Transforming flooded coal mines to large-scale geothermal and heat storage reservoirs: what can we expect?

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Abstract The Heerlen mine water system is a unique renewable energy project providing heat and cold from the flooded mines to clients in several parts of the city. In order to answer surface demands, the behaviour of the underground reservoir should be understood. VITO developed several models to describe flow within the reservoir. Flooded mines are atypical reservoirs characterized by a complex geometry and by the combination of at least three types of flow: through open pipes, fractures and porous zones. Modeling the water and heat flow in such reservoirs is a challenge, as existing numerical codes are developed for specific environments. This paper describes the modeling-approaches that have been followed. Monitoring of geochemical parameters in the mine water during time helped validating and calibrating the models. Provided a strategic match between surface demands and subsurface supply, mine water can contribute to smart cities through renewable energy use and temporal energy storage.

Key Words geothermal energy, mine water, flow modeling, monitoring

Introduction

Since October 2008 a mine water network and two interconnected mine water energy plants opened in the municipality of Heerlen (Netherlands). The network was set up as large-scale geothermal & cold-heat storage system. It extracts low-enthalpy geothermal energy from the water-flooded Oranje Nassau mines. Five interconnected wells at different depths extract and/or store heat or cold. About 300 dwellings and a number of service centers are served by the district heating system.

This Interreg-IIIb demonstration project proved the technical feasibility of such mine water plants. Today, the system still is unique in its set-up and the geochemical monitoring data is of high learning value. VITO developed a series of hydrogeological models in order to predict the flow and temperature behaviour of the mine. Each approach describes part of the system, providing insight in certain processes, but also has its limitations. The goal of our modeling efforts is not to build a heavy, integrated model – which would always be a simplification of the remaining underground structure of the mines - but to dispose of efficient tools that will contribute to more adequately match the variable heat demands through time with the reservoir capabilities.

The mine water reservoir

In fact, the Heerlen mine is a large complex of four interconnected mines belonging to the Oranje Nassau (ON) colliery, extending over more than 50 km^2, and encompassing six main depth levels of stonedrifts (Figure 1). The shallowest mined out areas up to above zero (Dutch sea level standard: NAP) level are situated in the south, while the deepest mined levels are below -600m NAP. Vertical interconnections between stonedrifts, galleries and mined panels are omnipresent in the form of shafts and blindshafts. During the exploitation period old mined out parts were backfilled or left over to collapse. The result is a huge complex reservoir full of heterogeneities. Since the closure of the mines in 1974, the condition of former open structures has become unsure, hence complicating the set up of a 3D geometric model of open and interconnected spaces through the mine.

After closure of the mines in Dutch Limburg, all shafts were sealed off for safety reasons and the connections between neighboring collieries dammed. Only a small sounding tube within the main shaft of three regional mines (Oranje Nassau-I, Wilhelmina and Julia) was left open for regular monitoring of the rising mine water level. Between 1999 and 2011 the water level in the ON mines rose from -30m NAP to +10m NAP. Today the ON-mines have been flooded nearly completely, leaving open spaces only in the southernmost part of the ON-I mine, i.e. the shallowest area of the mine. Nevertheless, monitoring records of the water level and water chemistry in the various wells indicate that the flooded part has not yet reached saturation and active inflow from the coal massif to the water-filled pipes is still going on.

The geothermal gradient in the mine water reservoir revealed to be between 3.2 and 3.4 °C/100 m, while the overburden sediments show a lower gradient around 2 °C/100m. Actually, warm water between 27° and 32 °C is available from the deepest mined out areas in the north (HH1 and HH2 wells; Fig. 1) and cold water from the shallower levels to the south (HLN1 and HLN2 wells) can be produced at a temperature between 15° and 18 °C. Because of the numerous existing interconnections between depth levels, the location

