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Modelling geothermal conditions in part of the Szczecin Trough – the Chociwel area

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Abstract

The Chociwel region is part of the Szczecin Trough and constitutes the northeastern segment of the extended Szczecin-Gorzów Synclinorium . Lower Jurassic reservoirs of high permeability of up to 1145 mD can discharge geothermal waters with a rate exceeding 250 m^3/h and temperatures reach over 90°C in the lowermost part of the reservoirs. These conditions provide an opportunity to generate electricity from heat accumulated in geothermal waters using binary ORC (Organic Rankine Cycle) systems. A numerical model of the natural state and exploitation conditions was created for the Chociwel area with the use of TOUGH2 geothermal simulator (i.e., integral finite-difference method). An analysis of geological and hydrogeothermal data indicates that the best conditions are found to the southeast of the town of Chociwel, where the bottom part of the reservoir reaches 3 km below ground . This would require drilling two new wells, namely one production and one injection. Simulated production with a flow rate of 275 m^3/h, a temperature of 89°C at the wellhead, 30°C injection temperature and wells being 1.2 km separated from each other leads to a small temperature drop and moderate requirements for pumping power over a 50 years' time span. The ORC binary system can produce at maximum 592.5 kW gross power with the R227ea found as the most suitable working fluid. Geothermal brine leaving the ORC system with a temperature *c.* 53°C can be used for other purposes, namely mushroom growing, balneology, swimming pools, soil warming, de-icing, fish farming and for heat pumps.

Keywords: Szczecin Trough, geothermal conditions, numerical model, binary system, ORC

1. Introduction

Recognition of geological structures for direct and indirect use of geothermal energy is an important step in applied geological research. In many parts of the world both basic research, in order to understand geological structures better (Chowaniec, 2009; Zuber & Chowaniec, 2009; Sowiżdżał, 2010, 2012; Stankowski, 2012; Özgür & Çalışkan, 2013; Sowiżdżał et al., 2013; Pussak et al., 2014), but also works aimed at optimisation of geothermal systems in terms of their operation have been carried out (Tomaszewska & Pająk, 2012; Żbikowska et al., 2013; Demir et al., 2014; Baba et al., 2015). Fundamental issues are, for instance, geothermal potential estimates assisted by numerical modelling (Szczepański & Szklarczyk, 2006) and analysis of geochemical composition of groundwaters in the context of scaling and corrosion prediction in geothermal systems. An important role is played by the numerous studies aimed at a comprehensive and optimised management of those valuable natural resources (Koseoglu et al., 2010; Öner et al., 2011; Tomaszewska & Bodzek, 2013; Tomaszewska & Szczepański, 2014; Tomaszewska et al., 2014).

In Poland geological conditions for the comprehensive utilisation of thermal waters are suitable. So far, geothermal energy resources here have been developed directly for heating, recreation and balneology (Bujakowski, 2010; Ciężkowski et al., 2010; Kępińska, 2013). The main thermal water resources in the Polish lowlands are associated with Mesozoic reservoirs, accumulated primarily in Lower Cretaceous and Lower Jurassic sandy units. Significant geothermal resources are also found in Upper and Middle Jurassic and in Upper and Lower Triassic reservoirs (Górecki et al., 2006).

One of the most promising geothermal reservoirs in terms of using geothermal waters for energy purposes is the Lower Jurassic unit within the Szczecin Trough (Górecki et al., 2006, 2010; Sowiżdżał, 2009, 2010; Górecki et al., 2010; Tarkowski & Wdowin, 2011; Sowiżdżał et al., 2013). Due to salt tectonics, manifested among others by local disappearance of the Kamień Pomorski Beds and the partial removal of the Gryfice Beds, the thickness of the Lower Jurassic strata within the Szczecin Trough is highly variable. In most of the area, especially in the southern and southwestern part of the trough, the thickness of the Lower Jurassic sediments generally is in the range of 300 to 400 m, while in the northeastern part of the basin, in the vicinity of Nowogard, they reach up to 1,400 m. The top of the Lower Jurassic strata rises to the marginal parts of the Szczecin Trough to a depth of –300 m a.s.l. and drops in the central part, reaching a maximum depth of –2500 m a.s.l. in the vicinity of Chociwel (Sowiżdżał, 2009). Waters in the top of the Lower Jurassic unit have a temperature ranging from less than 20°C to nearly 90°C (Sowiżdżał, 2009, 2010). The highest temperature (89°C) recorded here was found in the Chociwel 3 well, located in the axial part of the basin (Sowiżdżał, 2012). The high flow rates from wells and temperatures exceeding 90°C make it possible to use a binary system to produce electricity (Bujakowski & Tomaszewska, 2014). A preliminary assessment of geothermal conditions of the Szczecin Trough have allowed to nominate the Chociwel region (3.5 thousand inhabitants, Stargard county, West Pomeranian Voivodeship) as a prospective area for use of geothermal energy in the energy sector.

