Man-made, low-temperature geothermal reservoirs in abandoned workings of underground mines on example of Nowa Ruda coal mine, Poland

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Abstract

The flooded, abandoned underground mines form low-temperature geothermal reservoirs, are characterized by the site-specific geological, hydrogeological, and technical conditions of mining fields. The large volumeof underground open spaces with high permeabilities that are left after mining activity, in areas with relatively high geothermal gradients, may be considered as man-made reservoirs of warm mine waters. In the process of adaptation of mine workings for reservoir purposes, the subsidence of the mining area should be considered, which reduces the volume of water-filled spaces in the mine, and also the high amount of total dissolved solids (TDS) and gas in mine waters. The rate of cooling of the rock mass during mining activity and the time for thermal recovery to natural, undisturbed thermal conditions are also important. The former coal mine of Nowa Ruda in southwestern Poland is presented as an example. In the Piast mining field, the abandoned and flooded workings in the Carboniferous Lower Zacler beds contain about 5,000,000 cubic meters of water at a temperature of 16-26°C. The exploitation of the mine water for geothermal heat pumps is planned. Two two-dimensional (2-D) numerical models based on the TOUGH2 program have been developed to introduce heat exchange modeling into this mining field. The model of temperature recovery of abandoned workings shows the time required to return to natural thermal conditions in a rock massif that has cooled down during coal mining. The expected time for temperature recovery is approximately 10 years. The model of a geothermal doublet producing water at a temperature of 23°C from abandoned workings presents the rate of cooling of the reservoir at production rates of 10 l/s (thermal output power ~800 kW_{th}) and 20 l/s (thermal output power ~1600 kW_{th}).

Keywords: *geothermal reservoir, coalmine, modelling.*

1 Introduction

In recent decades, coal mining has declined in many regions of the world, causing abandonment of underground mines. Problems of reclamation and utilization of surface and underground remains of former mines arise as an important aspect of sustainable development of post-mining industrial areas. There are many abandoned coalfields around the world. Mines in France, Germany, Great Britain, the Netherlands, Poland, Spain, Slovakia and the Ukraine are the subjects of detailed reservoir engineering studies and development of geothermal utilization in abandoned workings. Several installations based on geothermal heat pumps are already working in Canada, Germany, and Scotland (Jessop, 1995; Rottluff, 1998; Burke, 2002). These show that mines that have extracted fossil fuel in the past can produce clean and renewable geothermal energy. Underground openings of abandoned, flooded mines can also be utilized as stores for discarded thermal energy from industry, or that recovered from cooling systems (Ostaficzuk, 2001).

Several examples from Poland (Malolepszy and Ostaficzuk 1999; Kurowska, 1999) show that temperatures of water in flooded mines reach more than 45°C at depths of up to 1000 m. However, it is known from some European coalfields that formation temperatures at this depth exceed 50°C. Abandoned workings of individual coal mines contain tens of millions of cubic meters of warm water, which can be recovered at the surface and utilized in heat pumps for heating as well as cooling purposes, in agriculture and snow-melting systems.

2 Reservoir characteristics

Water reservoirs can be found in almost all kinds of underground mines after termination of exploitation and abandonment of mine workings. However, this paper focuses on coalmines and their specific geological conditions. Extraction of laterally distributed coal seams forms large areas of horizontal or sub-horizontal zones of empty openings and voids, which are defined, after flooding of the mine, as water reservoirs in abandoned workings (Figure 1). The site-specific conditions of each coalfield or coal-mining area impact on the potential utilization of reservoirs for geothermal purposes (Malolepszy, 1998). Some of the factors are described below.

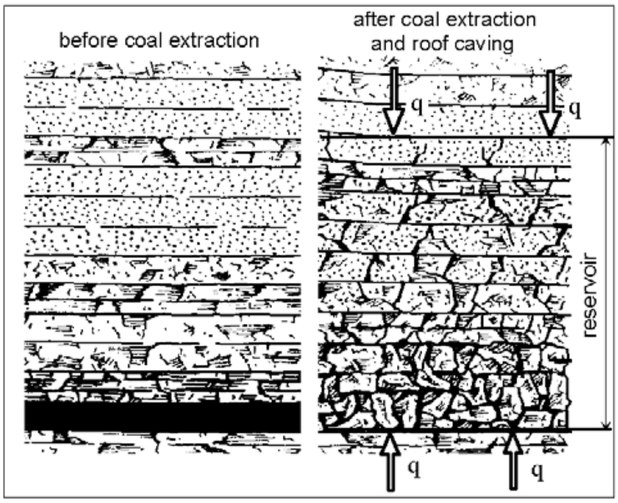

Figure 1: Water reservoir in the mine workings after extraction of coal seam and caving in of the roof. Arrows q mark heat inflow.

