Modelling heat and salinity related convective processes in deep mining flooded wells

Guillaume Reichart[1], Laurent Vaute[2], Pauline Collon-Drouaillet[3], Michel A. Buès[1]

[1]LAEGO, Nancy Université, rue du doyen Marcel Roubault - F 54501 Vandoeuvre-lès-Nancy,, France, guillaume.reichart@ensg.inpl-nancy.fr; [2]BRGM, 1 avenue du Parc de Brabois, F-54500 Vandoeuvre-lès-Nancy, France, l.vaute@brgm.fr; [3]CRPG-CNRS, Nancy Université, ENSG, rue du doyen Marcel Roubault, BP 40, F-54501 Vandoeuvre-lès-Nancy, France, pauline.collon@ensg.inpl-nancy.fr

Abstract The twenty-first century sees a generalization of the consideration of sustainable development issues. In the Lorraine Coal Basin (France) after an intensive mining activity, the cessation of mine water extraction has led to the flooding of old mining exploitations: the resulting reservoirs could be valorized by using a geothermal solution. In this context, characterizing and modelling the thermal-hydrodynamic-chemical functioning of those reservoirs are primordial. Convective processes in the Vouters 2 well account for its temperature and electric conductivity logs. Logs profiles are interpreted as a thermohaline staircase, which can appear when salinity and temperature gradients both increase with depth.

Key Words flooded mine, modelling, convection, heat, hydrodynamics, Lorraine

Introduction

In Lorraine (France), industrial mining began in the 19th century and reached a peak in the 1960s, followed by a decline that had finally led to mines closure in the 1980s-1990s. Today, two main facts can lead to a geothermal solution: (i) flooded coal mines represent a major water resource and (ii) the search for non-fossil new energies coincides with the end of the coal extraction cycle in this region.

Many approaches for modelling the functioning of flooded reservoirs exist. An investigation uses physically-based distributed flow and solute-transport models, considering that flow and transport take place only in channel or pipe networks (Hamm *et al.* 2008). More complex developments consider interactions between the porous media and the flooded mine workings through coupling continuum porous media with a box model (Brouyère *et al.* 2009) or a pipe-network model (Adams *et al.* 2001) used for mine conducts. Before considering a larger scale where the well interacts with the surrounding mine network and porous medium, our study is currently focused on the functioning of a well with its connected entrances and associated inflows or outflows of water. Complex convective processes can occur in wells (Wolkersdorfer 2008) and common modelling approaches are not suitable. The software used for simulating flow, heat and transport in the well is COMSOL Multiphysics®, which is able to deal with many different coupled physics.

Site description

The Lorraine coal basin is located along the eastern edge of the Paris Basin (France). It covers an area that is 140 km long (W-E) and 70—80 km wide. The Lorraine coal-bearing deposit dates from the Westphalian and Stephanian (Carboniferous) and is formed of intercalated veins in a complex sequence of argillites, sandstones and conglomerates of laterally various nature and thickness. The north-east fraction of the deposit was the only part exploited as it is shallower (80 m deep minimum) than western deposits (up to 1400 m deep) which are increasingly buried under upper Permian conglomerates overlain by the Trias sandstone and limestone aquifer formation. Due to fracturation and partial destruction of the Permian conglomerates, collapsed zones enabled water from the Trias sandstone aquifer to infiltrate into the mine galleries. A major folding phase called Saalian phase occurred at the end of the Hercynian compression and accounts for the numerous faults of the basin, the most important ones delimiting the exploitation areas, as the WNW Saint Nicolas fault and the NE-SW Hombourg fault in the studied zone of the Vouters 2 and Simon 5 reservoirs (respectively SW and NE rectangles in fig.1). 58 wells were bored in the concession, 3 of them still accessible and useful for the study: Vouters 2, Marienau and Simon 5 (respectively labeled V, M and S in fig. 1).

As for water chemistry in the site, samples taken in the mine during its exploitation highlight three main types of water (Fabriol 2008): (i) low mineralized water coming from the Trias sandstone aquifer, (ii) sulfate-rich water resulting from flows in the mine and (iii) highly mineralized water found in the lowest levels of the mine.

