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Flow and Heat Transfer Modelling in the Hainaut Limestone Geothermal Reservoir: Study at Local and Regional Scales

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ABSTRACT

Nowadays, Europe needs to produce more sustainable energy. A possible solution includes geothermal energy. Many geothermal sites are already actively being used in France, Germany or Italy for example. In Belgium, research is currently performed in the Campine Basin. In the Mons area (South-West Belgium), some wells have been exploited since the 80's. They were drilled in a deep limestone reservoir characterized by some highly permeable breccia levels.

This reservoir has not been studied extensively, despite potentially significant heat reserves. In this context, the MOREGEO project has been initiated by the University of Mons and the IDEA (inter-municipality active in the area) with financial support from the ERDF European program. The general objective of this project is to drill a new geothermal doublet to provide heat to the largest city hospital. Hot water will be pumped from a well and cold water will be reinjected in another one. Specific objectives of the project include: (1) Modelling heat transfers at the scale of the new geothermal doublet; and (2) Modelling the whole geothermal reservoir in order to provide an efficient management tool for the future development of additional geothermal wells.

The geothermal reservoir of Hainaut is mainly composed of limestone from the Carboniferous period, with breccia and evaporite levels. Three wells currently provide energy for the heat production of two hospitals, schools, station, housings and an economic area. The depth of the exploited layers is around 2000 meters and the pumping groundwater temperature is about 70°C.

A first numerical model has been developed at the scale of the future new geothermal doublet. Numerical models are implemented using HydroGeoSphere and Feflow. These calculation codes simulate fluid flow, solute and heat transport in porous and fractured media. The models aim to analyze the conditions of the exploitation, the longevity of the system, and the possible interactions with surrounding geothermal wells. An important challenge lies in the representation of the complex geology. The reservoir includes layers of anhydrite that is partly or totally dissolved depending on the location. Another challenge is to find a good setting for the border conditions of the model. This difficulty comes from the effect of high temperature and pressure in the reservoir, which affect the value of the hydraulic head.

Simulations show that the parameters expected in the area allow the exploitation of geothermal wells to provide hot water for heating. Cold water injected at the reinjection well goes in the direction of the pumping well, located 1,400 m away. The longevity of the exploitation depends on the time taken by cold water to induce a decrease of temperature at the pumping well. Simulations show that a decrease of temperature at the pumping well is expected to be around 2°C after 100 years. A sensitivity analysis of the model parameters has also been carried out to see which parameters have the most significant impact on the exploited rock layer and the layers have situated next to this one. The thickness of the layer and the rate of flow in the pumping and injection wells have also to be considered as important parameters.

1. INTRODUCTION AND CONTEXT

Nowadays, Europe needs to produce more sustainable energy to gain an energetical independence and to fight climate change. In some places on the continent, deep geothermal energy can contribute to the electricity production or district heating. Many sites are already in activity for example in France, Germany or Italy. In Belgium, research and new projects are currently performed in the Campine Basin (North Belgium) and in the Mons area (South-West Belgium). In the Mons area, some single wells have been exploited since the eighties. They were drilled in a deep limestone reservoir characterized by some highly permeable breccia levels. This reservoir has not been studied extensively despite potentially significant heat reserves. In this context, the MOREGEO project has been initiated by the University of Mons and the IDEA (inter-municipality active in the area) with financial support from the ERDF European program. The general objective of this project is to improve the characterization of the limestone reservoir and to drill a new geothermal doublet to provide heat to the largest city hospital.

The new geothermal doublet will be in the Mons area and will be the first doublet in activity in this part of the country, in complement to three already existing other geothermal single wells (Figure 1). The new doublet will be in a densely populated area at the limit of the old city center of Mons. At the level of the ground surface, production and injection wells are progressively deviated to reach two points of the limestone reservoir: 2,150 m and 1,850 m deep, and distant from 1.4 km. Hot water is expected to be pumped at about 70-75°C and reinjected in the same limestone reservoir, after flow in the heat exchangers located at the surface.

