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SUMMARY OF PHD THESIS

ANALYSIS AND EVALUATION OF ELECTRICITY PRODUCTION USING HEAT ACCUMULATED IN GEOTHERMAL WATERS IN MAŁOPOLSKA REGION

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The aim of the study was to analyze the geological structure of the Malopolska province for the presence and the possibility of using geothermal waters for electricity production. The following theses were adopted:

- Analysis of geological and hydrogeological parameters for obtaining geothermal energy allows to determine the potential of electricity production that can be achieved in a geothermal power plant.
- A decisive impact on the efficiency of electricity production and installed capacity of geothermal power plants are: geothermal water temperature and flow rate of the production well, determined by the physical parameters of the rock medium.
- Geothermal power plants operating in the world confirm the possibility of electricity production form low enthalpy geothermal waters using organic and inorganic working fluids.

To determine the parameters of geothermal waters temperature and production well flow rate, as the factors necessary to take consideration in the case of electricity production, technological solutions used in in the world were analyzed. It was found that the methods of electricity production using geothermal energy waters characterized by low enthalpy are Organic Rankine Cycle (ORC) and Kalina Cycle. The term low enthalpy, in this case, means that the temperature in the geothermal reservoir is not exceeding 90–125□C (Muffler and Cataldi, 1978; Hochstein, 1990; Benderitter and Cormy, 1990; Lee, 1996). Enthalpy is defined as a function of the state having the dimension of energy and is expressed in J/kg, hence should not be confused with the temperature but treated as a parameter additional to temperature which help to classify geothermal resources (Muffler and Cataldi, 1978; Hochstein 1990; Benderitter and Cormy, 1990; Lee, 1996). Among installations using geothermal water resources at a temperature not exceeding 150□C selected for analyze were: ORC plants in Chena Hot Springs, Neustadt Glewe, Altheim, Bad-Blumau and installations based on the Kalina Cycle in Husavik, Unterhaching and Bruchsal. This is due to the parameters of the geothermal water used in these installations, similar to the Polish hydrogeothermal conditions.

The analysis of data (Mirolli et al., 2002; Brasz and Bilbow, 2004; DiPippo, 2005; Borsukiewicz-Gozdur et al., 2007; DiPippo, 2012; Borsukiewicz-Gozdur et al., 2013; Akbari et al., 2014 ; Bujakowski, Tomaszewska [ed.], 2014), and taking into account the parameters of geothermal power plants in the world, in the consideration as the minimum temperature of

geothermal water was taken 74□C and minimum flow rate 100 m^3/ h. The temperature criterion is an effect of operating parameters of the ORC plant in Chena Hot Spring on Alaska, where electricity is generated by using the lowest geothermal water temperature (Lund, 2006; Bertani, 2015; Mink et al., 2015). In the case of flow rate, assumed value of 100 m^3/h was dictated by a similar performance of flow rates in Chena Hot Spring (115 m^3/h) and in Neustadt-Glewe (110 m^3 /h) in Germany (Lund, 2006; Bertani, 2007; Knapek et al., 2007; Wolfgramm et al., 2007; Whittaker, 2009; Herzberger et al., 2010; Bertani, 2015; Ganz et al., 2013; Mink et al., 2015; Ragnarsson, 2015; Weber et al., 2015).

In order to identify prospective locations the analysis of geological and hydrogeological parameters in the province of Małopolska was carried out. This is due to the fact that the temperature of the geothermal waters and the flow rate of the production well are determined by the physical parameters of the rock medium. To diagnosis the geological and hydrogeothermal conditions, data from 184 wells located in the Małopolska have been used. Documentation for individual wells were analyzed for acquisition of thermal data, especially temperature profile. Boreholes documentations were collected at the National Geological Archives of Polish Geological Institute in Warsaw, in the archives of the Polish Oil and Gas Company S.A located in Krakow, and also in the archives of Geotermia Podhalańska SA in Bańska Niżna.