Double-diffusive convection (DDC)

Briefly, there are broadly two regimes for DDC (Love *et al.* 2007): monotonic convection (sometimes referred to as the fingering regime) and oscillatory convection.

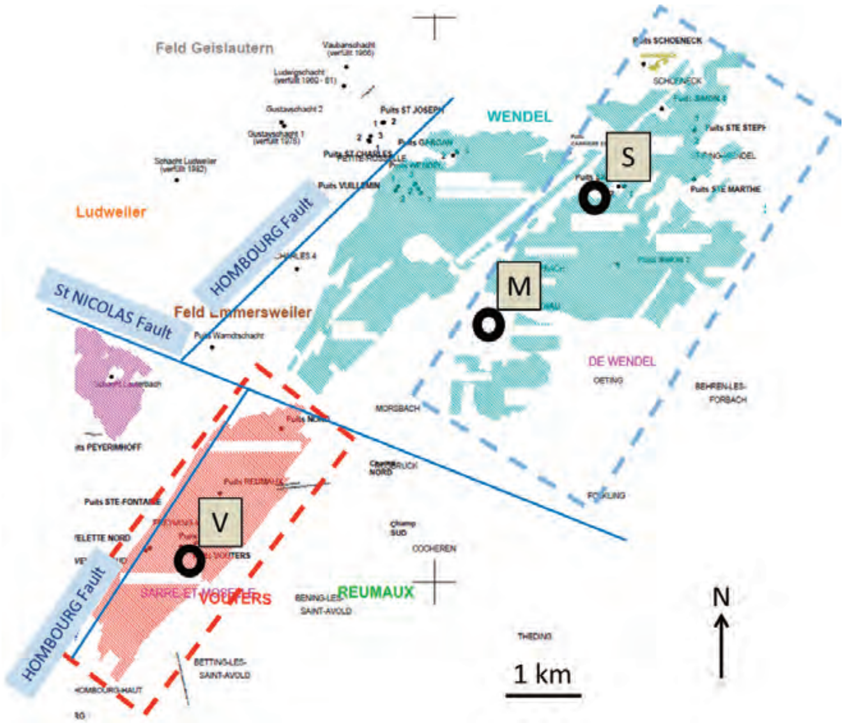

Figure 1 *Map of studied exploited area of the Lorraine coal basin (V, M and S stand for the Vouters 2, Marienau and Simon 5 wells).*

DDC can occur where the density of the fluid is affected by at least two components with different diffusivities. Combined heat and salt transport (thermohaline convection) is one specific subset of the more general DDC problems. In thermohaline phenomena, the thermal diffusivity D_T (m^2/s) is approximately two orders of magnitude higher than the solute diffusivity D_S (m^2/s). Under certain conditions, this may result in gravitational instabilities due to the phase lag between the faster diffusing heat and the slower diffusing solute.

If one considers a parcel of hot salty water that is displaced upward, the parcel will diffuse heat more rapidly than it diffuses salt, which will result in instability across the interface. As the perturbed parcel of water still rises (losing heat more rapidly than it loses salt) it eventually becomes heavier than the surrounding fluid at which point it begins to descend. The parcel of water will descend beyond its original position, warming as it sinks. The parcel eventually becomes less dense than the surrounding fluid at which point it begins to rise again. An oscillatory motion results.

The initial instability starts as a growing oscillation near the bottom (Kundu 1990). As the heating is continued beyond the initial appearance of the instability, a well-mixed layer develops (as shown for Vouters 2 in A - fig. 2), capped by a salinity step and a temperature step. The heat flux through this step forms a thermal boundary layer (A – fig. 2). As the well-mixed layer grows, the temperature step across the thermal boundary layer becomes larger. Eventually, the Rayleigh number across the thermal boundary layer becomes critical, and a second convective layer forms on top of the first (B – fig. 2). The second layer is maintained by heat flux (and negligible salt flux) across a sharp laminar interface on top of the first layer. This process continues until a stack of horizontal layers forms one upon another. From comparison with the Bénard convection, it is clear that inclusion of a stable salinity gradient has prevented a complete overturning from top to bottom. In the case of the Vouters 2 well, the location of the sharp interfaces corresponds to gallery entrances (C – fig. 2), suggesting that convection is forced by incoming water flows at those levels.

