Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Review on the reservoir engineering and operation of 16 MW Yangyi geothermal project

Haibing Shao[1,*], Feng Luo[2], Chaofan Chen[1], Shanmin Wang[3] and Xiaolin Chen[2]

[1]Helmholtz Centre for Environmental Research – UFZ, Permoserstr. 15, 04318 Leipzig, Germany
[2]Yangyi Geothermal Power Plant, Yangyi Village, Dangxiong County, 851512 Tibet, China
[3]Tibet Geothermal Industry Association, Lhasa, 850000 Tibet, China

*Haibing.Shao@ufz.de

Keywords: Yangyi; Geothermal Power Production; Organic Rankine Cycle; Binary Plant; Operation and Maintenance.

ABSTRACT

The Yangyi geothermal field is located in Tibet, China. It was first explored in the late 1980s and early 1990s. The Yangyi geothermal reservoir was estimated to be a medium- and high-temperature reservoir. By 2012, 2x500 kW screw expanders were installed on site by the previous owner operator. In 2016, 2x2MW screw expanders units were added additionally. However, due to a failed 72h pilot-scale power production test, the two big units could not be connected to the grid. In 2015, Hangzhou Jinjiang Group became the new owner operator of the plant, bringing in additional financial investments along with a completely new operation team. Due to the low system efficiency with the old units and severe calcite scaling in production wells, the new owner ceased the operation of the screw expanders.

From 2016 to 2017, a series of reservoir exploration and development work was carried out, including gravity and magnetic-telluric surveys, well repair and logging, production and re-injection tests. Based on a comprehensive evaluation and interpretation of all available data, ZK203 and ZK208 were chosen as the production wells, while ZK403 is converted to the re-injection well. After confirmation of the resource, a 16 MW Organic Rankine Cycle (ORC) based binary power plant was purchased from Ormat Inc and installed on site for the Phase I project. In October 2018, the power plant was connected to the grid, starting from just a few MW and slowly increasing its output. In Feb 2019, after resolving several technical issues, the power plant reached its 16 MW full capacity power output.

Before the start of the production, a downhole inhibitor injection system was installed in both production wells, and calcite inhibitor is continuously injected and mixed with the geothermal fluids. After overcoming several technical difficulties, the injected inhibitor completely resolves the calcite scaling problem, as no scaling minerals are observed in either the wellbores or the separator. Shortly after the start of power production, a long-term tracer injection and monitoring program was conducted. Based on the one-year observation data, it is confirmed that the re-injected geothermal brine flows back into the production well after just a couple of days in the 200~400m shallow reservoir. Despite of the short retention time, the thermal decay in production temperature is very limited. From 2019 to 2022, a minor temperature decrease is observed in the production wells. Although the power output of the plant is only marginally influenced, a deeper re-injection well is recommended to completely remove risk of thermal breakthrough in the future.

In average, the geothermal brine and steam are produced from the two wells at a combined total flow rate of ca. 650 t/h. With a dryness factor of 10%, the separated fluids enter the plant at 143℃. At the outlet of the preheater, the re-injection brine temperature is kept around 60℃ to prevent potential silica scaling. With this setting, a gross power output of 15.92 MW can be achieved in average. With about 11% auxiliary power consumption, a net production of 14.17 MW can be sold to the grid. From 2019 to 2022, the annual net power sale accounts for 88.9, 110.4, 113.1 and 96.8 GWh. Since the feed-in tariff scheme for geothermal power production has not been finally determined yet, Yangyi currently only receives a price of 0.25 RMB/kWh from the state grid. This price is considerably lower than other renewable power sources such as wind and photo-voltaic. Although the plant has a positive cash flow in the last 4 years, when the depreciation of equipment is calculated, the Phase I project still has a negative investment return. Considering the strong will of reducing carbon emission by the Chinese government, the owner of the plant is expecting a more favorable sale price for the geothermal power. The Yangyi Geothermal Power Plant remains confident to extend its capacity, and has made a detailed drilling plan for a new 15~16 MW plant in the Phase II project. The successful deployment and operation of Yangyi project show that geothermal energy can make considerable contribution to achieve China's carbon neutrality goal by 2060.

1. INTRODUCTION

The Yangyi geothermal reservoir is located to the west side of Yangyi Village in the south of Jida Township, Dangxiong County, Tibet Autonomous Region of China. It is about 72km away from Lhasa, the capital city of the region. The Nimu Highway passes through the east side of the work area (see Figure 1). The production and re-injection wells are located at 4700~4800m elevation, while the power plant is at 4650 m (N29.725894, E90.383095, WGS84). Therefore it is one of the highest geothermal power plants in the world. The exploration and development of Yangyi started in the late 1980s. After the completion of Yangbajain geothermal power plant, Yangyi was considered to be the second best geothermal resource in the region and most promising for commercial development. In 1988. The Tibet Geothermal and Geological Survey team completed the field exploration of the reservoir and submitted the final report (Liang et al., 1990). On Dec 23, 1991, the National Mineral Resource Committee reviewed the report and approved the decision of developing a geothermal power plant in Yangyi. Unfortunately, not much work was conducted in the 1990's, due to the lack of funding.

Starting from late 2000, geothermal energy sector starts to attract interest again. Surface geological survey and geochemical exploration work were supported in form of scientific research projects. Wang and Guo (2010) reported the result of surface geological survey conducted in Yangyi. Guo (2012) summarized the data obtained from the geochemical exploration, which can also be found in Zheng et al. (2013). Since 2011, China Huadian Group made considerable investment in Yangyi and officially started the commercial development process. During the process, several new wells were drilled, and pressure-temperature logging of these wells were reported (Zheng et al., 2016). By the end of 2012, 2x500 kW screw expanders were installed (Yu et al., 2015). In 2016, 2x2MW screw expanders units were also added. However, due to the failed 72h pilot-scale power production test, the two big units were not connected to the grid. In 2015, Hangzhou Jinjiang Group became the new owner of Yangyi project, bringing in additional financial investment along with a completely new operation team. This proceeding provides a review on the commercial development workflow conducted in Yangyi since 2016. It covers the additional geophysical survey, well testing and logging, tracer tests, and the current reservoir conceptual model. This proceeding also provides major operational data such as the evolution of wellhead temperature and pressure, flow rate, power production and financial analysis. As Yangyi is the only newly-built geothermal power plant in mainland China in recent years, a lot of lessons have been learned from this project and will be discussed in detail. General suggestions are made in the end for stake holders who are interested in the Chinese geothermal power industry.