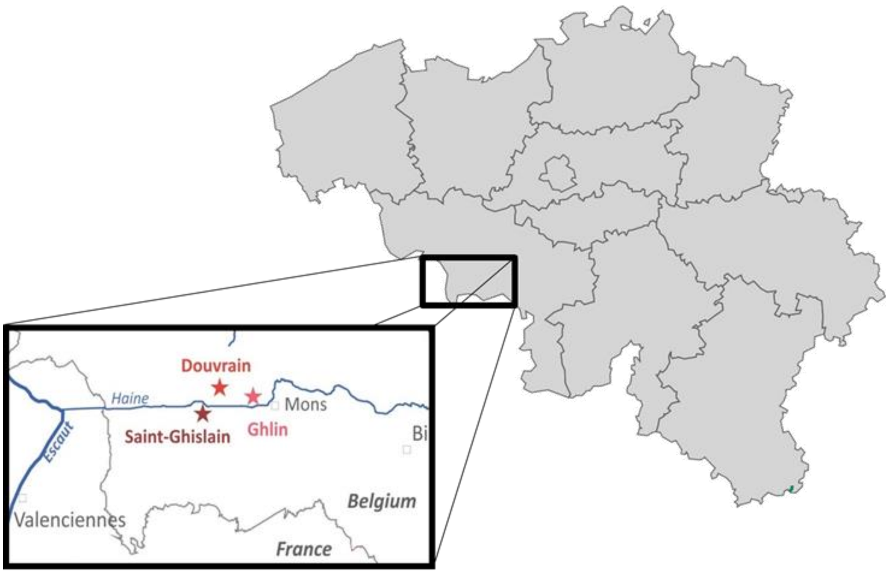

Figure 1: Location of the three existing geothermal pumping wells in the Mons area, South-West Belgium.

This paper describes the geological and hydrogeological context and shows the simulated impact on the limestone geothermal reservoir by the long term pumping and injection operations. In the context of cold-water reinjection, pressure increase in the reservoir can be observed around the injection well and need to be estimated. The model will estimate the pressure variation and will also show the cold-water flow to analyze the decrease of temperature in the pumping well. If the decrease is too significant, the production will not be possible.

2. GEOLOGICAL CONTEXT AND DOUBLET CONFIGURATION

The geothermal reservoir is located in the Visean limestone (Lower Carboniferous), below the Upper Carboniferous shale and sandstone layers, ands as part of the "Paraautochtone brabançon" structural unit. At the level of Mons city, the top of these Visean units are observed about 1,500 m deep (Figure 2). The geological layers have a dip around 12-15° to the South.

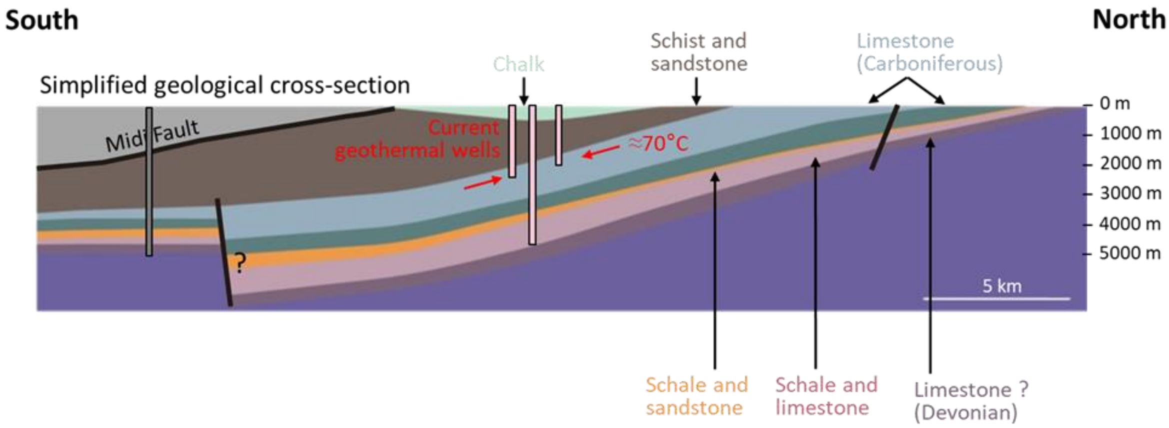

Figure 2: Simplified geological cross-section in the Mons area. Localizations of the three existing geothermal pumping wells, Licour (2012).

Little information is available concerning the geology and the structure of the reservoir at this depth and in this area. The data that's available comes from the three geothermal wells drilled during the 80's (Saint-Ghislain, Ghlin and Douvrain) and from some seismic campaign performed during the last decades. In the Visean reservoir, anhydrite layers are observed within the limestone geological formations. These layers are not continuous and not observed everywhere in the reservoir as concluded from the lithological logs of the three existing wells. These anhydrite layers have been locally dissolved through geological time scales, leading to the formation of thick breccia layers. These breccia layers are characterized by a high and well connected porosity. They are characterized by a significantly higher permeability than the limestone layers and constitute the productive zones to be reached by two wells of new doublet. It is however quite complex to determine in advance the number and location of productive layers in any new wells. This is partly due to the uncertainty related to the knowledge of the regional scale geological structure. This is also explained by the heterogeneity of the anhydrite dissolution processes. In the three existing deep wells, the productive levels are observed at different locations (Figure 3). In the Saint-Ghislain borehole, groundwater is mainly coming between 2,550 and 2,630 m deep from breccia level located below anhydrites layers, in the "Ecacheries" geological formation. Less lithological formation is available at the level of the two other deep wells as they were drilled only to the upper part of the reservoir until the first productive layer is reached. These two wells reach productive levels at about 1,300 – 1,500 m deep. In the Ghlin borehole, the productive layer is located in the "Grande Brèche" geological formation. In the Douvrain borehole, the productive layer corresponds to a "karstic conduit" in the limestone "Lives" geological formation (Robaszynski and Dupuis (1983), Bultynck and Dejonghe (2001), Poty et al. (2001), Delmer et al. (2001), Licour (2012)).