2.1 Geology and hydrogeology

Rock formations of coalfields generally consist of a variety of thin intercalated layers of terrigenous deposits, which are in most cases horizontally bedded. Claystone, siltstone, and sandstone rather than conglomerates are characterized by low porosities and permeabilities.

The hydrogeological regime of an abandoned mine gradually returns to its natural state if de-watering systems are terminated. At present, that process is only possible in isolated mining areas without hydraulic connection to adjacent mines, which are still in operation. Therefore, de-watering systems in abandoned mines are maintained, and waters are pumped from levels at which connected mines are preserved from. The deepest levels of abandoned workings are flooded out with cold water flowing from the shallower levels.

2.2 Geothermics

Geothermal surveying in coal exploitation areas is one of the most important branches of the underground mining industry. Numerous formation temperature measurements are made during the evaluation and monitoring of climatic conditions to ensure safe and efficient mining. This is especially important at deeper levels (depths of 1000 m and even up to 1200 m in some localities). Temperatures of rocks are measured in exploration wells drilled from the surface as well as in horizontal shallow holes drilled in shafts, roadways or coal faces deep in the mine. Results of both types of measurements can be used for the estimation of the cooling rate of the rock mass during periods of mining when ventilation air and mine waters flowing down from shallower strata act as heat absorbents. The necessity for detailed research on rates of cooling of mine rock formations, and the estimation of their thermal recovery period, is at odds with some opinions that cooled-down mine workings are useless as sources of geothermal energy. Preliminary research presented later in this paper shows optimistic results.

Coalfields are generally located in areas where the mean geothermal gradient varies between 17°C/km and 45°C/km, with an average value of 32°C/km in Polish coal fields, for example. These values give temperatures of 30-50°C at the deepest levels of the mines. The geothermal gradient has significant changes in the depth of exploitation caused by lithological variation in geological profiles of mining areas.

Terrestrial heat flow measured in coal-mining areas does not exceed average values which for European coal fields fit in the range of 40-80 mW/m^2, with regional anomalies of up to 110 mW/m^2 in the south-western Upper Silesian Coal Basin where formation temperatures are higher. Horizontally bedded rock layers with low heat conductivity coefficients form cap rocks for the inflow of geothermal heat. It is expected that thermal anomalies occur beneath thick layers of coal-bearing formations, as in many other sedimentary basins. The local anomalies are observed at exploitation depths of 1000 m in coal-mining areas where there are vertical tectonic structures and vertical or inclined rock stratification, but they do not have much impact on overall formation temperatures.

Spontaneous coal-seam fires in mines often occur in protecting pillars and other unexploited parts of the mines. Together with sulfide mineral oxidation processes, they cause considerable local temperature anomalies, which disturb the natural thermal regime of the mine. Flooding of the abandoned mines extinguishes fires, but the oxidation processes can be continued by oxygen dissolved in the water (Jessop, 1995).

2.3 Water capacity of abandoned mine workings

The water reservoir in a mine working is created by extraction of coal and waste rock. The volume of the mined spaces is equal to the volume of removed material, but after removal of the pillars supporting the roof, the volume of the remaining openings decreases significantly due to subsidence and back filling. Depending on natural and technological conditions, 5-40% of the initial volume remains open, and after flooding of the mine, is filled with water. The water capacity coefficient *c* is a major factor in the following formula (Rogoz, 1974):

$$V_z = \frac{AM}{\cos\alpha} c \qquad (1)$$

where: V_z - water capacity of mine workings [m^3]
A - area of mine workings [m^2]
M - thickness of extracted coal seam [m]
α - inclination of coal seam
c - water capacity coefficient

The coefficient *c* is determined by empirical methods in Polish coal mines. It depends on the depth of exploitation and the type of abandonment of mine workings.

In many cases, the convergence of the roof with the floor occurs under high pressures at deep levels. Generally, debris and rubble that have fallen from the roof protect against this. A considerable part of the volume of a reservoir is distributed above the extracted coal seam in the form of fractures created in the de-stressed roof (Figure 1).

Many of the shafts, drifts, and roadways remain open if the roof-supporting devices have not been removed. These open tunnels, accounting for considerable volumes in the mine as a whole, could act as possible routes of inflow/outflow into/from reservoirs in mine workings.

2.4 Post-mining conditions

Mining areas are very well mapped. Underground mapping survey work at the large scale of 1:1000 gives very detailed documentation on the abandoned workings of every extracted coal seam. Post-mining conditions occurring underground in the flooded abandoned mine can be precisely estimated when considering the potential for geothermal reservoirs.

