solution in case of a borehole in Konstantynów Łódzki seems to be the most appropriate one, even more so that reaming is from $8^1/_2''$ to almost 14″.

3. WELL LOGGING AND TESTING

The logs most relevant for the drilling operations are temperature, caliper and CBL logs along with gyro surveys, but several geological wireline logs are also done to study the rock formations of the well and with pressure tests, the permeability (or transmissivity) of the formation can be determined along with other formation parameters. In addition, spinner logging is often applied to estimate fluid flow in wellbores as well as inflow or outflow through feed-zones. Caliper log is used to locate washout zones and to estimate the volume of cement necessary to fill up the annulus between the casing and the formation.

The single most important parameters in geothermal well is the temperature. During drilling and soon after the temperature will give locations on feed-zones and possible the bottom hole temperature. It can take up to several months for the formation around a well to recover in temperature after drilling. It depends on the drilling method, time and type of formation drilled through. It is very important that geothermal wells should be temperature logged as close to the time of total recovery as possible. By logging the well soon after end of drilling and with increasing time between logs it can be estimated how long time is needed for total recovery. Temperature logs are used to locate feed zones and feed points and to evaluate the heating up rate (heat recovery) of the well after circulation is stopped.

3.1. Logs during drilling

During the drilling phase of a well temperature and pressure logging has a few different research purposes; firstly to evaluate well conditions regarding the drilling operation itself, secondly to locate feed-zones (inflow or outflow zones) and thirdly to estimate reservoir temperature and pressure. During drilling temperature and pressure are, however, greatly disturbed and it is difficult to estimate reservoir temperature and pressure accurately. Temperature is e.g. always lowered by drilling fluid circulation as well as being often affected by inflow or outflow through feed-zones or internal flow between feed-zones. Undisturbed temperature is sometimes approximated by measuring temperature warm-up during short breaks (sometimes overnight) in the drilling operation, either planned or unplanned. Then the temperature recovery is measured as a function of time at a specific depth (often well bottom) and particular methods, such as the Horner method, used to assess the undisturbed temperature. The application of temperature and pressure logging will be discussed further below (Axelsson and Steingrímsson 2012).

3.2. Logs at end of drilling (completion)

At well completion reservoir physics research kicks in at full force, with the main purpose being to assess the result of the drilling operation. If the outcome is deemed satisfactory the drilling operation is stopped, otherwise drilling may be continued to greater depth or a program of well stimulation may be initiated. The main phases of conventional completion program for a geothermal production well are as follows:

— temperature and pressure logging, sometimes accompanied by spinner logging, to evaluated location and relative importance of feed-zones as well as temperature conditions prior to later phases of the completion test (due to temperature limitations of instruments used),
— geophysical logging and fracture imaging of the production part of the well,
— step-rate well-testing; through injection or production. Pressure (and sometimes temperature) transients measured down-hole,
— temperature and pressure logging is normally performed after, sometimes even during step-rate testing. Spinner logging can be beneficial to assess feed-zones.

3.3. Well tests

The purpose of the step-rate well-testing, which is the main reservoir physics research conducted at the end of drilling a well, is to obtain a first estimate of the possible production capacity of a well and to estimate its production characteristics. Step-rate well-testing usually lasts from several hours to a few days. The following are the parameters usually estimated on basis of step-rate test data:

— injectivity index, defined as $II = \Delta q/\Delta p$, with Δq the change in flow-rate and Δp the change in down-hole pressure, usually based on measured values at the end of each step. In the case of low-temperature wells tested through production step testing a comparable index is defined, termed productivity index (*PI*),
— formation transissivity or permeability-thickness defined as $T = kh/\mu$ (or $kh\rho/v$) and kh, respectively, with k the formation permeability, h the reservoir thickness, μ and v the dynamic and kinematic viscosity of the fluid, respectively, and ρ the fluid density,
— formation storage coefficient defined as $S = sh$ (or shg), with s the storativity of the geothermal reservoir involved, h its thickness again and g the acceleration of gravity. The storativity (with units $kg/(m^3Pa)$) describes the storage capacity per unit reservoir volume and depends on rock and fluid compressibility, free surface mobility or phase change activity (two-phase storativity),
— skin factor of the well, which describes an additional pressure drop next to a well due to so-called wellbore damage, often caused by clogging of formation pore-space by drilling mud. A negative skin factor, however, reflects a well with stimulated near-well permeability,
— wellbore storage capacity, which simply depends on wellbore volume and the well-fluid com-pressibility.