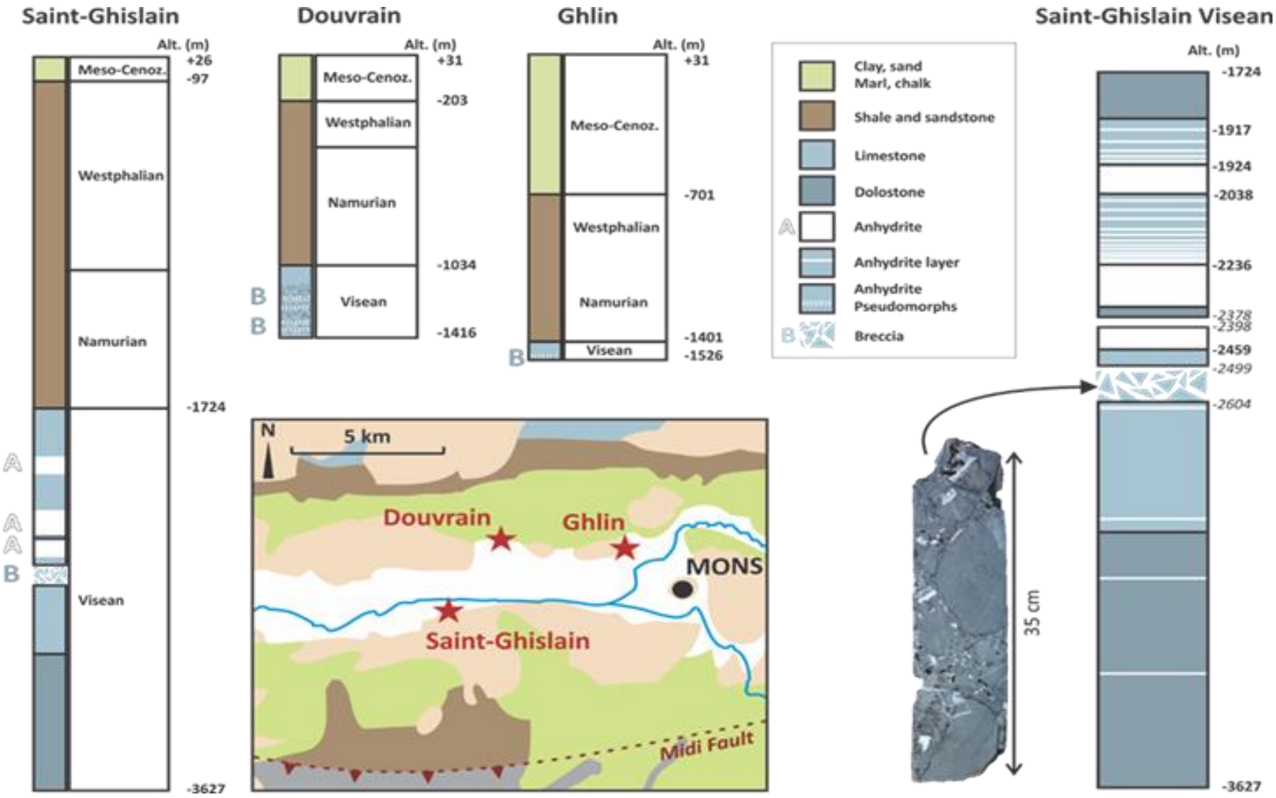

Figure 3: Visean geological formations observed in the geothermal wells in Hainaut, Licour (2012).

According to the available data, the geological structure of the basin, the 3D geological model implemented for the Visean limestone reservoir and the assumption concerning the anhydrite dissolution continuity of these layers, productive breccia layers at the level of the new drilling site are expected to be reached between 1,950 and 2,400 m deep.