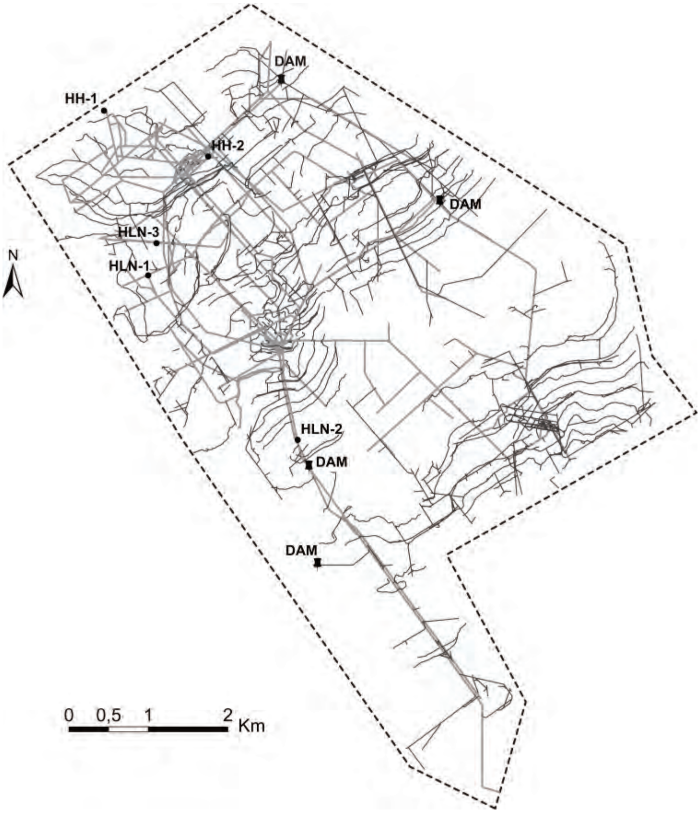

Figure 1 *Schematic plan of the combined four Oranje-Nassau (ON) mines in Heerlen with indication of the concession area (shaded line), the hot wells HH1 and HH2, the cold wells HLN1 and HLN2 and the "intermediate" HLN3 well, dams, major stonedrifts (bold lines) and main galleries (thin lines).*

of the production and injection wells, as well as fluid flow and heat modeling, is crucial for a sustainable exploitation of the project. Sustainability can be improved easily by using the reservoir also for storage of excess surface cold and heat through the use of buffer wells (e.g. HH2) and the temperature zones in the mine. According to the return temperature-level, injection can be performed flexibly into cold, warm or intermediate zones. Through the application of low-exergy building principles for the mine water-served clients, the extra temperature shift that needs to be added by electric heat pumps can be kept minimally. Heat and cold thus are provided largely by the mine water reservoir.

Water quality of the ON-mine water varies from fresh to slightly brackish. Analysis of geochemical data from the old mine archive allowed to distinguish between at least three types of water (dominant $Ca(H_2CO_3)_2$, $NaHCO_3$ and NaCl types) that infiltrated at different depths during and after mining. These identified water types correspond well with the regional aquifer water zones described by Kimpe (1963). Original geochemical zonation is still reflected to some degree in recent water samples from the flooded mine at various depths and suggests geochemical stratification of the mine water. pH mostly varies between 6.5 and 7.5 in line with carbonate buffering and moderate iron (1—7, locally up to 14 mg/L) and sulfate (500—650, locally up to 1100 mg/L) concentrations. Geochemical parameters such as major ion concentrations, pH and electric conductivity (EC), have been used for monitoring and following up flow patterns through the mine. EC tends to increase with depth - varying between 0.6 and 8.5mS/cm - making it a useful marker for distinguishing between shallow and deeper sources. Minor concentrations of dissolved CO_2 and CH_4 could be perfectly handled by controlling the pressure in the system and by keeping the circuit closed.