The injectivity index (as well as the productivity index) is a simple relationship, approximately reflecting the capacity of a well, which is useful for determining whether a well is sufficiently open to be a successful producer and for comparison with other wells. It neglects however transient changes and turbulence pressure drop at high flow-rates.

The pressure can either be measured as down-hole pressure, depth to water-level if pumping from the well is required or well-head pressure if flow from the well is artesian.

The permeability-thickness (item (b)) and storage coefficient (item (c)) are estimated through an analysis of pressure transients measured during completion well-tests (called pressure transient analysis), which is a more accurate analysis than involved in the simple estimation of an injectivity index.

3.4. Logs during warm-up

After the drilling of a geothermal well is completed a well is usually allowed to recover in temperature (heat up) from the cooling caused by drilling fluid circulation and cold water injection. How long depends on local conditions and the development project being followed, but this usually takes a few months. The principal reservoir engineering research conducted during this period is repeated temperature and pressure logging. The temperature data thus collected is used to estimate the undisturbed system temperature, often called formation temperature, as wells usually does not recover completely during the recovery period.

3.5. Logs during output testing

In the case of lower temperature wells either sufficient overpressure in the reservoir, which creates free-flow (artesian) from wells, or pumping, is required for output testing.

The productivity of geothermal wells is often presented through a simple relationship between mass flow-rate or production (measured as mentioned above) and the corresponding pressure change, either in down-hole or well-head pressure, as a first-order approximation, as already discussed (see discussion on injectivity/productivity above). This relationship is often termed production characteristics or well deliverability (output curve). In general the productivity of geothermal wells is a complex function of well-bore parameters (diameter, friction factors, feed-zone depth, skin factor, etc.), feed-zone temperature and enthalpy, feed -zone pressure, reservoir permeability and storativity, well-head pressure or depth to water level during production and temperature conditions around the well.

CONCLUSIONS

1. Iceland is a pioneer in the geothermal energy development of low and high temperature systems.

2. Drilling contributes the most to the total project costs of any geothermal well. A reliable and safe well design based on good drilling experience is the first step to an effective and productive geothermal system.

3. Investment costs of drilling operations in hard and abrasive rocks might be considerably decreased, when new technologies such as Down-The-Hole fluid driven hammer are utilised.

4. Well logging and hydrogeological production tests will undeniably help selecting appropriate well completion techniques. Mathematical modelling can be a useful tool to forecast fluid production from geothermal reservoirs.

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ANALIZA TECHNOLOGII WIERCENIA ORAZ KONSTRUKCJI OTWORÓW GEOTERMALNYCH W POLSCE JAKO REZULTAT MIEDZYNARODOWEGO PROJEKTU EOG WE WSPÓŁPRACY Z ISLANDIĄ

STRESZCZENIE

Islandia, dzięki swojej unikalnej geologii, dużej aktywności wulkanicznej, jest obecnie krajem, który przoduje w rozwoju energetyki geotermalnej. Około 90% zapotrzebowania na ogrzewanie oraz gorącą wodę na wyspie jest

dostarczane dzięki energii geotermalnej. Proces wiercenia otworu geotermalnego jest wysoko skomplikowanym zabiegiem. Wymaga uwzględnienia wielu różnych czynników jeszcze przed rozpoczęciem projektu, aby zapobiec niespodziewanym wypadkom oraz zapewnić bezpieczne urabianie górotworu. Ostatnie wiercenia na Islandii pokazały, że użycie instalacji geotermalnej niskich entalpii wraz z pompą ciepła może okazać się bardziej efektywne niż kosztowne oraz ryzykowne wysokotemperaturowe, głębokie wiercenia geotermalne. Technologia wiercenia otworów geotermalnych niskich i wysokich entalpii na Islandii oraz udane przypadki otworów o dużej produktywności niewątpliwie pomogą w rozwoju energetyki geotermalnej, szczególnie niskich temperatur, w Polsce.

W pracy opisano wiele zagadnień związanych z planowanymi do wykonania otworami geotermalnymi w Lądku-Zdroju, w Sochaczewie oraz w Konstantynowie Łódzkim. Pozytywny efekt wiercenia tych otworów ma duże znaczenie dla rozwoju geotermii w Polsce. Dodatkowo opisano najważniejsze zagadnienia związane z testowaniem wykonanych otworów pod kątem zasobów.

SŁOWA KLUCZOWE

Wiercenia geotermalne, otwory geotermalne, odwierty geotermalne, konstrukcje otworów geotermalnych

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