3. MODELLING

3.1 Conceptual Modelling

A first numerical model was implemented at the scale of the geothermal doublet. The objectives of this model are:

- modelling heat transfers at the scale of the new geothermal doublet;

- analyzing the life expectancy of the new geothermal doublet;

- analyzing the pressure change in the geothermal reservoir;

- evaluating interactions between the new geothermal doublet and the existing actual pumping wells nearby.

Due to structural and geological uncertainties inherent to the geothermal reservoir, at large and local scales, different assumptions were considered about:

- the continuity of the geological formations at large scale;

- the geological layer thicknesses. The thickness of the Carboniferous limestone aquifer seems to vary from North to South and from East to West. The layers seem to be thinner in the South-East.

- the occurrence and location of breccia and anhydrites layers.

In the doublet-scale numerical model, anhydrite layers are considered as dissolved, inducing the occurrence of a breccia level in the "Grande Brèche" geological formation, as actually observed in the Ghlin and Douvrain boreholes. In comparison to the lithostratigraphic log of the Saint-Ghislain borehole, which is the only one location where a full lithological series is available, the layer thicknesses have been decreased to be in adequation with the geological model based on seismic surveys and boreholes data. The figure 4 shows the geological layers included in the model.

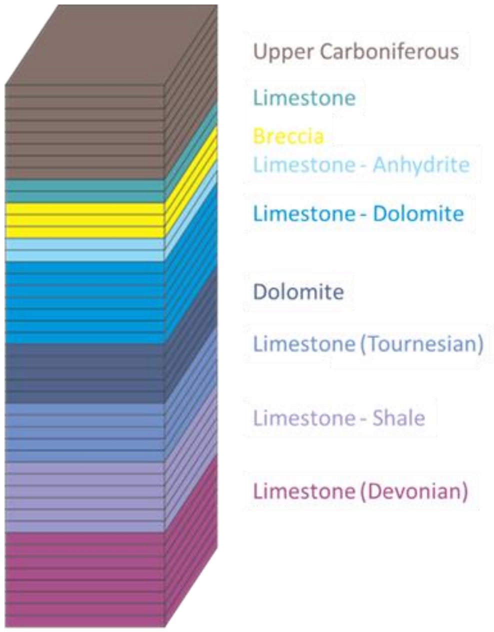

Figure 4: Geological layers in the doublet model.

3.2 Numerical Model

Different calculation codes give the opportunity to simulate flow and heat transfers in rocks. The simulations shown in the next chapter have been performed with HydroGeoSphere (Therrien et al. (2010). HydroGeoSphere is a three-dimensional control-volume-finite element simulator which calculates groundwater flow, solute and heat transport and takes into account the density dependence to temperature. In the studied geothermal reservoir, temperature gap is significant and density effect must be considered. In the model, the temperature gap will be significant with a low temperature at the injection point (30°C) and a higher temperature in the reservoir (about 75°C in the productive level). Viscosity and density decrease with temperature increase.

3.2.1 Equations and Parametrization

Due to hydraulic and thermal properties in the geothermal reservoir, heat transfers occurred by thermal conduction and advection. Advection is preponderant when the permeability of rocks is high enough to allow significant groundwater flow. From Darcy law, the equation of flow transfer in porous media is derived.

From Darcy law (Castany, 1998):

$$\vec{v} = -K.\overrightarrow{grad}\,H$$

where *v, K, H* are Darcy velocity [m/s], hydraulic conductivity [m/s] and hydraulic head [m].

The definitions of hydraulic conductivity and hydraulic head give:

$$\vec{v} = -\frac{k\rho g}{\mu}\,.\overrightarrow{grad}\,H = -\frac{k}{\mu}\,.(\overrightarrow{grad}\,P + \rho g\overrightarrow{grad}\,z)$$

where *k, ρ, g, μ, P, z* are intrinsic permeability [m²], density [kg/m³], gravitational acceleration [m²/s], dynamic viscosity [kg/(m.s)], reservoir pressure [bars] and elevation [m].

In transient conditions, the flow transfer equation is written:

$$S_s\,.\,\frac{\partial(H_0)}{\partial t} = div\left(\frac{k\rho\rho_0 g}{\mu}\,.\left(\overrightarrow{grad}\,H_0 + \rho_r\overrightarrow{grad}\,z\right)\right) + \frac{\rho^*}{\rho_0}\,W$$

where S_s, t, H_0, ρ_0, W are specific storage [/], time [s], equivalent hydraulic conductivity at 20°C [m/s], density at 20°C [kg/m³] and water losses/gains.