2. Conceptual model and geothermal parameters

The Chociwel region is part of the Szczecin Trough, a fragment of the Szczecin-Gorzów Synclinorium – one of the main tectonic units in Poland (Fig. 1). The highly elongated and folded area of the Szczecin Trough has asymmetrical flanks: NE – steeper and SW – less tilted (Stupnicka, 1997). The Zechstein-Mesozoic sedimentary basin was shaped by diverse vertical movements of pre-Zechstein rock massifs, mostly along the planes of subsurface tectonic discontinuities. These movements generally are slow and long-term, causing a change of pace and type of sedimentation, expressed in variable sediment thickness, presence of deposits of different facies and formation of erosion surfaces. The second – equally important factor in the tectonic construction of the Szczecin Trough were horizontal and vertical displacement of Zechstein salts, which, since the Late Triassic, occurred with minor breaks almost all the time during sedimentation of the Mesozoic complex (Sowiżdżał, 2010). Due to the halotectonic processes at the base of the Cretaceous strata the axes of syncline and anticline of the predominantly northwest-southeast course are clearly marked, at the same time pointing to diversification of local tectonics. The zone of strong interaction of salt tectonics along the Szczecin Trough includes several salt structures, arranged linearly on the transom area Szamotuły-Oborniki to Kamień Pomorski-Międzyzdroje (Garlicki & Szybist, 1986). In most cases, these structures partially penetrate the Mesozoic sediments (Dadlez & Jaroszewski, 1994). Near the northwestern border of the Chociwel area, salt pillow associated with the Ińsk salt dome uplifts Mesozoic formations.

In northwest Poland, the most promising geological unit for the location of a binary power plant would be the Lower Jurassic sequence. In the Chociwel area, this forms the axial part of the Szczecin Trough. The sequence consists of alternatively overlapping deposits that formed in lacustrine and fluvial environments (Deczkowski, 1997). Here the greatest sediment thickness occurs within the basin and the top of the formation is found at the greatest depths. In the modelled area, four wells penetrate Lower Jurassic strata: Chociwel 2, Chociwel 3, Chociwel IG-1 and Oświno IG-1 (Fig. 2). The top of the Lower Jurassic formation occurs in the Chociwel region at a depth of –1900 m a.s.l. in the west and –2500 m a.s.l. in the east (Fig. 2). The thickness increases from less than 350 m in the south to more than 650 m towards the north. The base of the Lower Jurassic formation varies from –2250 m a.s.l. in the southwestern part of the modelled area to –2950 m a.s.l. in the vicinity of the Chociwel IG-1 well. The heat flux density in the area is estimated at 72 to 77 mW/m^2, increasing from east to west (Szewczyk & Gientka, 2009), while the average geothermal gradient is 3,12°C/100 m. Water temperature at the top of the reservoir in the axial part of the Szczecin Trough reaches almost 90°C (in Chociwel IG-1 well: 89°C). Taking into account the geothermal gradient and the thickness of about 450 m of the Lower Jurassic sediments, the temperature in the bottom part of the Mechowo Beds reservoir may exceed 95°C (Fig.