Effects of the studies and calculations where shown on the maps of geothermal gradient distribution and maps of downhole temperature distribution at depths of 1000, 2000, 3000 and 4000 m. Thermal analysis of the data shown on the maps allowed to identify the most favorable areas. For further analysis where selected existing production wells: Banska PGP-1, Banska IG-1, Banska PGP-3, Chocholow PIG-1. In addition, the analysis was done for production well Bukowina PGP-1, despite the fact that its parameters do not meet the minimum criteria of temperature and flow rate. However, the purpose of the calculations undertaken was to show whether the initial assumptions were set correctly. Although, to a detailed analysis has been selected existing boreholes, thermodynamic models presented in the work can be implement in the future to take into consideration the potential of EGS technology.

In each case, two variants of the system were analyzed: I – the use of the maximum flow rate, II – partial use of flow rate, assuming the possibility of utilizing part of the geothermal water to produce heat or other purposes, eg. recreation (variant for boreholes with maximum flow rate Bańska PGP-1, Bańska PGP-3).

The studies showed that both technologies: ORC and Kalina Cycle, are possible to implement in Małopolska geothermal conditions, however significantly higher gross power capacity was obtained for the second of these technologies, up to 48% compared with ORC. The results concerning the potential gross power plants and analysis of plants operating in the world, confirmed the legitimacy of the use of energy accumulated in low enthalpy geothermal waters for electricity production, which confirms the thesis: "*geothermal power plants operating in the world confirm the possibility of electricity production form low enthalpy geothermal waters using organic and inorganic working fluids*." Gross power plant which is obtainable in the Malopolska province corresponds with the installed capacity of geothermal power plants operating in the world e.g. Chena Hot Springs (power plant 730 kW), Altheim (1000 kW) Bad-Blumau (250 kW) and Bruchsal (550 kW).

The analysis and calculations showed that in the province of Malopolska it is possible to generate electricity using geothermal waters. The potential gross power calculated for the selected geothermal wells, shall not exceed in the case of ORC 900 kW, and for the Kalina Cycle 1600 kW. Amount of electricity in the case of ORC technology does not exceed 3300 MWh and in the case of the Kalina Cycle does not exceed 6,300 MWh.

The results showed that assuming full utilization of flow rate (variant I), the largest gross power is possible to obtain in the case of the Banska PGP-1 and is 1,568.23 kW (efficiency 7%) assuming the use of the Kalina Cycle and share 87% of ammonia in the mixture. Capacity over 500 kW (823.68 kW) is possible to provide for Bańska PGP-3. The calculation results confirmed the crucial importance of which for the production of electricity using geothermal waters are temperature and flow rate. Both wells: Bańska PGP-1 and Bańska PGP-3 characterized the highest temperature of geothermal waters (86□C) and flow rates of 550 m^3/h and 290 m^3 h. That confirms the thesis: "*a decisive impact on the efficiency of electricity production and installed capacity of geothermal power plants are: geothermal water temperature and flow rate of the production well, determined by the physical parameters of the rock medium*" and *"analysis of geological and hydrogeological parameters for obtaining geothermal energy allows to determine the potential of electricity production that can be achieved in a geothermal power plant".*

The main problem in implementing ORC and Kalina Cycle, in the analyzed geothermal water temperature range, is low system efficiency <10% (in most cases 6–7%). This is a result of geothermal waters temperature not exceeding 90□C. The analysis does not confirm the statement made by Knapek (2007), that the Kalina Cycle is more efficient than ORC for approx. 25%. Efficiencies of the ORC calculated for dry working fluids are approx.

6%, and for wet working fluids are approx. 8%. Kalina Cycle efficiency was estimated at 6% for the mixture containing 85% of ammonia, and for mixtures containing 87% and 89% ammonia at 7%. It is right to say that in the case of power plants, which is possible using both systems, the Kalina Cycle capacity is far greater. In the case of ORC the largest possible gross capacity is 823.28 kW (R134a) for the Banska PGP-1 and it is about 48% less than the maximum gross power for the Kalina Cycle, which is 1,568.23 kW (ammonia content in the mixture of 87%).