The advective and conductive heat transfer equation in porous media is written:

$$(\rho c)\frac{\partial T}{\partial t} = div\left(\bar{\bar{\lambda}}\overrightarrow{grad}\,T - (\rho c)_f\vec{v}T\right) + A$$

where ρc, $(\rho c)_f$, A are thermal capacity of the rock [m²/s².K], thermal capacity of the fluid [m²/s².K], heat source in porous media [/].

3.3.2 Spatial Discretization

Horizontally, the model has an area of 8.5 × 5 km to cover the new doublet and the nearby geothermal pumping well in activity in the Ghlin locality (Figure 5). This well is located about 3 km to the West from the drilling point of the new doublet. The limits of the model have been chosen far enough to avoid influence on the wells operations. Vertically, the elevations of the top and bottom of the model are -467 m and -4,130 m, respectively. These limits correspond to specific lithological interfaces, considered to act as very low permeability limits, far enough from the productive breccia layer.

The mesh is composed by irregular rectangular parallelepipeds. The vertical discretization corresponds to the succession of geological layers with a dip of 12°. Each geological layer is divided in different layers of elements to benefit from a roughly homogeneous vertical mesh. Vertically, the size of elements varies from 40 to 100 m. Horizontally; the element size varies from 10 to 400 m, smaller around the wells.

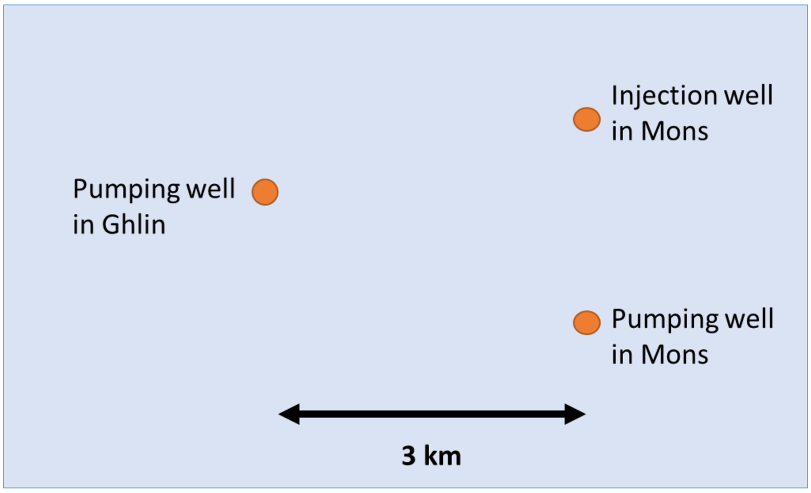

Figure 5: Locations of the three wells in the model. The two wells in Mons are the new doublet.

3.2.3 Boundary and Initial Conditions

Along the external limits of the model, no-flux Neumann boundary conditions are implemented except at the level of the breccia layer, which is considered as the productive layer in the reservoir. For this level, Dirichlet conditions are implemented with a constant hydraulic head prescribed at 86 m. This value is actually observed in the pumping well of Saint-Ghislain.

Temperature is implemented at top of the model, with a geothermal gradient of 2.8°C/100 m.

The initial spatial distribution for hydraulic head values is calculated thanks to a steady-state simulation without pumping and injection. Output results are subsequently used as the initial conditions for transient simulations. Density effect had complicated the definition of the initial conditions. No convection is simulated at the scale of the new geothermal doublet. The convection will be studied and simulated at the reservoir scale.

3.2.4 Parameters Values and Simulations Scenarios

Several simulations have been performed to assess the impact of the new geothermal doublet within the reservoir and to study the sensitivity of some uncertain hydraulic parameters.

For the following parameters, different simulations were performed using a set of values:

- Intrinsic permeability of the productive layer: from 10^{-13} to 10^{-11} m², or from 10^{-6} to 10^{-4} m/s in equivalent hydraulic conductivity at 20°C.

- Thickness of breccia productive layer: from 20 to 200 m.

- Pumping and injection flow rate in the new geothermal doublet: from 100 to 300 m³/h.

Solicitations come from the pumping and injection of water. Two wells pump hot water and another one injects cold water. The pumping well in Ghlin pumps water with a flow rate of 100 m³/h. The flow rate for the two wells of Mons will vary between 100 and 300 m³/h. 150 m³/h is the minimum needed to provide energy to the hospital. Table 1 gives some hydraulic and thermic parameters values for the lithologies modelized.

Table 1: Table with some hydraulic and thermic parameters for the different lithologies modelized.