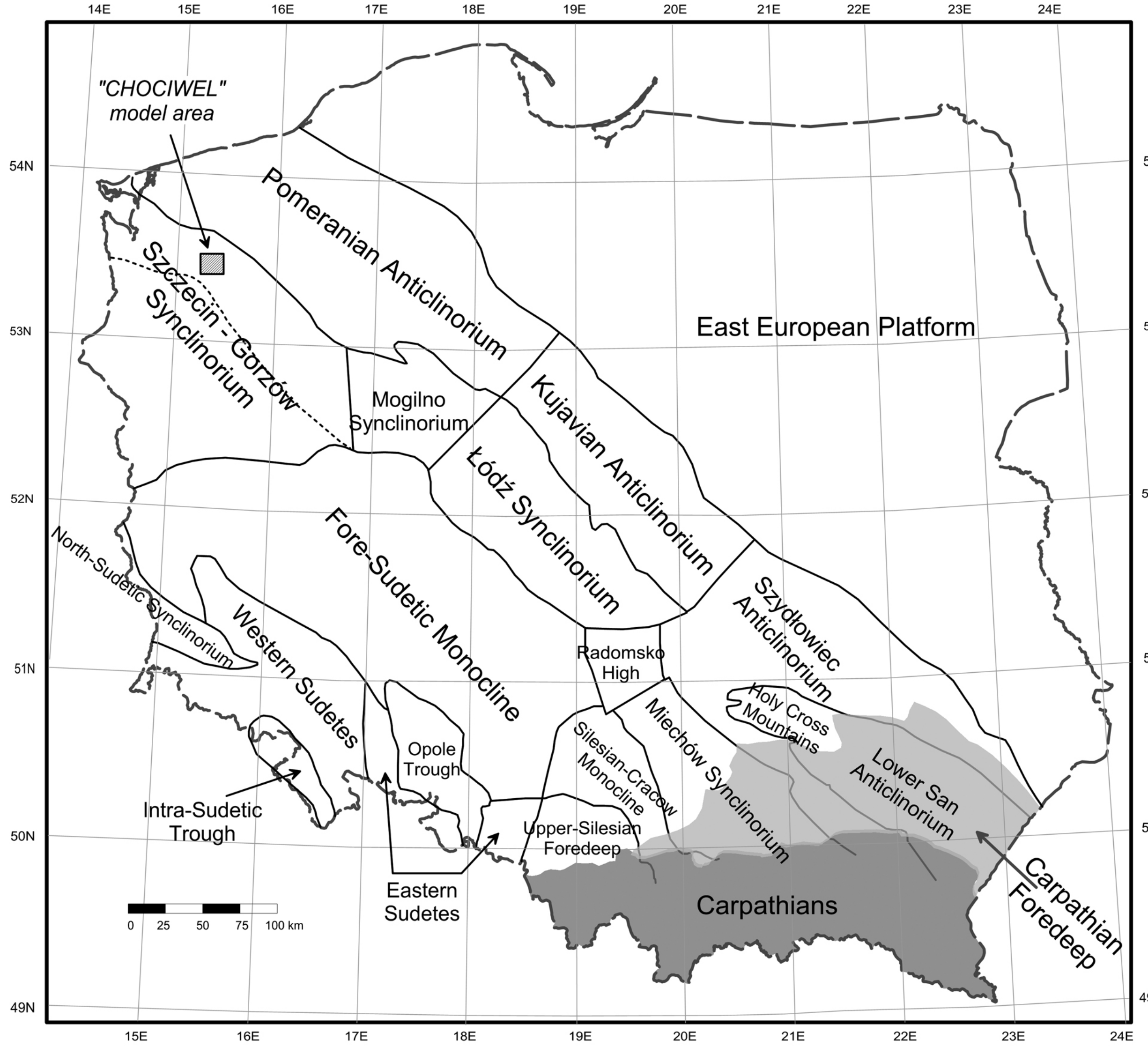

Fig. 1. The area covered by the Chociwel numerical model, plotted on major tectonic units in Poland (modified after Karnkowski, 2008).

3). The mineralisation of waters in the Chociwel region is at level from less than 100 g/dm^3 in the SW to more than 125 g/dm^3 in the northeast.

The best reservoir parameters in the Lower Jurassic sequence are found in sandy layers of the Mechowo Beds (Hettangian–lower Sinemurian) at the bottom of the reservoir, and slightly less good in sandy layers of the Radowo Beds (upper Sinemurian) containing interbedding with poorly permeable and impermeable mudstones and claystones (Sowiżdżał, 2010). The hydraulic conductivity of the Lower Jurassic aquifer is from approximately $3.5 \cdot 10^{-2}$ m/s to approximately $4.0 \cdot 10^{-2}$ m/s, while transmissivity is from around $1.0 \cdot 10^{-2}$ m^2/s to $3.5 \cdot 10^{-2}$ m/s, rising towards the northwest (Sowiżdżał, 2009). Favourable reservoir parameters translates into potentially high flow rates, which in the Chociwel area may exceed 250 m^3/h (Górecki et al., 2006; Sowiżdżał, 2009).

The bottom level of the Lower Jurassic aquifers is composed of Upper Triassic (Keuper) claystones, mudstones and sandstones, which in the Chociwel 3 well have total thickness of 500 m (Zboińska, 1987). The permeability in these variegated schists is 0.41 mD and in the lower Keuper sandy schists amounts to 42.3 mD.

The top of the potential Lower Jurassic reservoir in the Chociwel 3 borehole consists of the following rocks, in sequence: the Middle Jurassic mudstones and sandstones, the Upper Jurassic sandstones, mudstones and claystones and Lower Cretaceous mudstones with a thickness of 70, 90 and 10 m, respectively. They are covered by a 1,460-m-thick complex of Upper Cretaceous limestones, marls