2. YANGYI RESERVOIR

2.1 Geology of the Yangyi reservoir

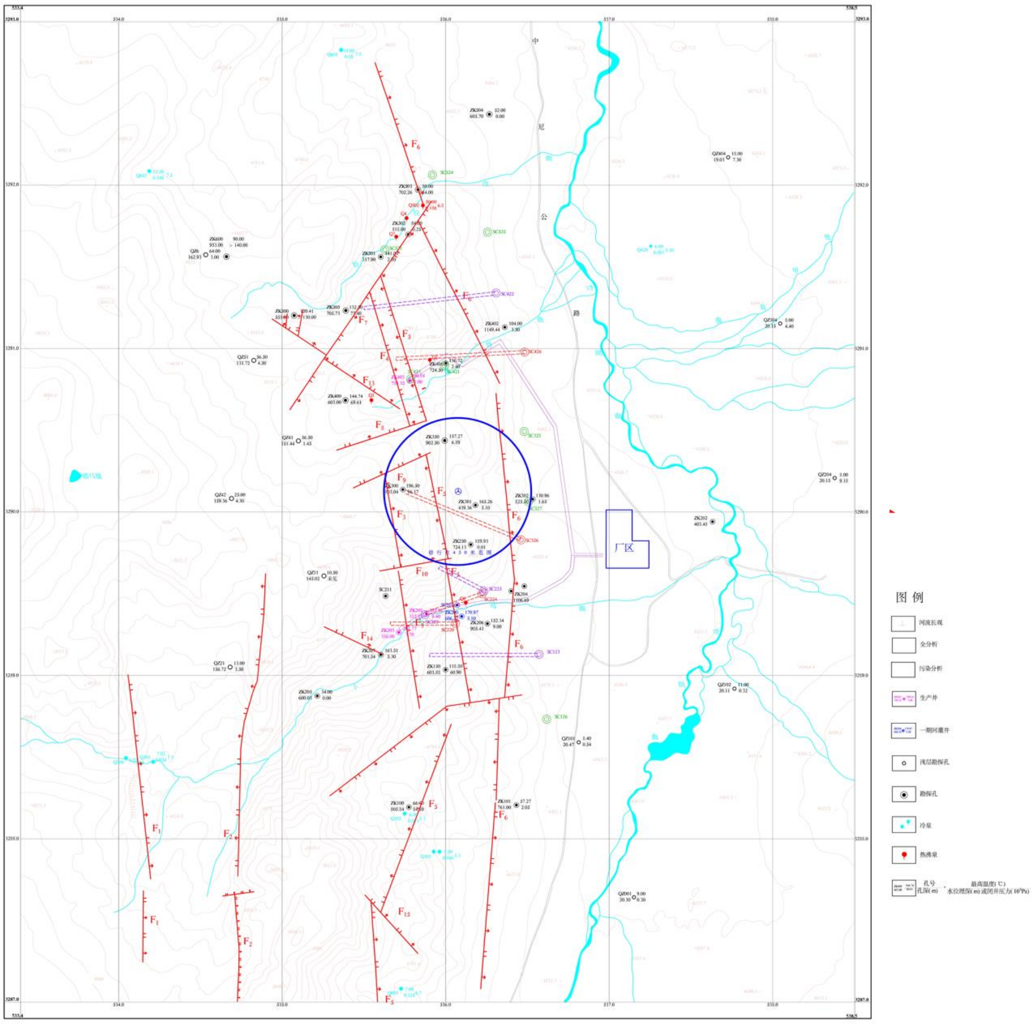

Figure 1: Wellhead position and major fracture distribution in the Yangyi geothermal reservoir, with a scale of 1:10000.

The surface geology of Yangyi is dominated by a horst structure stretching from north to south. Several major normal faults have developed in same N-S direction (red lines in Figure 1). In perpendicular direction to the major faults, secondary fractures are also present and clearly identified from the surface. An uplifting structure can be identified, characterized by the mountain ridge stretching in the same N-S direction. The elevation is the highest around the 300-series wells, and gradually dropping to 4700 m both to the north and south end. Close to the ZK301 well, a traditional small Tibetan Buddhism temple can be found. This forms a 300-m radius no-construction zone (the blue circle in Figure 1), in which no new drilling or installation activities have to be approved. Outside the uplift area to the east, flat river basin has an elevation of 4650 m, providing ideal location for the current binary power plant (blue rectangle in Figure 1).

When combining the surface geological survey and historical well profile, the Yangyi geothermal system is believed to be hosted in the granite porphyry basement layer. According to the drilling profile, the average depth of the basement granite is more than 1200 m. It is Cretaceous to early Tertiary rocks related to the Gangdese batholith process. The basement is overlaid by Miocene (Neogene) trachy-andesite layer, suggesting historic volcanic activities. The andesite layer is interbedded with tuff (ash to lithic facies), and also pyroclastic flows. The andesite layer is thicker in the north, and thinner to the south. Above and also between the andesite layers, older and younger alluvium interlayers are identified in the drilling log, with sand, clay and conglomerate in composition. The alluvium sediment typically covers the 0 to 600 m. The older alluvium layer found in the high elevations is believed to be uplifted by recent tectonic and faulting activities. To the east of the horst structure, at location of the power plant, similar alluvium layers can be found in the river basin.