Pump tests and production monitoring

In 2006 and 2008 pump tests (simultaneous production and injection between two wells with gradually increasing flow rates) were performed on the newly drilled wells to test the connectivity inside the reservoir and the performance of the productions wells. Very good pressure communication and only slight draw-down were observed. At moderate flow rates and in large stonedrifts pseudolaminar flow conditions, reflected by linear draw-down, apply. In the narrowest gallery (maximum transection of $9m^2$) transition to turbulent flow conditions started around $80m^3/h$, although it should be noticed that here the liner is placed very close to the gallery wall. Targeting a narrow gallery at 700m depth based on ancient mine maps and without knowing the post-closure deformation history indeed is a challenge. In the stonedrifts (transection of 12 to $18m^2$) transition to more turbulent flow started between 170 and $220m^3/h$.

Zigzag patterns in pressure evolution indicate local and downstream pressure build-ups and releases. Such cyclic storage patterns testify of critical flow rates and pressure thresholds that need to be overcome before the reinjected water effectively enters the reservoir pore spaces.

Pump tests showed that production and injection rates of up to $250m^3/h$ in the stonedrift system are possible thanks to an efficient flow towards the wells. Draw-down on each well differs according to its connection to nearby open mine infrastructure (e.g. close to shaft area). However, high flow rates can cause early short-circuiting and thermal breakthrough as the volumes of water at a certain temperature are limited and vertical connections can cause mixing between temperature zones. Actually, relatively low flow rates (maximum $55m^3/h$) are required to deliver the needed heat and cold to the clients. At such flow rates, delivery of the desired temperatures can be secured if return flows are adequately handled. The temperature evolution through time at a production well depends on the combination of active wells (producers and injectors), their interconnectivity and distance to shaft areas, the applied flow rates and the volume of water available from a certain depth (temperature) level. Because of the complex geometry and coupled parameters this temperature evolution can only be predicted by numerical modeling. The monitoring data from pump tests and regular heat/cold delivery serves to validate and calibrate models.

One complexity inherent to mine water reservoirs which highly complicates the modeling of flow and heat transfer is the combination of (i) matrix, (ii) fracture and (iii) open pipe flow. Our monitoring data proves that the three types of flow are effectively involved, although locally the effect of one or another type of flow may be more or less important. Nearby the cold well HLN1 the presence of a fractured zone in connection to the overburden rock has been inferred, which is responsible for the inflow of anomalously cold and sweet water to the well. Although the contribution of open pipe flow is predominant, especially at higher flow rates, after each production stop the cold anomaly is regenerated. The other cold well HLN2 unexpectedly produced slightly warmer water than elsewhere at the same depth level. Here, the effect of still active inflow from the coal massif to the already completely flooded open pipes may be responsible for a quite important flow from north (completely flooded) to south (undersaturated area). This inflow occurs at all depth levels at corresponding temperatures and gets concentrated in the shaft area where it flows upward and subsequently, the mixed water at intermediate temperature is transported to the main south-directed stonedrift. HLN2 thus receives a significant contribution of water from deeper levels via the nearby shaft area.

Modeling

The first approach followed to set up numerical models for describing the water flow and heat transfer in the mine water reservoir was to use fully coupled (fluid flow, heat transfer, chemical reactions) finite difference codes. As the coupled models get heavy and slow with increasing degree of heterogeneity and detail requiring grid refinements and adequate time-steps, the mine geometry needed to be simplified and abstracted to its most basic structure (Fig. 2). Lessons learnt from these modeling exercises, making use of the SHEMAT software, are the relative importance of advection and conduction, the impact of induced flow circuits, the time needed to reinstall thermal equilibrium between water and rock after a period of production / injection. Although the direction of temperature changes can be predicted with this type of models, no absolute capacity estimations can be performed as the number of interconnections between depth levels is strongly limited and the volumetric capacities highly underestimated. Using the same numeric code for a fully detailed geometry is quite impossible because of the computing capacity required and the multiplication of numeric instabilities. As a comparison, the basic models run by SHEMAT already comprised about 500.000 grid cells and required weeks of computing time to simulate a complete pump test consisting of 10 to 20 transient periods.