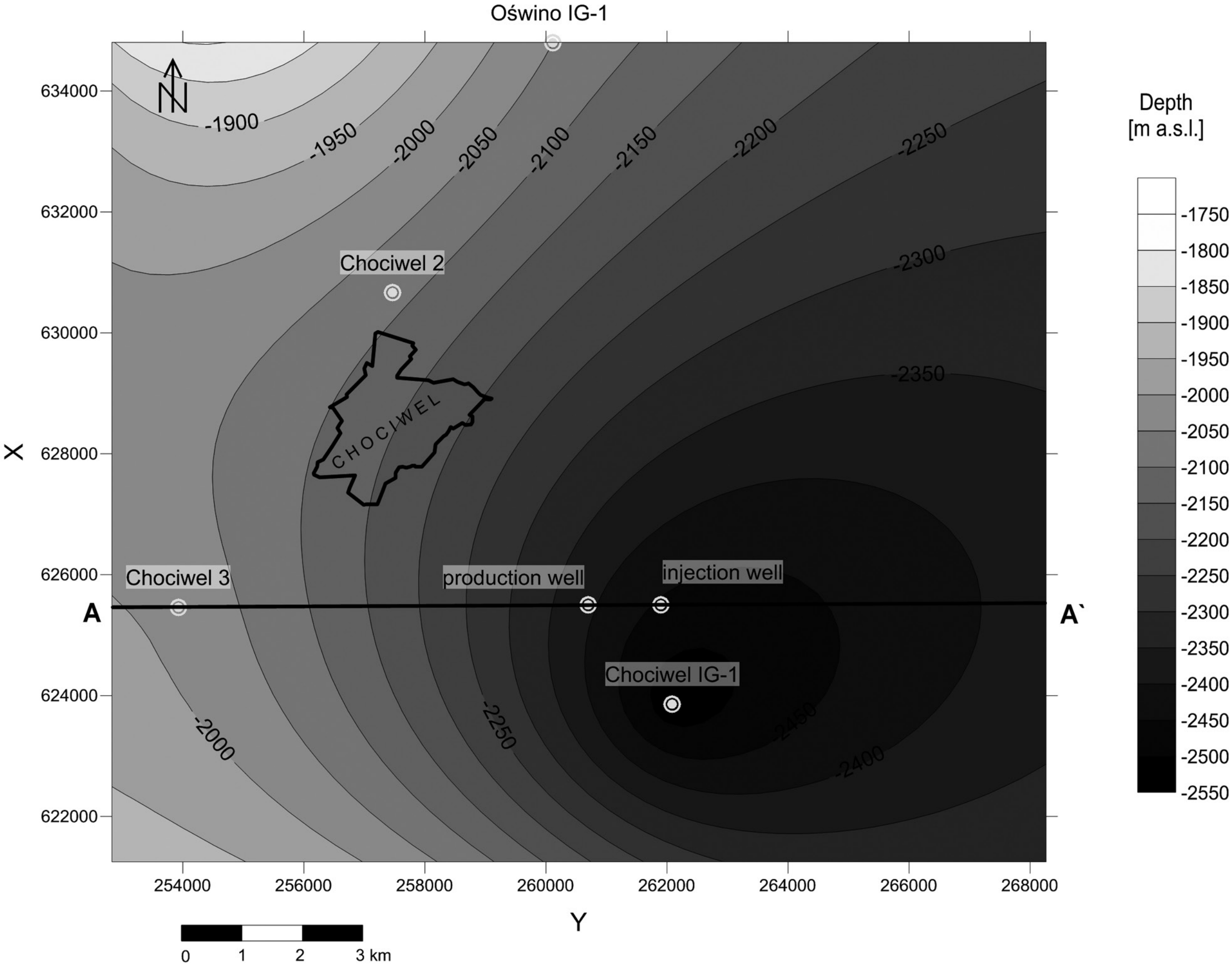

Fig. 2. Graphic representation of the Lower Jurassic sequence in the Chociwel area, with assumed localisation of new wells (doublet).

and claystones. The bulk permeability of the sandstone series of the Upper Jurassic and claystones and mudstones of the Lower Cretaceous is 4.5 mD here (Bujakowski & Tomaszewska, 2014).

3. Numerical model of thermal conditions

Mathematical modelling of the spatial distribution of geothermal conditions and the possibility of exploitation of energy from the Lower Jurassic reservoir was performed using TOUGH2 code based on the integral finite difference method (Pruess et al., 1999). The numerical model of the Chociwel region covered an area of 15.44 km x 13.56 km (Figs. 1, 4). The top layer of the model at –1700 m a.s.l. represents Cretaceous and Middle and Upper Jurassic sediments. Elevation of the top of the Lower Jurassic in the modelled domain varies from approx. –1800 m a.s.l. to approx. –2530 m a.s.l. The lowermost layer of the model, which is located mostly within the Upper and partly within the Middle Triassic rocks is set at –3300 m a.s.l. The numerical model has been divided into 52 horizontal sections, 48 of which – each having a thickness of 25 m – cover the entire Lower Jurassic reservoir of the area (Fig. 4). As part of the model assumption, the hydrodynamic field distribution of the Lower Jurassic reservoir was not taken into account. This was due to the difficulty of reaching the groundwater flow direction presented at the regional level by Górecki et al. (1995), even taking into account mineralisation in individual layers and applying appropriate lateral boundary conditions.

Boundary conditions of the 1st (T(t), p(t) = const)) and 2nd type (heat flux density = const.) were used at model borders. Top layer of the model which represents deposits of Lower and Upper Cretaceous and Middle and Upper Jurassic was fixed with constant pressure and temperature value throughout total simulation time. However, these values vary