2.2 Geophysical Exploration Results

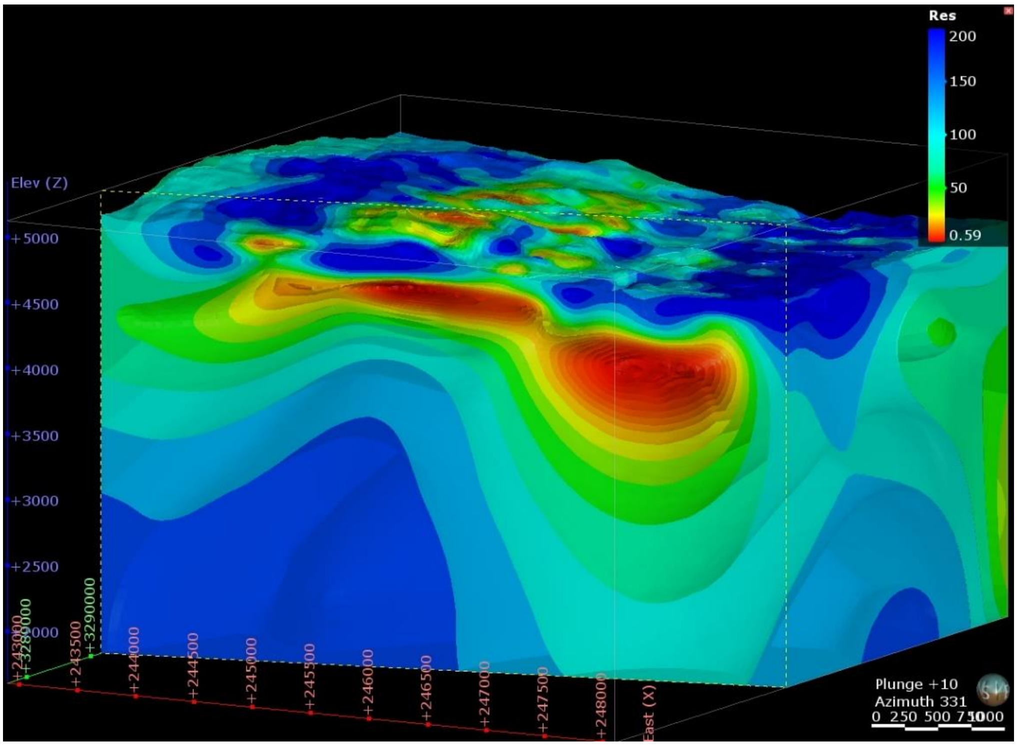

Figure 2: North-South cross section of magnetic-telluric exploration result, with color illustrating inverted apparent resistivity values in Ohm meter (Spielman et al., 2017).

In 2017, a series of geophysical and geochemical surveys were conducted on the Yangyi site. From the previous owner, Controlled-source Audio-frequency Magnetotellurics (CSAMT) survey results were available and had been inverted to produce 2D vertical cross-section profiles of apparent resistivity. However, the CSAMT survey is mostly suited for a depth less than 1000 m. Although the profile gives certain hints on the underlying structure, a more detailed magnetotellurics (MT) exploration was added to reveal more information down to a depth of 4000 m. A total of 91 MT stations were measured on site, with approximately 500 m distance between the stations. Multiple round of calibration was conducted to assure the quality of the data. After the MT survey, inversion was performed to produce the 3D distribution of apparent resistivity value in Ohm-meter, as illustrated in Figure 2. Usually for loosely packed alluvial layers, its apparent viscosity values are very low, which is dominated by water stored in the pore space. Low resistivity zones may also be found in layers with high content of clay minerals like kaolinite and illite. They are typically present in geothermal reservoirs due to hydro-thermal alteration. Here in Figure 2, two low resistivity zones can be observed. They are marked with yellow-to-red color, indicating a resistivity value lower than 3.5 Ohm meter. Among the two zones, the northern one is rather shallow, with an average burial depth of 200~400 m. This shallow reservoir extends from the 200-series wells toward north to the 400-series wells, and finally connects with the surface at places of the 500-series wells. Another low-resistivity zone, is much larger and buried also deeper. It is to the south of the 200-series wells and has a depth from 600 to 1500 m. These two zones are believed to be a single permeable reservoir composed of alluvial sediments at the beginning, and then broken apart due to volcanic and faulting activities. The result of this structure movement is a deep-cutting falling-wall structure along the 200-series wells. The fault and also filling alluvial material not only connects the two zones, they also provides fluid flow pathway for the deep geothermal fluid to move upward (see also the conceptual model in section 2.5). The two most productive wells, namely ZK203 and ZK208, are both located along this structure. Due to the high permeability of the fault, the wellhead pressure measured under shut-in condition can reach 8 bar and 12 bar at the two wells accordingly.

2.3 Well repair and tests

When the new management team took over the Yangyi project, a total of 33 wells can be found in record. Most of these wells were drilled in the 1990's and do not exceed a depth of 300 m. These are all vertical wells and located along the 5 different fracture zones from the south (100-series) to the north (500-series). Most of the wells do not have much productivity or just have limited flow rate. Wells that are still repairable and have considerable flow rate were screened out and repaired. All the repaired wells were installed with new wellheads equipment so that they can be properly logged and operated.

For these productive wells, PT logging were performed to give hints on the possible permeable zones and location of the fractures. Production tests were conducted on several potential wells, measuring the response of Well Head Pressure (WHP) versus flow rate under different main valve opening positions. Such valuable data is further derived to calculate the dryness factor of the geothermal fluid, and further be used to predict its behavior under full production condition. Combined with static and dynamic PT logs, which were performed under shut-in and production conditions, specific wellbore models can be calibrated using the data obtained from these tests (see the green curve in Figure 3). For example, the wellbore model predicts that ZK208 should be able to produce about 370 t/h of total fluid with 8 bar of WHP (the turning point in the green curve), which was proven to be very close to the real flow rate in full-scale production condition.

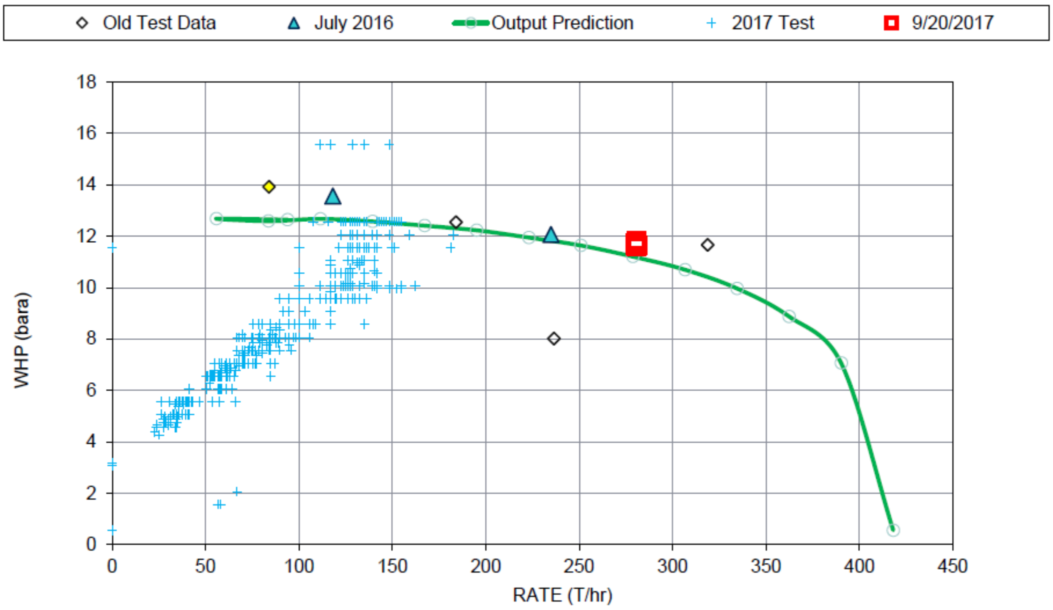

Figure 3: ZK208 Production test data, together with fitted wellbore model for flow rate prediction (Spielman et al., 2017).