Lithology	Hydraulic parameters		Thermic parameters	
	k [m²]	φ [%]	λ [W/m.K]	c [10^6 J/m.K]
Upper Carboniferous	10^{-13}	3	2	2.3
Limestone	10^{-13}	5	2.6	2.3
Breccia	10^{-13} à 10^{-11}	10	2.6	2.3
Limestone/Anhydrite	8×10^{-15}	3	4	2.45
Limestone/Dolomite	10^{-14}	7	2.8	2.3
Dolomite	10^{-13}	8	3	2.3
Limestone (Tournaisian)	10^{-13}	5	2.6	2.3
Limestone/shale	10^{-17}	2	2	2.3
Limestone (Devonian)	10^{-13}	3	2.6	2.3

3.3 Results

Simulations are used to assess the sensibility of 4 aspects: (1) breccia permeability, (2) breccia layer thickness, (3) constant transmissivity but with thickness variations, (4) pumping and injection flow rate values. The variations of two parameters are analyzed: pressure at the injection well and temperature in the reservoir especially at the pumping point.

3.3.1 Sensitivity to the Breccia Layer Permeability

The breccia intrinsic permeability in the Saint-Ghislain borehole is estimated at 10^{-12} m², Licour (2012). Various simulations were performed with different permeability values for the breccia layer. Values vary in a range of 2 orders of magnitude around the mean value measured in the existing boreholes, from 10^{-13} to 10^{-11} m², or between 10^{-6} to 10^{-4} m/s regarding the equivalent hydraulic conductivity at 20°C, for a corresponding layer thickness of 200 m. Flow rate for injection and pumping in the doublet is 300 m³/h. Results show that the pressure at the injection and pumping points locally increases and decreases, respectively. The difference of pressure compared to the initial natural value reaches 32 bars in the case with the lowest intrinsic permeability. At the level of the pumping well, temperature increases during the first years due to the influence of the hot water located below the pumping well. After few years, a decrease is observed. In the worst case, corresponding to an equivalent hydraulic conductivity of 10^{-4} m/s, with a fall of temperature around 7°C after 120 years. Fifty years after the start of the exploitation, a decrease of 2°C is observed.

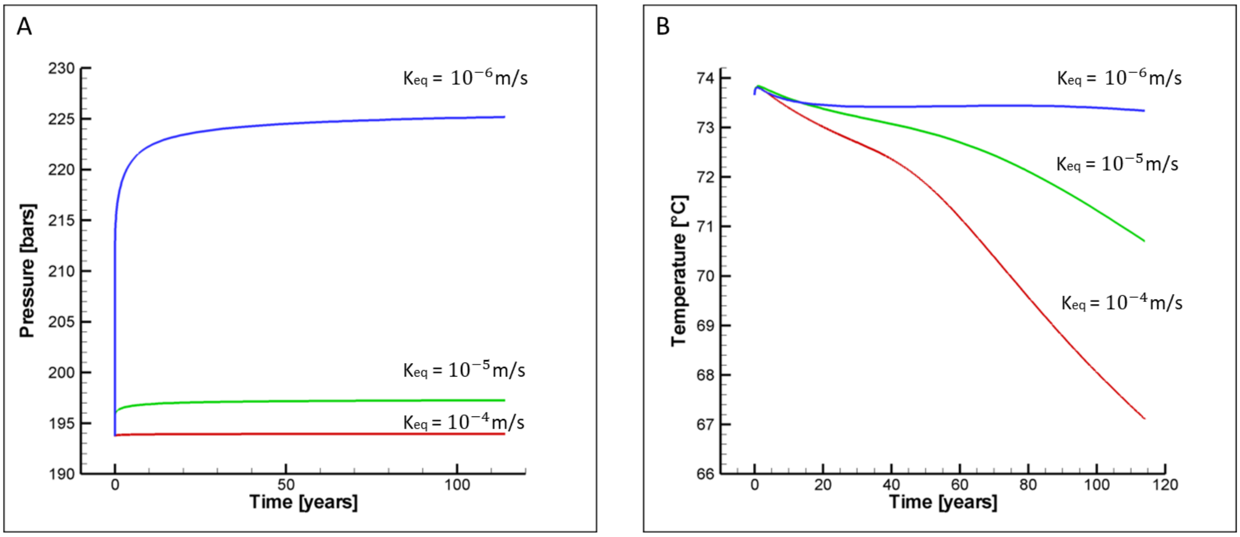

Figure 6: Results of the sensitivity to the breccia layer permeability. (A) Evolution of pressure at the injection well for 120 years. (B) Evolution of temperature at the pumping well for 120 years.

3.3.2 Sensitivity to the Breccia Layer Thickness

In the model, the thickness of the breccia layer, where groundwater is pumped and injected, varies from 20 to 200 m. In these simulations, the intrinsic permeability is fixed at 10^{-12} m². The thickness increase induces a transmissivity increase. Figure 7 shows that a higher transmissivity logically decreases the pressure rise. For a productive layer of 20 m, the pressure increase is about 20 bars and it was only about 5 bars for a productive layer of 200m. With the decrease of the breccia layer thickness, temperature at the pumping well decreases faster. The difference appears clearly after 50 years. Cold water spreads in a smaller volume.