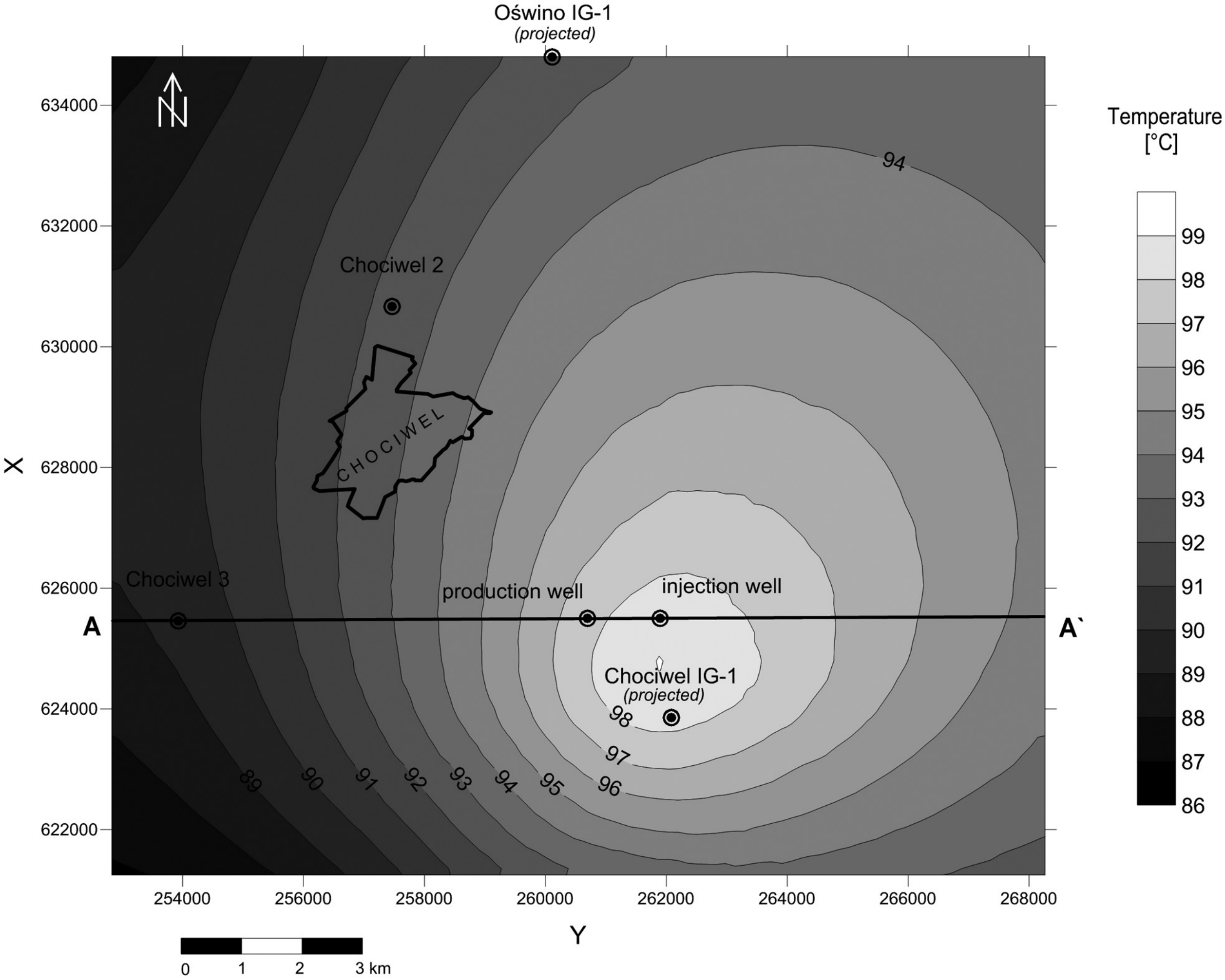

Fig. 3. Forecast of temperature distribution at bottom of the Lower Jurassic sequence in the Chociwel area, with assumed localisation of new wells (doublet).

spatially at certain depths (Fig. 4). In the bottom of the model, at a depth of –3250 m a.s.l., a constant heat flux density was assumed in the range from 72 mW/m^2 to 77 mW/m^2, rising from east to west (Szewczyk & Gientka, 2009).

The Lower Jurassic sequence in the area covered by the Chociwel model consists of five lithostratigraphic units. Starting from the top of the formation in the Chociwel 3 well (z = –2013.5 m a.s.l.) to the bottom (z = –2353.5 m a.s.l.) the following lithostratigraphic units are encountered: Kamień Pomorski Beds (thickness h = 10 m), Gryfice Beds (h = 10 m), Komorowo Beds (h = 142 m), Łobez Beds (h = 17 m) and Radowo and Mechowo beds (h = 153 m in total) (Zboińska, 1987). In addition to the immediate proximity to the Chociwel 3 well, the contribution of individual layers (beds) in the layered model was interpolated by kriging method based on the deep wells penetrating Lower Jurassic located in the area modelled (Chociwel 2) and in the vicinity (Kania 1, Grzęzno 2, Dobrzany 1). The bottom of the Lower Jurassic reaches the greatest depth of –2950 m a.s.l. in the vicinity of the Chociwel IG-1 well.

Water-bearing layers are primarily sandstone complexes in the lower part of the Lower Jurassic, i.e., the Mechowo and Radowo beds. The permeability of this reservoir is on average 1145 mD (Sowizdżał, 2009). Slightly worse hydraulic parameters are recognised in built of sandstone and mudstone interbedded with claystones of the Komorowo Beds (k = 531 mD) and Kamień Pomorski Beds (k = 435 mD). Łobez Beds (k = 1 mD) and Gryfice Beds (k = 0.01 mD), which are composed mainly of poorly permeable and impermeable claystones. Lower Jurassic formation is underlain by Upper Triassic claystone of considerable thickness (537 m in Chociwel 3 well).

Bulk density of rock matrix, porosity, permeability, thermal conductivity and specific heat was assigned to each stratigraphic unit that was specified in the conceptual model phase. These physical