The water reservoirs in abandoned mines are very accessible. Many of the vertical shafts remain for mine de-watering or other technological purposes and give access to deep levels of the mines where geothermal reservoirs can be located. Proper adaptation of the shafts before abandonment can help in further development of geothermal installations. Some of the wells drilled from the surface down to coal seams can still be recovered for use as production or injection wells.

For efficient geothermal utilization, local users should be in the area above the reservoirs. In mining fields, there are commonly densely populated urban areas where today many people are looking for new and environmentally clean sources of energy. The concepts of establishing low-temperature geothermal reservoirs in mine workings below these areas should meet their requirements.

3 The "Nowa Ruda" coal mine

The former coalmine of Nowa Ruda is located in southwestern Poland in the Sudety Mts. (Figure 2). The mine is divided into four mining fields. One of these is the Piast mining field, where underground workings follow several parallel coal seams, which dip from east to west at an average angle of 23°. The abandoned workings are located under the northern suburbs of the town of Nowa Ruda, approximately 1 km from the town centre. Abandoned workings are divided into two parts due to their depth. The deeper part is distributed between 460 and 890 m under the surface (+40 to -390 m a.s.l.) over a lateral area of 1 km^2. Mine staff evaluated the total water capacity of this part of the workings to be approximately 5,000,000 m^3. According to estimations from the Nova Scotia mines (Jessop, 1995), this volume of water at an average temperature of ca 21°C, if cooled down to a temperature of 3°C, would yield 376×10^{12} J or 105 GWh of thermal energy. Following the termination of mining at Nowa Ruda in 1994, the de-watering system was shut off in 1995 and during the following 5 years most of the workings were filled with water. It is expected that at the deepest levels of the mine, the temperature of water filling these workings may reach 26°C. The idea of the utilization of heat from warm mine waters using heat pumps has been considered for a few years by local authorities, and the Board of the former mine in

Nowa Ruda. It may be possible to pump water from abandoned mine shafts, as well as from wells drilled from the surface down to the mine workings.

The geothermal gradient in the area was calculated on the basis of temperature logs of wells GN-17 and GN-12 located in the western part of the mining field. Bottom temperatures measured in the wells are 34.8°C in well GN-17 at 1220 m depth and 30°C in well GN-12 at 930 m depth. Considering the annual average air temperature of 8°C, the average value of the geothermal gradient is ca 23°C/km. Terrestrial heat flow in the area has been evaluated at approximately 60 mW/m^2.

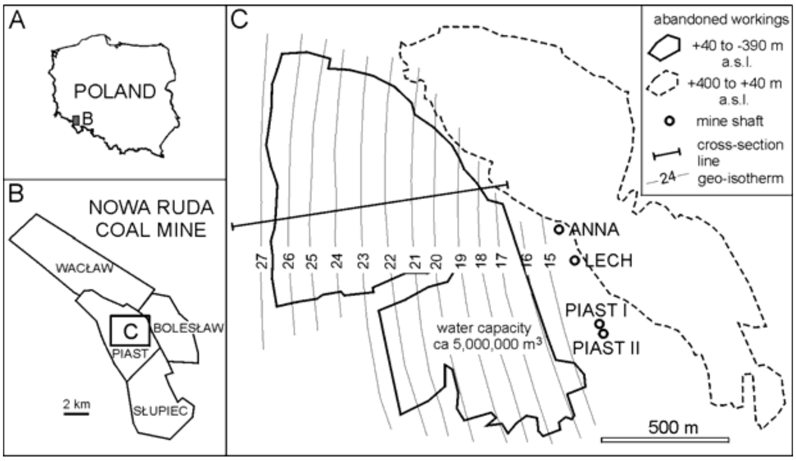

Figure 2: Location map of abandoned workings within the Piast mining fields of the Nowa Ruda coal mine. Formation temperatures at the base of deeper workings demarcated with the solid bold line are shown by geo-isotherms (after "Nowa Ruda" Mining Survey Documentation).

3.1 Numerical Simulation

Two 2-D models based on TOUGH2 code (Pruess *et al.*, 1997) have been developed for the numerical simulation of heat exchange processes in the flooded workings of the Nowa Ruda mine.