Conceptual model of the mine shaft

The well is modelled as a vertical circular cylinder (fig. 3) whose top and bottom are rigid and at constant temperature and constant concentration and whose lateral wall is impermeable and rigid and at a constant temperature and constant con-

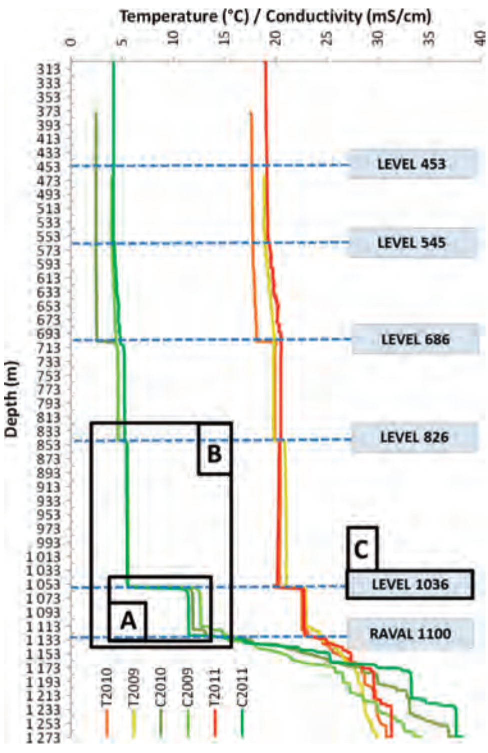

***Figure 2** Electrical conductivity (on the left) and temperature profiles (on the right) in Vouters 2 well for years 2009, 2010 and 2011(A: Well-mixed layer capped by a step – B: thermohaline staircase – C: step corresponding to a gallery entrance).*

centration. Constant gradients are applied in both T (z) and C (z) boundary conditions on the lateral wall.

The basic theory of the used set of equations was first published by Gershuni and Zhukhovitskii (1976). The Oberbeck-Boussinesq approximation is invoked: the fluid is considered incompressible, and density differences are sufficiently small to be neglected, except if they appear in gravity terms with g (m/s^2), acceleration due to gravity. In this case, density can be expressed as a function of temperature and salinity by

$$\rho = \rho_0\big(1 - \alpha(T - T_0) + \beta(S - S_0)\big), \quad (1)$$

where ρ, ρ_0, α, T, T_0, β, S, S_0 are respectively the density (kg/m^3), reference density, thermal expansion coefficient (K^{-1}), temperature (K), reference temperature, solute expansion coefficient (m^3/mol), salinity (mol/m^3) and reference salinity.

Velocity $\vec{v}$, pressure P, temperature T and salinity S depend on the set of equations

$$\vec{\nabla}.\vec{v} = 0 \quad (2)$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v} = -\frac{\vec{\nabla} P}{\rho_0} + \frac{\rho}{\rho_0}\vec{g} + \upsilon\vec{\nabla}^2\vec{v} \quad (3)$$

$$\frac{\partial T}{\partial t} + (\vec{v}.\vec{\nabla})T = D_T\nabla^2 T \quad (4)$$

$$\frac{\partial S}{\partial t} + (\vec{v}.\vec{\nabla})S = D_S\nabla^2 S. \quad (5)$$

A basic solution ($\vec{v}_0$, P_0, T_0, S_0, ρ_0) is obtained: constant temperature, hydrostatic pressure, and salinity and density fields without any motion of the fluid. This solution is perturbed by a small amount ($\vec{v}'$,P', T', S' ρ') = ($\vec{v}$, P, T, S, ρ) - ($\vec{v}_0$, P_0, T_0, S_0, ρ_0) and the system is linearized, then reduced, so that $(\vec{v'}, P', T', S', \rho')$ becomes $(\vec{\bar{v}}, \bar{P}, \bar{T}, \bar{S}, \bar{\rho})$.