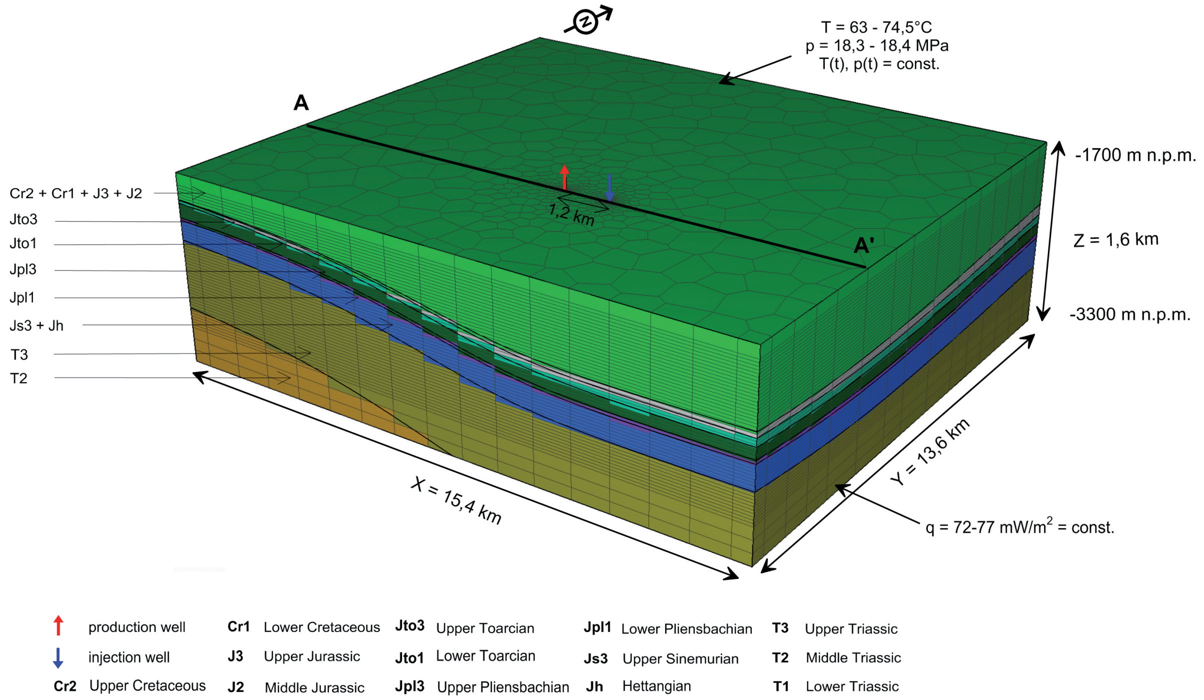

Fig. 4. Numerical model grid and boundary conditions applied in the Chociwel area.

properties make up the so-called materials – groups of elements with the same physical characteristics (Table 1). Calibration of the model consisted of a series of simulations performed in order to restore

Table 1. Geological units of the numerical model and their properties.

No.	Stratigraphy	Description	Porosity [%]	Bulk density [kg/m³]	Permeability [mD] XY	Permeability [mD] Z	Specific heat [J/(kg·K)]	Thermal conductivity [W/(m·K)]
1	T2	Claystones, mudstones and limestones of Middle Triassic	5.0	2600	0.01	0.01	900	2.2
2	T3	Upper Triassic claystones	15.0	2600	0.01	0.01	900	2.9
3	Jh+Js3	Sandstone complexes of Lower Jurassic Radowo and Mechowo Beds	4.6	2600	1145	1000	850	3.5
4	Jpl1	Claystones with sandstone interbeddings of the Lower Jurassic Łobez Beds	13.0	2600	1	1	870	2.3
5	Jpl3	Sandstone complexes with claystone and mudstone interbeddings of the Lower Jurassic Komorowo Beds	11.4	2600	531	101	850	2.2
6	Jto1	Claystone complexes with sandstone interbeddings of the Lower Jurassic Gryfice Beds	10.0	2600	0.01	0.01	900	2.5
7	Jto3	Sandstone complexes with claystone interbeddings of the Lower Jurassic Kamień Pomorski Beds	13.5	2600	435	101	870	2.7
8	J2+J3+ Cr1+Cr2	Rocks of Lower and Upper Jurassic and Lower and Upper Cretaceous	10.0	2600	10	1	850	3.7

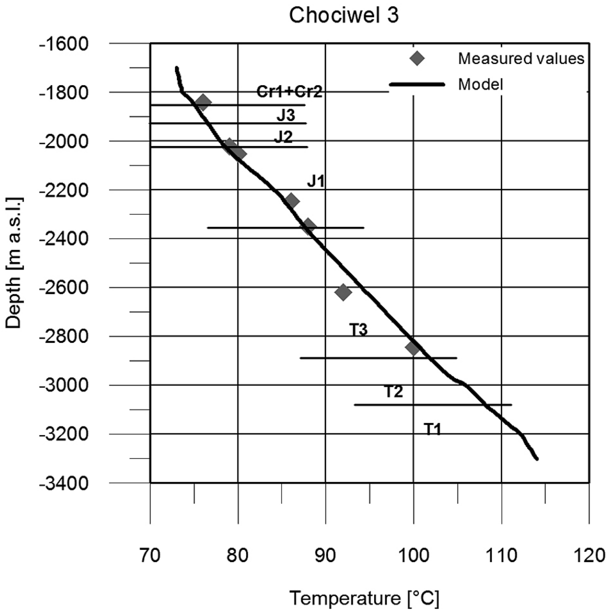

Fig. 5. Thermal calibration of the numerical model.

the steady-state temperatures close to the thermal profile obtained in the Chociwel 3 borehole (Fig. 5). Due to depth, the highest temperatures in the bottom of the Lower Jurassic formations are expected in the vicinity of the Chociwel IG-1 well (Fig. 3).