1. A vertical cross-section model in the E-W direction for simulation of temperature recovery of mine workings to natural, undisturbed thermal conditions. The disturbed conditions due to mining activity were simulated in a set of 14 runs representing gradual excavation of the workings over 200 years. The conductive heat flow proceeds from the surrounding rock mass into five grid blocks representing abandoned workings at various depths. The simulation, in the deepest part of the workings heat flow, exceeds 1.2 W/m^2, which is 20 times greater than terrestrial heat flow in the area. The temperature rise due to heat flow into separate blocks is also presented and it shows the time of temperature recovery. The highest increase of temperature is predicted to occur during the first 10 years, when it would reach 80-90% of the natural temperature. This is a rather optimistic result compared to the expectation of temperature recovery over a few hundred years (Jessop, 1995).
2. Planar model of abandoned workings. The 2-D model covers a total area of 4.5 km^2 and represents one 50-m-thick layer of rocks in the deeper part of the abandoned workings of the Piast mining field. This model has 1632 grid blocks. The layer dips to the west at an angle of 23°. In the first stage of simulation, natural conditions were modeled assuming terrestrial heat flow from the lowest part of the model. In the next stage, the production and injection of mine water were simulated. Two hypothetical wells of a geothermal doublet were placed at a

horizontal distance of 1500 m. The producer was drilled to the deepest part of the workings (660 m) in order to take the water at a temperature of 23°C. The injector was drilled to a shallow part of the workings (350 m). It injects water cooled to 2-4°C. Two production flow rates were considered: 10 and 20 l/s. Assuming cooling of water at the surface by 19°C, the doublet provides 800 or 1600 kW_{th} according to flow rates. The temperature drop in the reservoir has been simulated for production of water over a period of 40 years. The temperature drop was calculated at 4°C for 10 l/s and 10°C for 20 l/s.

4 Conclusions

Abandoned, water-filled mine workings form reservoirs of low-temperature geothermal water constitute a significant, but little-studied, geothermal resource that can be used with the application of heat pumps for space heating, recreation, agriculture, and industry. Direct use of warm water from the mines is possible in, for example, snow-melting systems.

The preliminary numerical simulations of heat exchange in abandoned workings within the Nowa Ruda coal mine show that the Piast mining field is the most suitable location for geothermal water exploitation. Developed 2-D models present the temperature recovery in cooled workings and the temperature drop in the reservoir due to production/injection of mine waters by a geothermal doublet. The temperature recovery time in abandoned workings was evaluated at approximately 10 years. Assuming natural-state temperatures in the second model, it is expected that producing 1.6 MW_{th} by pumping water at rate of 20 l/s would cause the water temperature to drop from 23°C to 18°C over a period of 25 years.

Acknowledgments

The author wishes to acknowledge the Coal Mines Restructurization Board for the archival data on the Nowa Ruda coal mine. Thanks to Dr Ingvar B. Fridleifsson, the director of the UNU Geothermal Training Programme, for encouragement for writing this paper and financial support for participation in IGC 2003.

5 References

Burke T. (2002). *The use in Scotland of flooded mine workings as a source of geothermal energy*. In: Geothermal Energy in Underground Mines. Z. Malolepszy (Ed.), pp. 191-200, Sosnowiec.

Jessop A. (1995). Geothermal energy from old mines at Springhill, Nova Scotia, Canada, *World Geothermal Congress Proceedings*, pp. 463-468, Florence.

Kurowska E. (1999). Disturbance of geothermal field of the Upper Silesian Coal Basin due to mining activity. *Bulletin d'Hydrogeologie.* Peter Lang (Ed.), Centre d'Hydrogeologie, Universite de Neuchatel Vol. 17, pp. 77-82.

Malolepszy Z. (1998). *Modelling of geothermal resources within abandoned coal mines, Upper Silesia, Poland.* In: UNU Geothermal Training Programme Reports, pp. 217-238, Reykjavik.

Malolepszy Z., and Ostaficzuk S. (1999). Geothermal potential of the Upper Silesian Coal Basin *Bulletin d'Hydrogeologie.* Peter Lang (Ed.), Centre d'Hydrogeologie, Universite de Neuchatel Vol. 17, pp. 67-76.

Ostaficzuk S. (2001). The underground store for thermal energy. *Technika Poszukiwan Geologicznych, Geosynpotyka i Geotermia*. No. 5, pp. 89-94, Krakow.

Pruess K., Finsterle S., Moridis G., Oldenburg C., Yu-Shu Wu. (1997). *General-purpose reservoir simulators: the TOUGH2 family,* Lawrence Berkeley National Laboratory Reports, No. 40140.

Rogoz M. (1974). *Water capacity of coal mine workings.* Prace Glownego Instytutu Gornictwa, Komunikat 628, Katowice (in Polish).

Rottluff F. (1998). NeueWarmepumpenanlage im Besucherbergwerk Zinngrube Ehrenfriedersdorf. *Geotermische Energie,* No. 21, pp. 8-11, Geeste.