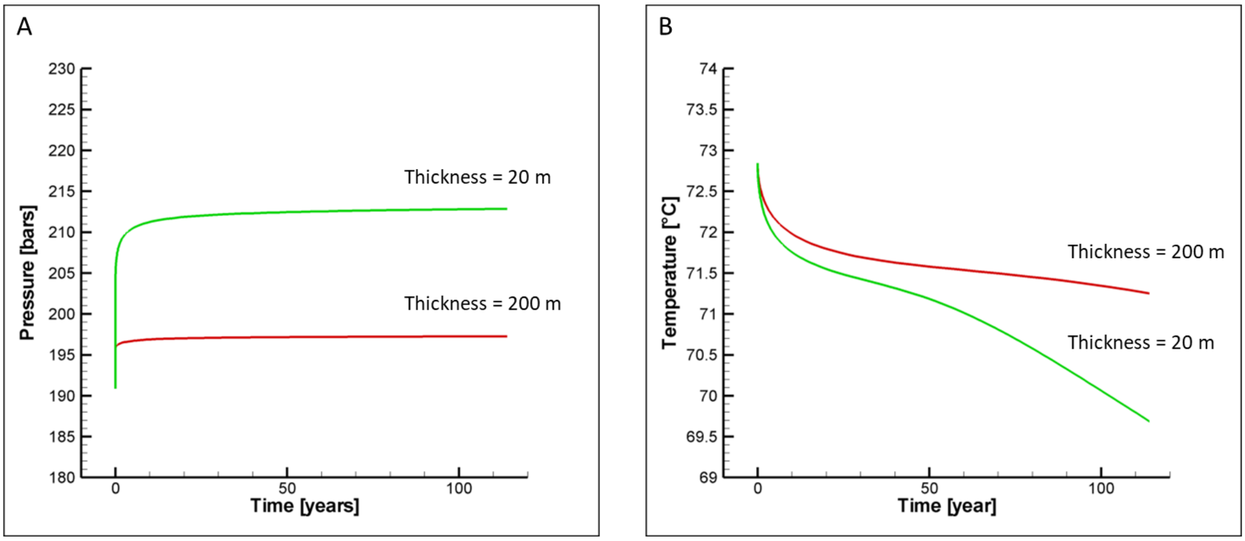

Figure 7: Results of the sensitivity to the breccia layer thickness. (A) Evolution of the pressure at the injection well for 120 years. (B) Evolution of the temperature at the pumping well for 120 years.

3.3.3 Sensitivity to the Thickness with a Constant Transmissivity

In these simulations, intrinsic permeability and breccia layer thickness are modified to keep a constant transmissivity value. These changes induce no modification in the pressure increase at the injection well. The impact is observed at the pumping well. For a same transmissivity value, temperature decrease occurs more rapidly when the layer is thinner. The decrease is twice higher when breccia layer thickness is 10 times thinner (Figure 8).