2.4 Production and Injection Wells

For a 3-month period from May to July 2017, short-term tracer test was conducted along with the production and injection tests. Five different tracers were injected in each of the five injection wells (SC211, SC202, ZK200, ZK402 and ZK503), while samples were collected at the three potential production wells (ZK203, ZK208 and ZK403). The monitored tracer concentration is illustrated in Figure 4. The major results of the short-term tracer tests are follows,

- SC211 tracer was found to return to ZK203 in high concentration. This means SC211 cannot be used for re-injection.
- SC202 tracer returned to ZK208 in moderately high concentration. Therefore SC202 may only be useful for small amount of injection for a limited time.
- SC202 tracer also returned to ZK403 in low concentration, confirming high north-south fluid flow connection.
- ZK200 tracer returned to ZK208 in low concentration, meaning ZK200 can be used for injection.

With the above results from short-term tracer test in mind, it is clear that the 200-series wells have very good connectivity between them. Considering ZK403 has relatively lower production flow rate, and also is far away from the 200-series production zone, the Yangyi team decided to use ZK203 and ZK208 as the production well, and convert ZK403 into a re-injection well. On one side, this is a financially optimum arrangement, as all existing wells can then be utilized to set up a hydro-thermal circulation, with no new investment to drill new wells. On the other side, there are potential hydraulic connections between the 400- and 200-series wells. It is not clear to reservoir engineers how fast the cold fluid will return back to ZK203 and ZK208. This potential risk needs to be properly addressed during the production.

Following this thought, the long-term tracer test was conducted right after the power plant start. On March 18, 2019, a 100-kg pack hydro-soluble fluorescent tracer (1,3,6,8-pyrenesulfonic acid tetrasodium, also written as 1,3,6,8-PTSA) was first diluted into 1 m^3 of geothermal brine and then injected into ZK403. Continuous sampling at ZK203 and ZK208 was conducted for a period of over 8 months. At both production wells, the 304L stainless steel tube was formed into a coil shape and connected with the sampling port on the wellhead. The fluid sample passes through the coil, which is submerged in a cold water bucket, and being controlled by a valve to make sure the two-phase geothermal fluid from the well was fully cooled down to lukewarm liquid phase. The collected water samples was then sent to the lab to measure the tracer concentration. In the first month, samples were collected every day. Thereafter, the sampling interval was gradually increased to once a week and later every two weeks. The tracer breakthrough curves observed at the two wells are depicted in Figure 5. For ZK208, peak tracer concentration of over 500 ppb was observed after 4 days from injection. For ZK203, the peak comes much later in 45th day. This suggests that ZK208 is hydraulically well-connected with ZK403. In comparison, the flow path to ZK203 is much longer.

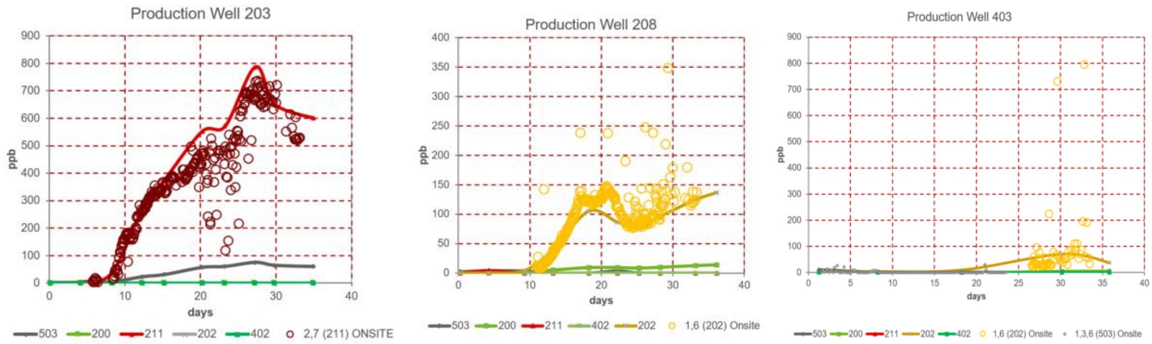

Figure 4: Monitored concentration profiles during the short-term tracer test from May to July 2017 (Spielman et al., 2017).

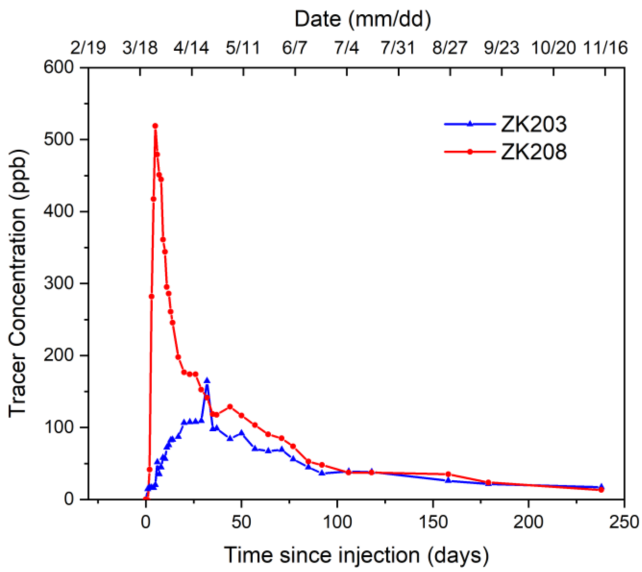

Figure 5: Monitored concentration profiles during the long-term tracer test in 2019 (Shao et al., 2021).