4. Numerical model of thermal water exploitation

The Radowo and Mechowo beds, which form bottom part of the Lower Jurassic reservoir, are characterised by the highest values of permeability and reservoir temperatures in the range of 90–95°C in the vicinity of the presumed location of the doublet. Simulated production was performed from both these layers with a total thickness of approximately 200 m. It is assumed that the temperature of the injected brine will be 30°C, which would allow the use of geothermal heat both for generating electricity in binary systems, as well as developing residual heat cascade. The model assumes that the distance between the production and the injection well will be 1,200 m. In a highly permeable sandstone aquifer, this distance should be sufficient to achieve a stable temperature at the outlet throughout the period of operation. The model assumes a constant discharge of the doublet at a rate of 275 m^3/h. The possibility of obtaining similar flow rates is confirmed by documented resources of other geothermal wells drilled in the past within the geological structures analysed (Sowiżdżał, 2010).

The simulation results of the presumed exploitation scheme indicate that cooling of reservoir waters in the vicinity of the production well will be merely 2°C after 50 years of operation (Fig. 6A). Pressure drops at the feed zone depth in the production well will be equal to approx. 0.16 MPa (Fig. 6A and Fig. 7). The rise of pressure in the injection well is estimated at 0.33 MPa (Fig. 6B, Fig. 7). The higher absolute value of pressure rise compared to pressure decline is caused by the increased viscosity of cooled water. Values of pressure change listed above take into account flow conditions through the water-bearing layer only. At the same time, flow resistance in the well bore is not considered, whereas real pressure drop, in fact, will exceed pressure changes calculated at reservoir conditions. This phenomenon, caused by

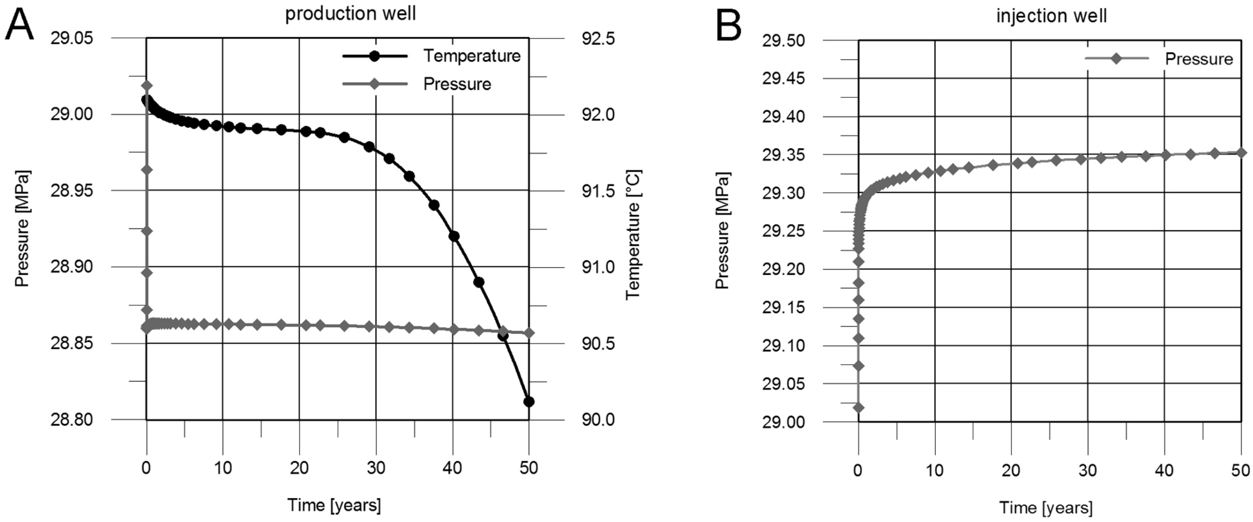

Fig. 6. A – Change of reservoir pressure and temperature versus time in production well; B – change of reservoir pressure versus time in injection well at a depth z = –2762 m a.s.l. for the doublet flow rate Q = 275 m3/h.