Small disturbances from the basic solution satisfy the set of equations

$$\vec{\nabla}.\vec{\bar{v}} = 0 \quad (6)$$

$$\frac{1}{P_r}\left[\frac{\partial \vec{\bar{v}}}{\partial t} + (\vec{\bar{v}}.\vec{\nabla})\vec{\bar{v}}\right] = -\vec{\nabla}\bar{P} + Ra_T\bar{T}\vec{e}_z - Ra_S\bar{S}\vec{e}_z + \vec{\nabla}^2\vec{\bar{v}} \quad (7)$$

$$\frac{\partial \bar{T}}{\partial t} + (\vec{\bar{v}}.\vec{\nabla})\bar{T} = \nabla^2\bar{T} \quad (8)$$

$$\frac{\partial \bar{S}}{\partial t} + (\vec{\bar{v}}.\vec{\nabla})\bar{S} = Le^{-1}\nabla^2\bar{S} \quad (9)$$

$$\bar{\rho} = -\alpha\Delta T.\bar{T} + \beta\Delta S.\bar{S}, \quad (10)$$

where ΔT and ΔS are the temperature and salinity gaps between top and bottom of the water column, Pr = υ / D_T is the fluid Prandtl number and Le = D_s / D_T the Lewis number. The thermal and solutal Rayleigh number (Ra_T and Ra_S) are defined by

$$Ra_T = \frac{g\alpha H_f^3\Delta T}{\upsilon D_T} \quad (11)$$

$$Ra_S = \frac{g\beta H_f^3\Delta S}{\upsilon D_S}. \quad (12)$$

Stability criteria (Love *et al.* 2007) mostly based critical, thermal and solutal Rayleigh numbers are used to choose adapted aspect ratio (radius r of the well divided by the length H_f of the water column) and to weigh respective influences of temperature and salinity gradients (represented by ΔT and ΔS). Parameters values of Vouters 2 were tested with these criteria and maintain the occurrence of oscillatory double-diffusion. The well has a 3.75 m radius for a 900 m high water column. The temperature gradient is the local geothermal one of 3 °C/100 m and the salinity gradient is taken at 0.19 mol/m^4 (or 11 mg/L/m), based on averaged values for different wells in the basin.

Simulation results

In order to study different convective processes, we activated separately the temperature gradient

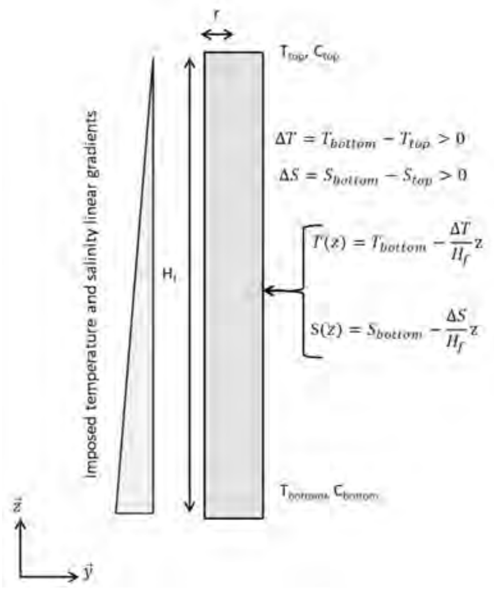

Figure 3 *Conceptual model of a 2D vertical cylindrical well and associated boundary conditions.*

and the salinity gradient before combining them. Water entrances in the well were added to test appearance of steps at these levels. Free thermal and free solutal convection simulations give good results, with development of convection cells in the water column (A - fig. 4). Velocities are observed and have a mm/s magnitude. Thermosolutal convection simulation results do not show thermohaline staircase at the date of the article, even if convection cells similar to these of free thermal convection can be observed. The presence of an additional gallery entrance does not trigger the phenomenon, but can make forced convection overpower free convection if inflow velocity is too high, with a cm/s magnitude here (B - fig. 4).

Conclusions

The Lorraine coal-basin is a complex hydrogeological system, formed by the superposition of a sandstone aquifer formation flowing through fractured conglomerates down to the flooded mine. We have selected a quasi-isolated reservoir from the entire exploited area to model its thermal-hydrodynamic-chemical (THC) functioning. Interpretation of electric conductivity-temperature logs in the Vouters 2 well highlighted the presence of free double-diffusive oscillating convection due to coupled actions of salinity and temperature gradients.