2.5 Conceptual Model of Yangyi Geothermal Reservoir

Combining information collected from the geophysical exploration, well production and re-injection tests, as well as the tracer profiles, the reservoir engineers of Yangyi and experts from Ormat achieved agreement on the conceptual model of the reservoir. This conceptual model is well illustrated as in Figure 6. Deep beneath the reservoir, partial meltdown and historic volcanic activities heat up the deep circulating groundwater and form the high pressure, high temperature geothermal fluids. The fluids upflow in the southern part of the reservoir and move upwards in the fault along the 200-series wells. Through fracture F3 and F5 (see Figure 6), the fluids continue to move north horizontally. During the movement, hot springs and fumaroles show up when the flow path connects with the surface. The highest point of hydraulic head can be found at ZK300, located on fracture F10. After crossing F10, the fluids enter highly permeable alluvial zone, which is rather shallow with a depth of 200~400 m. The geothermal fluids are finally discharged to the surface in forms of small hot springs. From the 200- to the 500-series wells, high-temperature geothermal fluids gradually mixes with cold surface recharge water, while heating up the surrounding sediments. Along with the movement, the highest temperature measured in the wells gradually drops, from >180 °C at the 200-series wells, down to 160 °C at ZK300, and finally to ca. 140 °C at ZK403.

3. OPERATION HISTORY

3.1 Pre-production operation

For the decision of which technology to adopt for power production, the Yangyi project made several failed trials. The Yangyi Geothermal Power Plant Ltd was founded in 2011 with major investment from China Huadian Group. In Sep 2011, the first 500 kW two-phase screw expander machine (also known as total flow machine) was installed on site and started pilot-scale production. It was quickly found that continuous production cannot be achieved due to scaling issue. In April 2012, a second 500 kW screw expander was installed and being operated together with the first machine in an alternative mode. Both installations have not considered brine re-injection to sustain the reservoir pressure. In Oct 2016, a 2-MW steam-based screw expander was installed on site. Test production was conducted for a short-period of time, but was not successful. One of the screw components developed a structure crack under the impact of condense water, causing the system to stop operation. After this failure, the Yangyi Geothermal Power Plant went through the corporate restructuring and reorganization. Subsequently, Hangzhou Jinjiang Group became the new majority shareholder in 2015. The new management team completely reviewed the reservoir engineering work and change the power plant technology from screw expanders to Oragnic Rankine Cycle (ORC) based binary plant. Along with the necessary geophysical exploration and well repair, the Ormat geology team was contracted to provide technical consultancy on the reservoir engineering work. At the same time, agreement was signed to purchase major equipment for a 16 MW binary plant from Ormat. By Sep 6th, 2018, all the equipment was transported to the site and major construction and installation work were completed. After the final inspection and approval from Ormat, the plant went for its first trial-run. On Oct 18th 2018, the 72-hour power production test was successfully completed and then the connection with the grid was achieved. At the beginning, only 1~2 MW of power production was allowed by the grid operator, due to suspicion on the robustness of the plant and sustainability of the reservoir. After a period of stable output, the grid operator gave final green light and Yangyi gradually increased its output and achieved full-capacity (16 MW) output in Feb 2019.

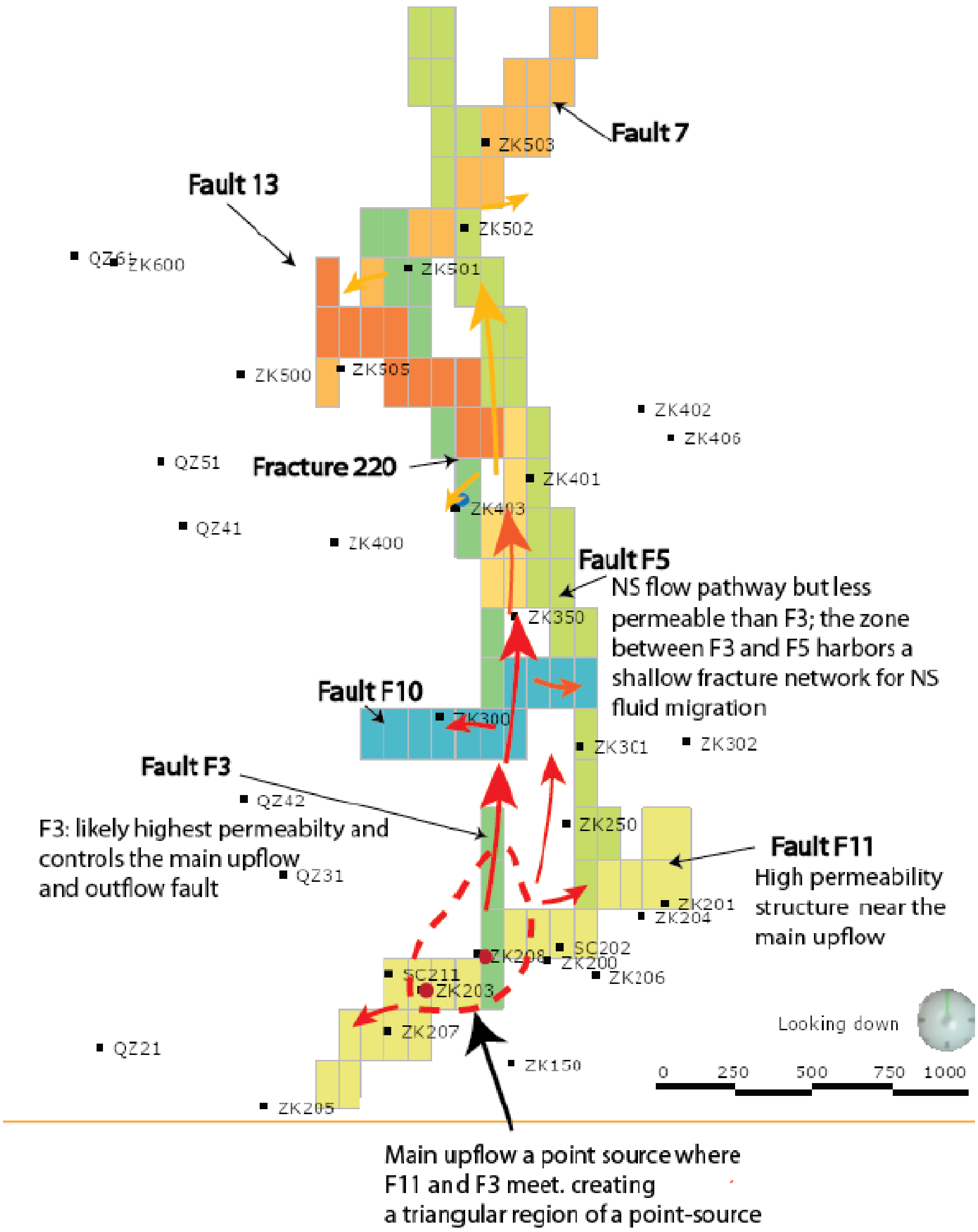

Figure 6: Conceptual sketch of fluid flow in Yangyi geothermal reservoir (Zuza (2019)).