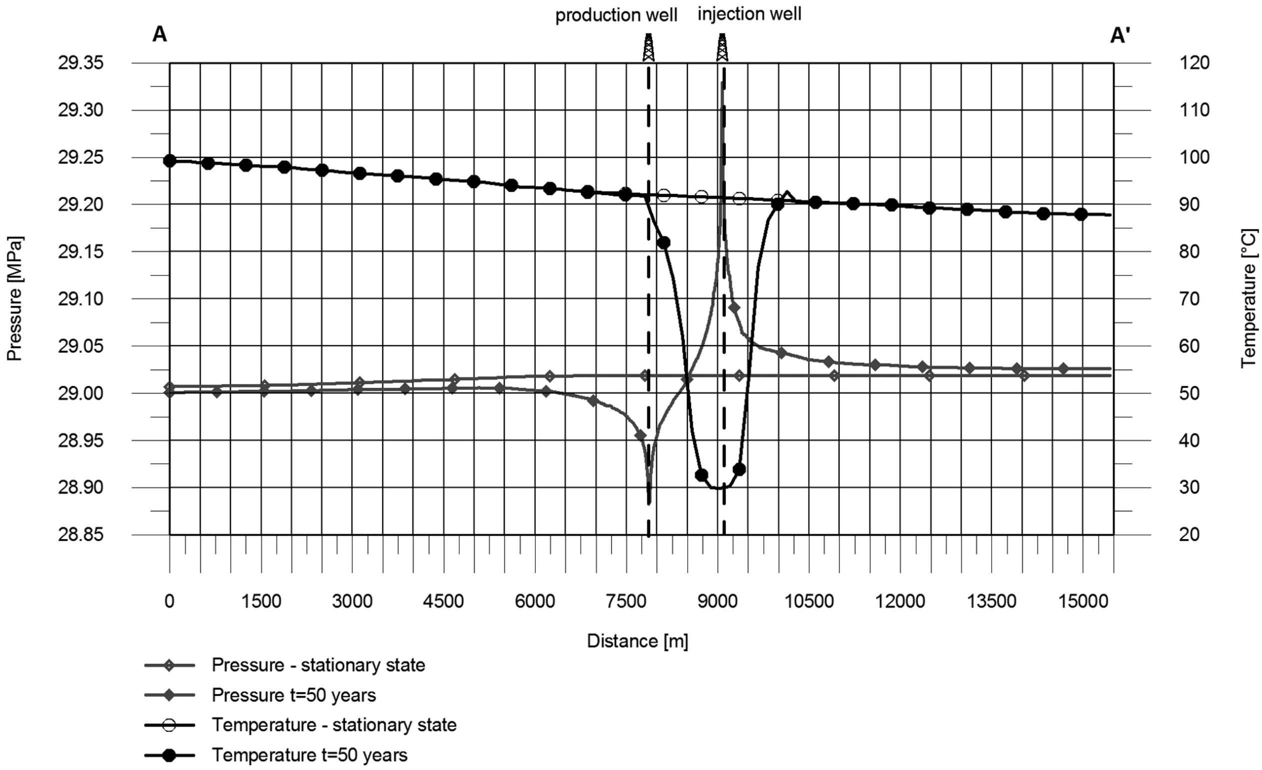

Fig. 7. Change of reservoir temperature and pressure along cross section A-A′ at a depth z = –2762,5 m a.s.l. for the doublet flow rate Q = 275 m^3.

pressure loss due to friction, may have fundamental significance especially at high flow rates. The model does not consider chemical processes occurring in the aquifer, i.e. precipitation and dissolution of rock-forming minerals either, which can have a significant impact on doublet performance (Tomaszewska & Pająk, 2012). Cooling of the reservoir layers will only take place in the zone adjacent to the injection well and the zone defined by the groundwater flow between the wells (Fig. 7).

5. Estimates of binary system energy potential

ORC (Organic Rankine Cycle) binary power plant is a system producing electricity, operating through the use of two different liquids separated from each other hydraulically. One of the fluids supplies energy and leads to evaporation of the second fluid. This working fluid has a low boiling point, and its steam drives the turbine. Geothermal brine, after heat delivery to the working fluid in the ORC system, can be injected back to the reservoir. In case of having sufficiently high temperature, it is used for heating purposes, and then cooled down injected through the injection well. The use of geothermal heat in cogeneration increases greatly the financial viability of the project (Pająk & Bujakowski, 2013).

The maximum estimated gross power of the binary plant can reach approx. 590 kW, at a flow rate equal to 275 m^3/h and a temperature of 89°C at the wellhead. Expected wellhead temperature is over a degree lower than the lowest water temperature at production depth (Fig. 6A). This assumption seems reasonable, whereas a high flow rate and an extended continuous operation of the production well is assumed to take place. Confirmation of the validity of this statement can be found in the literature (Barbacki et al., 2009) where assessment aimed at determining the impact of water flow rate and operation lifetime on wellhead temperature is performed. Under these conditions, the most favourable thermodynamic parameters of the working fluid is characterised by R227ea (Bujakowski & Tomaszewska, 2014). Geothermal brine, cooled down to 53.3°C after leaving the ORC system can be used for heating purposes. Assuming an injection temperature of 30°C an additional 6.9 MW of heating power can be further used. Brine density and specific heat dependence of temperature and salinity were used in the calculations (Miecznik, 2013). The geothermal doublet is characterised by significant overcapacity of extracted heat compared to heat demand that is restricted by the existing piping infrastructure. Currently, network heat in Chociwel meets the needs of approximately 20% of the population and is based on the 2.4 MW gas-powered boiler. The investment in geothermal ORC binary power plant may require drilling new wells. Unfortunately, this will significantly affect the level of investment costs, of which the costs of drilling and wells completion to a depth of approximately 3 km is estimated at >46 million PLN.

6. Conclusions

Selected areas of the Szczecin Trough, which is a fragment of a large tectonic unit of the Szczecin-Gorzów Synclinorium offer perspectives to use geothermal energy for electricity generation in binary systems. These waters, with estimated flow rates of up to 275 m^3/h, reservoir temperatures over 90°C and mineralisation rates of 125 g/dm^3 occur in sandy formations of Hettangian and Sinemurian (Early Jurassic) age at depths of approximately 2.8–3 km. The highest temperatures are associated with depths of the Lower Jurassic reservoirs. In order to obtain the highest electric power from geothermal sources, it seems necessary to drill new wells, namely one production and one injection well, approx. 4–5 km towards the southwestern boundaries of the town of Chociwel. Appropriate management of the heat surplus from geothermal source will have crucial importance of the economic viability of the investment. Optimising the selection of the doublet location and the acquisition of new heat consumers will require a detailed economic analysis, as well as additional research.

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