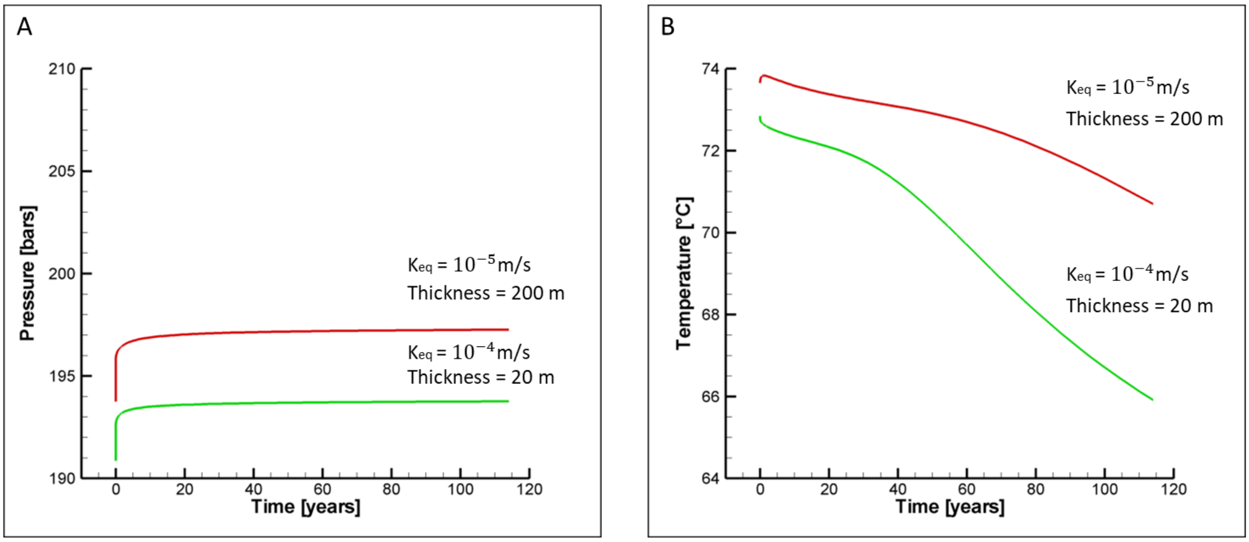

Figure 8: Results of the sensitivity to the thickness with a constant transmissivity. (A) Evolution of the pressure at the injection well for 12 years. (B) Evolution of the temperature at the pumping well for 120 years.

3.3.4 Sensitivity to the Pumping and Injection Flow Rate

Flow rate is the most sensitive parameter. The pressure increase varies proportionally with flow rate, but the temperature decrease is not proportional.

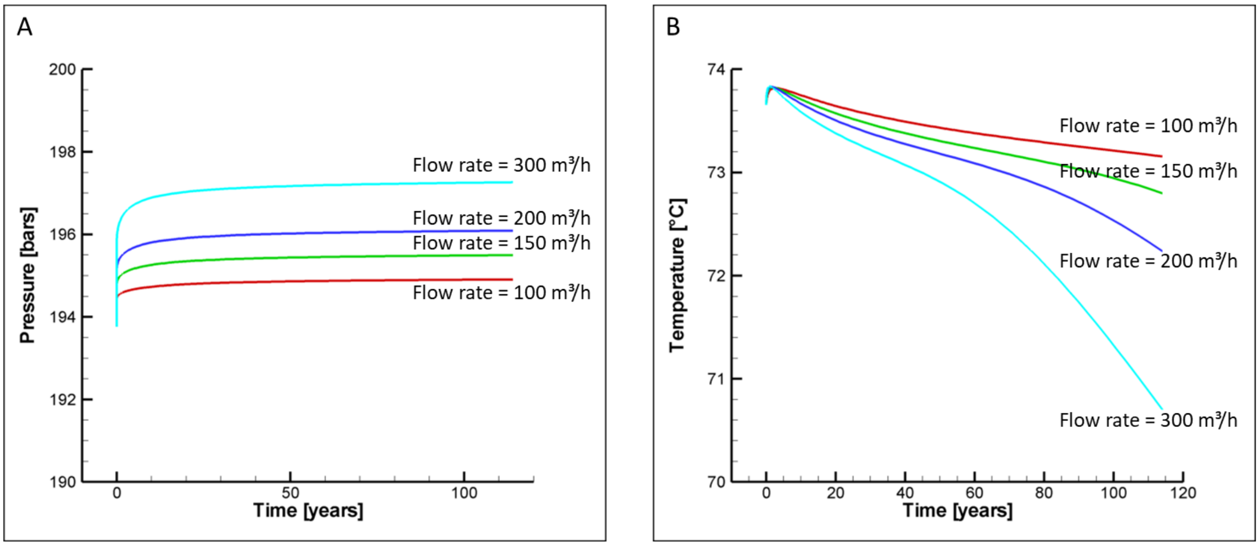

Figure 9: Results of the sensitivity to the pumping and injection flow rate. (A) Evolution of the pressure at the injection well for 120 years. (B) Evolution of the temperature at the pumping well for 120 years.

4. CONCLUSION

It seems with the different simulations performed that the geothermal reservoir could be exploited at this location with a geothermal doublet. The economic life expectancy of the doublet needed for this kind of project is about 50 years, which means that the temperature at the pumping well doesn't have to decrease more than 2°C during this time. In most cases, it was possible.

The simulations show the complexity in choosing the best layer for the exploitation. This geological layer must be permeable enough to avoid high pressure increase but still allow flow. But if the transmissivity is too high, the temperature decrease at the pumping well is more significant, thus cold water goes faster from the injection well to the pumping well.

All these simulations were performed in a case of maximum flow rate throughout the year. Realistically, variation will be observed during the year with a maximum during the winter months.

Due to geological uncertainties, the geological layers are considered homogeneous in the model. Models are performed to add different kind of heterogeneity in the model and visualize the impact on the doublet longevity.

Next step will be the expansion of the doublet model to a regional model which one will consider the more detailed hydrogeological and economic aspects.

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