3.2 Power Output and Capacity Factor

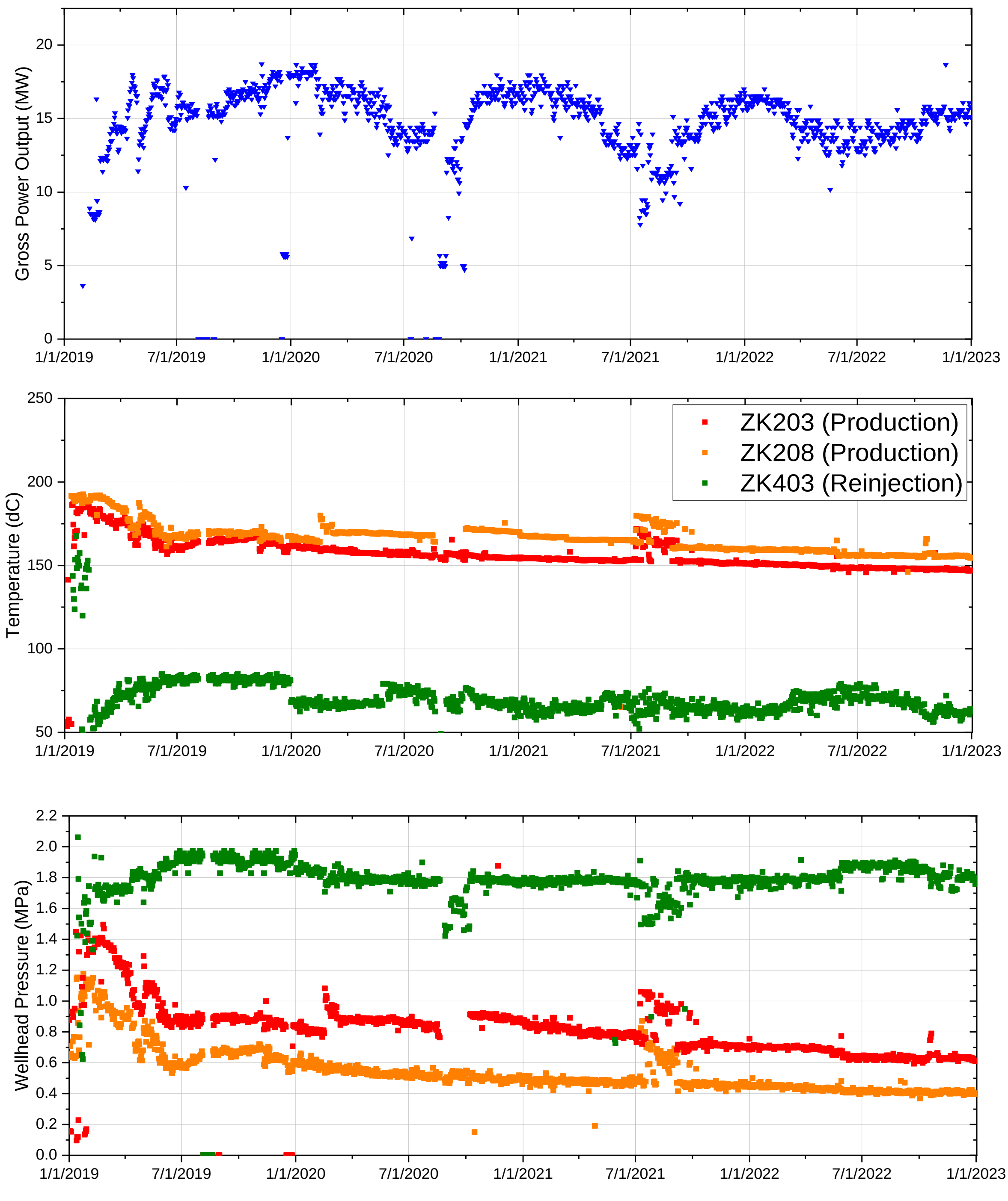

Figure 7: Key operational data of Yangyi Geothermal Power Plant, including the net power output (top), wellhead temperature (middle), and pressure (bottom) from 2019 to 2022

Figure 7 shows the plant operational data from 2019 to 2022. At the beginning of 2019, the plant is running in a testing mode. Only minimum flow rate of geothermal fluid is produced. In this condition, the wellhead temperature at ZK208 and ZK203 remains at the 170~180 °C range. Also, the wellhead pressure of the two wells are very high, which can reach 1.4 and 1.1 MPa accordingly. Through the first 7 months of 2019, along with the full-scale production, both temperature and pressure at the wellhead experienced a quick drop. This is due to the fact that cold water re-injected into ZK403 has been recirculated back to the production zone, as indicated also by the tracer profiles in Figure 5. The mixing with the cold water reduces the enthalpy of deep upflow fluids, and then leads to a quick decrease in the wellhead pressure. After July 2019, an equilibrium state was reached between the reservoir and the production/re-injection processes. The production temperature remains at the 150 ~ 160 °C range, with the well heat pressure holding at 0.6 and 0.8 MPa accordingly. In a typical condition, a total of 650 t/h of mixed geothermal brine and steam will be produced from ZK203 and ZK208. Through a separator, the mixed flow is introduced into separate transport pipes. Inside of the power plant, the steam and brine transfer their heat to the organic working fluid (iso-pentane) in the shell-tube heat exchangers. The tailing brine temperature is usually maintained at the 55 ~60 °C range, to prevent potential silica scaling in the re-injection well ZK403. For interested readers, Chen et al. (2022) provides technical details on the thermodynamic calculation of this Organic Rankine Cycle power plant. With this typical setting, a gross power output of 15.92 MW can be achieved in average over the year. Considering about 11% auxiliary power consumption, a net production of 14.17 MW can be sold to the grid. From 2019 to 2022, the annual net power sale accounts for 88.9, 110.4, 113.1 and 96.8 GWh. From 2020 to 2022, a slow but gradual decrease in production temperature and pressure can be observed. This is caused by the cooling of shallow reservoir between the 400- and 200-series wells, which has a negative impact on the production of the plant (see discussion in section 4.2).