A numerical model is being built to understand this phenomenon and its impact over the whole Vouters 2 reservoir. Thermal convection or solutal convection is properly reproduced in a water column with or without forced flows, though the combination of both convections does not produce a thermohaline staircase yet. Current efforts are focused on setting adapted parameters for the COMSOL solver. We are also building up a digital three-dimensional geometry model and intend to integrate the simulation results into the future THC model.

Acknowledgements

The authors wish to acknowledge financial support of the Conseil Régional de Lorraine and both ICEEL and IC-BRGM Carnot Institutes. This work forms part

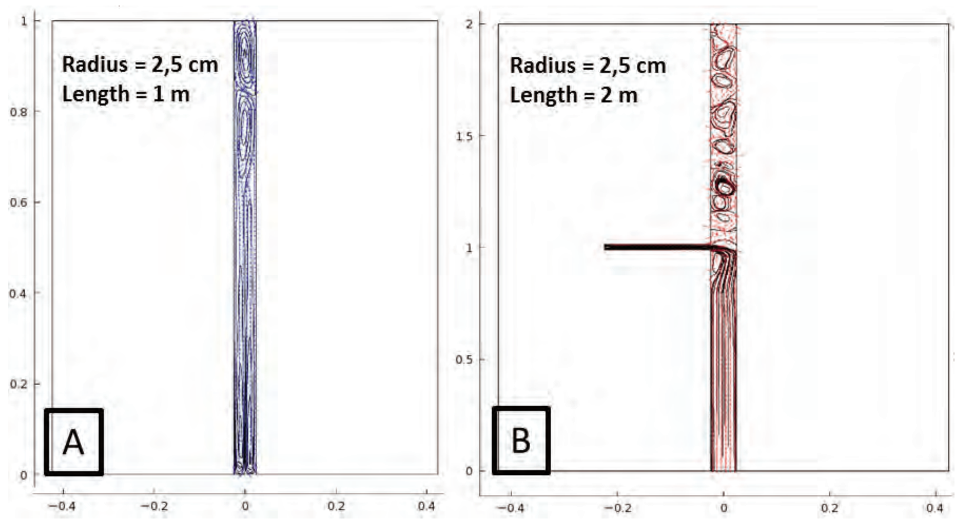

Figure 4 *Free thermal convection (A) and mixed thermosolutal convection (B): streamlines showing convection cells.*

of the research program carried out by the GISOS Research Group for the Impact and Safety of Underground Works.

References

Adams R, Younger PL (2001) A strategy for modeling groundwater rebound in abandoned deep mine systems. Groundwater, 39(2):249—261

Brouyère S, Orban P, Wildemeersch S, Couturier J, Gardin N, Dassargues A (2009) The hybrid finite element mixing cell method: a new flexible method for modelling mine groundwater problems. Mine Water Environ, 28:102—114

Fabriol R. (2008) Projet MINEWATER. Etude de préfaisabilité – Chimie de l'eau dans le bassin houiller lorrain. BRGM/RP-56907-FR, 48 p., 7 fig., 10 tab. 3 annexes.

Gershuni, G. Z., and E. M. Zhukhovitskii (1976), Convective Stability of Incompressible Fluids, Keter, Jerusalem.

Hamm V, Collon-Drouaillet P, Fabriol R (2008) Two modelling approaches to water-quality simulation in a flooded iron-ore mine (Saizerais, Lorraine, France): a semi-distributed chemical reactor model and a physically based distributed reactive transport pipe network model. J Contaminant Hydrology, 96(1—4):97—112

Kundu P. K., (1990) Fluid Mechanics, Academic.

Love, A. J., C. T. Simmons, and D. A. Nield (2007), Double-diffusive convection in groundwater wells, Water Resour. Res.43, W08428, doi: 10.1029/2007WR006001.

Wolkersdorfer C (2008) Water management at abandoned flooded underground mines: fundamentals, tracer tests, modelling, water treatment. Springer-Verlag, Heidelberg, 465 pp