Although coupled finite difference methods are appropriate in predicting directions of processes, the effect of a complex mine geometry cannot be verified and the predictions are time-consuming. A fast alternative is making use of analytical or semi-empirical approaches. Rodriguez and Díaz (2009) developed an algorithm to predict the temperature of produced mine water by considering a mine as a big heat exchanger consisting of one or more open standard pipes that can be divided in a series of slices. Heat transfer is simulated as pure conduction between the rock mass and the circulating mine water and through an iterative process that generates the temperature output of a cell based on the result in the previous cell. This gives an idea of the total energy

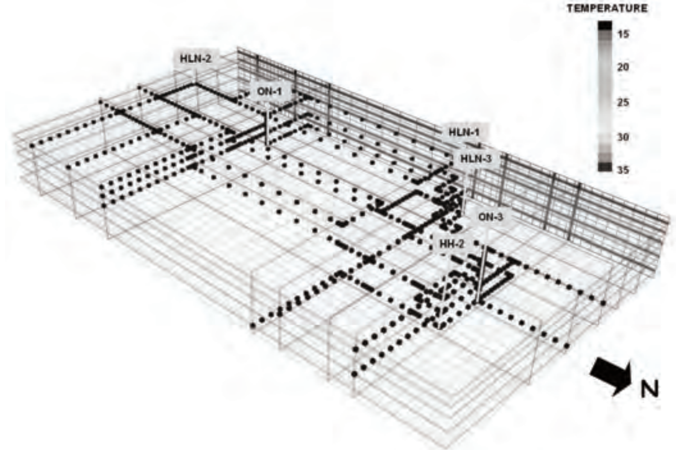

Figure 2 *Simplified geometry used for fully coupled flow-heat modeling showing the considered stonedrifts (shaded lines), shafts (ON1 and ON3) and wells.*

capacity of the mine water reservoir and of the general temperature evolution through time. Such approach works well for dry mines where water is pumped through in order to exploit geothermal heat by conductive heating of the water and for very simple geometries. However, if many vertical interconnections between various depth levels occur, or if advection from the rock massif towards the open pipes plays a role, the Rodriguez model becomes less accurate.

In order to come up with a fast-computing, flexible and accurate model that can handle the typical geometry of a mine VITO developed its own custom-made model. We combined a hybrid node-loop approach (based on the EPANET code from EPA; Rossman 2000) to integrate the complex geometry and advective flows, with a semi-empirical approach (based on Rodriguez and Díaz 2009) to simulate the heat transfer between water and pipe walls (Fig. 3). Simulation runs of different pump scenarios show that the shaft areas have a buffering effect with respect to temperature as flow vectors are split up many times. Also, a delay in thermal breakthrough is predicted thanks to the “averaging out” effect resulting from thermal equilibration through the many slow sideflows.

Conclusion and perspectives

Scaling up the mine water network is a prerequisite to guarantee sustainable exploitation. Also, in order to exploit the full capacity of the mine water network, proper matching between surface demands and subsurface supply is essential. Therefore, efficient modeling tools are needed to understand, predict and control the mine water reservoir behavior. Our modeling efforts aim at an efficient, flexible reservoir model that is able to handle the inherent complexity of a mine. Fur-

Figure 3 *Complex mine geometry with main connections used for the modeling of flow and heat by the adapted EPANET-code.*

thermore, it implies intelligent thermal grids on surface combined with a well-known and steerable geothermal reserve or buffer that can also store excess heat and make up shortages. Even hybrid systems are theoretically possible. The development of smart sustainable cities will increase in the future and - provided a good strategic setup - mine water projects can play a vital role in these developments.

Acknowledgements

Part of the research has been carried out within the framework of the “Remining” project funded by the European Commission (Concerto program). The Municipality of Heerlen and CorioEnergy are thanked for the permission to use test and production data.

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