3.3 Economics, Taxation and Policy

For the Yangyi phase-I project, the total investment is ca. 650 million RMB. It has to be noticed that the current owner purchased the Yangyi project in 2015. A considerable proportion of the investment went into clearing outstanding debts, repairing all available wells, building connecting roads, office and operation buildings of the plant. Being located at an elevation of 4650 m, all the field works become difficult and much more costly than normal. Since the full-capacity production in 2019, Yangyi has been continuously producing electricity with a very high capacity factor. In average, a running time of the plant is more than 8000 hours per year. This also proves the equipment from Ormat is of high-quality and needs only very limited maintenance. Most of the time, the power plant can be run in full automatic mode. In average, an annual revenue of 25 million RMB can be expected, which is then spent into about 2.8 million RMB of labor cost, 1 million RMB of material (chemical inhibitors and spare parts), 4.9 million administration and operational overhead, with the rest of cash flow goes into pay-back of bank loans. When equipment depreciation is considered, the Yangyi power plant has a negative financial return. This financial situation is mainly caused by the low power sale price. If geothermal power can be included in the feed-in-tariff scheme similar as biomass (which was the original motivation of the investor), the project will immediately turn profitable. Instead of a feed-in-tariff scheme, Yangyi only receives a price of 0.25 RMB per kWh from the grid, which is probably the lowest in China. Despite of low carbon emission and environmental friendliness, this price is even lower than what the coal-burning thermal power plant receives (typically >0.35 RMB per kWh). To this day, the investors are still expecting a nation-wide feed-in-tariff scheme for geothermal industry, which will greatly facilitate the growth of the industry.

Besides the electricity price, another uncertainty that prevents the owner of Yangyi from further investing in the Phase II project is the new Resource Tax Law that is in effective since Sep 1st 2021. According to the law, geothermal resource is subject to a tax rate of 1 RMB per m^3 of geothermal fluid produced. Despite of the high production rate in Yangyi, all geothermal fluid extracted from the production wells are 100% re-injected back into the reservoir through ZK403 well. The re-injection process is even audited and certified according to the NB/T 10088-2018 standard. This means the net amount of extracted geothermal fluid from Yangyi reservoir is zero. Based on this argument, the local authority decided not to collect resource tax from Yangyi. The current uncertainty related to the resource tax is whether the practice of Yangyi, i.e. the net-zero production of geothermal fluid, can be legally confirmed and then exempted from resource tax. Technically it is clear but no legal verdict yet to support this practice. For readers interested in this issue, detailed discussion can be found in Shao et al. (2021).

4. DISCUSSION

4.1 Choice of power production technology

At the beginning of Yangyi project, screw expanders were chosen as the technology of power production. Two 500 kW devices were installed at the wellhead of ZK203 as pilot scale tests (Yu et al., 2015). In theory, screw expanders can also be coupled with Organic Rankine Cycle, in which the organic working fluid is used to avoid scaling issue. However, it is mechanically difficult to manufacture large screw devices with capacity more than 1 MWe. Along with the increase of screw size, the difficulty of machining the components increases dramatically. As the size of the screw expanders is limited, it requires more than a dozen of such devices to run in parallel, so that same 16 MW power production capacity can be achieved. Another important factor is the high efficiency of the turbine binary plant (12~15%) in comparison to the screw expanders (normally 5~8%). Considering these factors, the owner of the Yangyi project chose the Organic Rankine Cycle turbine plant manufactured by Ormat, and successfully achieved continuous power production for more than 8000 hours every year.

4.2 Thermal breakthrough

As already mentioned previously, a gradual decrease of production temperature has been observed in Yangyi. This is related to the mixing of cold re-injection water with hot upflow fluid from the deep reservoir. Hydraulically, it is well proven by the long-term tracer test (see section 2.3) that the retention time in this shallow reservoir is merely a couple days (ZK403 to ZK208) to a couple of weeks (ZK403 to ZK203). However the thermal decay is much slower. One reason is the large amount of heat stored in the solid phase of the alluvial sediments lying between 400- and 200-series wells. Although there is ca. 650 t/h of cold water reinjected into ZK403 continuously, it will be heated up by surrounding sand, gravel and rock before reaching the 200-series wells. This cooling effect results in a drop in both total flow rate and well head temperature over the years. From 2019 to 2022, the total flow rate decreases from 650 t/h to ca. 600 t/h. The wellhead temperature drops from >160 °C down to the 150 °C range (see Figure 7). The strategy of the Yangyi team is to open SC202 well in May 2022. This increases the production flow rate by about 20 t/h. It is helpful to minimize the loss in power production, but will not completely resolve the problem. A more straight-forward approach would be to drill new wells targeting production from the deep reservoir towards the south of the 200-series wells. By directly accessing the high enthalpy upflow and minimize the mixing with cold reinjection, lower amount of flow rate is needed to achieve the same power output. Also, the reinjection should be moved either deeper, directly into the fractures, or further north towards the 500-series wells. The general rule-of-thumb is that production and reinjection should be placed in hydraulically separate structures, so that long and deep enough circulation path will assure the complete exchange of heat between the reservoir and circulating fluid.

4.3 Inhibitor Injection System

During well production test and also pilot-scale power production, scaling issues have already been observed both in production wells and in evaporator/separators. By taking samples and making chemical analysis, the scaling mineral was identified to be calcium carbonates. The scaling process is directly related to flashing, in which the carbonate mineral saturation index dramatically change along with the CO_2 degassing in the wellbore. To completely prevent scale formation both in the wellbore and in surface facilities, a downhole inhibitor injection system was designed, manufactured and installed. The general design of the system follows those in the literature (see e.g. Moya et al., 2005). A stainless-steel tank was installed (see Figure 8), in which the diluted chemical inhibitor needs to be filled every 2~3 days. The inhibitor solution will be continuously pressurized by a piston pump and goes through the 304L capillary tube. The tube allows the slow movement of the inhibitor solution to pass through the lubricator and released at a specific downhole position in the wellbore. There the inhibitor is mixed with geothermal brine. In Yangyi, the Accent 1216 inhibitor manufactured by Dow Chemical was first applied. This inhibitor shows very good effect in preventing carbonate scale formation both downhole and in surface pipelines. It was later-on substituted by a similar product produced domestically. In average, concentration of 25~30 ppm of inhibitor need to be injected along with the produced geothermal brine to suppress the scaling. The cost of the inhibitor is just 1~2 percent of the revenue from the power generation. As the inner diameter of the two production wells is relatively small, it is not possible to install Line Shaft Pump (LSP) or Electrical Submerged Pumps (ESP). Hence, the downhole inhibitor injection system remains the best engineering choice to prevent scale formation and maintain plant operation with reasonable cost.

Figure 8: Photos of inhibitor injection system installed at the ZK208 well.

4.4 General Suggestions

Through the exploration and development of Yangyi project, the team has learned several important lessons. First, the geophysical and geochemical exploration work at the beginning of the project is of great importance. No cost should be saved there! In comparison to the cost of drilling a new well without obtaining satisfied flow, the cost of conducting detailed gravity and magnetotellurics survey is much cheaper. In the Yangyi case, the 3D inversion of magnetotellurics survey data produces very clear picture of the reservoir structure. When combined with surface geological survey of fracture location, historical drilling log, as well as the geochemical and tracer tests data, a clear picture of the reservoir conceptual model can be obtained (see description in section 2.5). For the drilling part, Yangyi is lucky because 3 of the existing 33 wells can be repaired and re-used to set up fluid circulation. However, the large amount of un-productive wells were made in the history, because previous owners lack the expertise to properly understand the reservoir structure. Without data-driven conceptual model, it is not possible to identify the right drilling target and achieve high flow rate.

It has to be noticed that the understanding of reservoir structure must be further developed and continuously improved. In this process, the logging and testing of existing and newly drilled wells provides valuable knowledge on the structural information such as fracture orientation and permeable zones. Typical well test procedures, such as lubricator operation, Pressure-Temperature-Spin logging, acoustic logging, well production/reinjection test, dryness factor measurement, Non Condensable Gas quantification etc. were performed already in the 1980s during the Yangbajain project. Due to the lack of geothermal projects in the last 30+ years, capable reservoir and well-logging engineers are rarely found today. This suggest that training courses and study programs are badly needed in geoscientific universities and institutes.

5. SUMMERY AND OUTLOOK

From 2016 to 2019, the entire Yangyi team spent their time and effort working at a remote place with more than 4500 m elevation. Yangyi was successfully transformed from a nearly abandoned project to a modern geothermal power plant. Until today, Yangyi is still the best running geothermal plant in mainland China. When looking back, the most uncertainty in developing a geothermal power project is the reservoir engineering part, which has to establish a sustainable hydro-thermal circulation by a variety of engineering practices, including the geophysical survey, result interpretation, conceptual model formulation, drilling, well logging and testing etc. The real challenge for anyone who is new to the geothermal power industry is that this early exploration phase not only depends on the contributions from many different professionals, but more importantly they have to exchange and integrate ideas and information so that a more accurate picture of the reservoir structure can be drawn based on solid data. Here the information flow, idea discussion must be conducted by a group of experts, who not only know his/her own profession, but are capable of inter-disciplinary communication. Currently in the Chinese geothermal community, communication across disciplines remains the biggest challenge.

Looking into the future, the authors of this manuscript remain optimistic in the Chinese geothermal power industry. A country should not and will not achieve its carbon neutral target without the contribution from geothermal energy. We take the opportunity of the World Geothermal Congress 2023 to call on the Chinese government for a nation-wide, systematic feed-in-tariff policy for geothermal power generation. In addition, practice of resource tax on the geothermal industry must be further clarified. There is no reason to financially punish the activity of net-zero extraction of geothermal fluid. Like many other renewable energy sources, with the proper policy support, the Chinese geothermal industry has the potential to experience exponential growth in the future.

ACKNOWLEDGEMENT

The Yangyi geothermal project will not make all the achievements without the supports from the Ormat geology team. We would like to acknowledge Paul Spielman, Piyush Bakane, Robin Zuza, and Yvonne Xia for their time and effort dedicated to the Yangyi project. Appreciations are also given to former Yangyi colleagues and contractors, namely Benpa Jassa, Mike Rickman (Hades Systems) and Luke Ding (Shanghai Zhaosheng) for their technical support. It was a pleasure to work with all of you to make the Yangyi project successful.

REFERENCES

Chen, C., Witte, F., Tuschy, I., Kolditz, O., Shao, H.: Parameter optimization and comparative study of an organic Rankine cycle power plant for two-phase geothermal sources, *Energy*, **252**, (2022): 123910.

Liang, T., Zhang, D., Tan, Q., Xu Y.: Tibet Autonomous Region Dangxiong County Yangyi Geothermal Reservoir Survey Report (in Chinese), *Technical Report*, Tibet Geothermal and Geologic Survey Team (1990).

Guo, Q.: Hydrogeochemistry of high-temperature geothermal systems in China: A review, A*pplied Geochemistry*, **27**, (2012), 1887-1898.

Shao, H., Kong, Y., Shen, B.: Impact of resource tax law on the geothermal industry in China and corresponding policy suggestions (in Chinese), *Science & Technology Review*, **39**, (2021): 33-44.

Spielman, P., Rhodes, G., Owens, L., Bakane, P.: Yangyi Geothermal Power Station, Resource Review, *Presentation*, Ormat Technologies, Inc. Hangzhou, China (2017).

Moya, P., Nietzen, F., Yock, A.: Benefits from the Utilization of a Calcium Carbonate Inhibition System for Production Wells at the Miravalles Geothermal Field, *Proceedings*, World Geothermal Congress, Antalya, Turkey (2005).

Yu, Y., Hu D., and Wu F.: Applications of the Screw Expander in Geothermal Power Generation in China, *Proceedings,* World Geothermal Congress, Melbourne, Australia (2015).

Wang, Y., Guo, Q.: The Yangbajing geothermal field and the Yangyi geothermal field: two representative fields in Tibet, China, *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010).

Zheng, X., Duan, C., Liu, H.: The chemical properties of Yangyi high temperature geothermal field in Tibet, China, *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, U.S.A. (2013)

Zheng, X., Duan, C., Ye, H., Wang, Z.: Pressure Analysis and Balanced Drilling in Yangyi Geothermal Field of Tibet by Coupling with Temperature, *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, U.S.A. (2016)

Zuza, R., Yangyi Geology Overview, *Presentation*, Ormat Technologies, Inc. Lhasa, China (2019).