Geothermics 39 (2010) 177–186

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Modelling of fluid flow and heat transfer to assess the geothermal potential of a flooded coal mine in Lorraine, France

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ARTICLE INFO

Article history:
Received 10 November 2009
Accepted 22 March 2010

Keywords:
Geothermal
Mine water
Modelling
Thermo-hydrodynamic
Lorraine
Coal mine

ABSTRACT

The flooding of the Lorraine coal mines (France), representing a huge reservoir of about 154×10^6 m^3, began in June 2006. After attaining thermal equilibrium with the surrounding rocks, the water temperature in the deepest parts is expected to reach 55 °C, giving the opportunity for the extraction of low-enthalpy geothermal waters that may be suitable for district heating purposes. We present some numerical modelling results of the thermally driven convective flow in an open vertical shaft and in the entire mine reservoir. A dual permeability/porosity approach was used in the reservoir model, which includes open galleries and vertical shafts, coal panels backfilled with sand, and intact rock masses. Two scenarios of heat extraction with different flow regimes were investigated. A sensitivity analysis shows that the temperature decline in the production zone is highly dependent on the permeability of the surrounding porous rocks. Larger permeabilities result in higher water temperatures at the production shaft due to greater inflows of warm water from those rock masses.

1. Introduction

Most mines in Europe have been closed during the past decade or so. The closure of deep underground mines implies the cessation of pumping and the gradual flooding of large volumes of old workings. The transfer of heat from the surrounding rock mass to this water allows the development of low-enthalpy geothermal reservoirs that could be exploited through drilled wells or existing shafts, providing a suitable renewable energy source for heating purposes, consistent with sustainable development and ideally without any additional environmental drawbacks.

The technical approach for exploiting mine water may be very similar to the extraction of heat from deep aquifers using “doublets”. That is, the warm water is pumped from a production well to the district heating plant where the heat of the fluid is transferred via heat exchangers to a district-heating network. The cooled water (waste water) is then injected into the mine at a level with a similar temperature to minimize thermal impact, and at a location not directly connected to the production zone to avoid rapid breakthrough of the cold-water front. Similarly, cold water could be extracted from shallow parts of the mine and used for cooling purposes during the summer. The warmed water injected back into the mine could be stored in an adequate buffer zone (i.e. a deep region) and extracted during the winter.

Examples of potential geothermal exploitation of such reservoirs in coal mines are described by Malolepszy et al. (2005) in Czeladz (Poland), Heerlen (Netherlands) and Midlothian (United Kingdom). A more detailed reservoir characterisation with 2D numerical models is discussed by Malolepszy (2003) for the Nowa Ruda coal mine (Poland). Van Tongeren and Laenen (2005) give a further description of the Oranje-Nassau coal mine concession in Heerlen (the Netherlands) and present water-flow modelling results for three production/injection scenarios.

Bazargan et al. (2008), using an analytical approach, discuss the temperature recovery at the end of flooding and the temperature drop in the production zone due to injection of cooled water. The geothermal potential of other types of abandoned mines has also been investigated by several authors, e.g. the copper mines of Recsk in northeast Hungary (Toth and Bobok, 2007) and Gaspé in Québec, Canada (Raymond and Therrien, 2008). More recently, modelling of a flooded potassium mine was carried out by Renz et al. (2009). This study compared different numerical approaches using a coupled 2D Darcy flow model with either a laminar or turbulent one-dimensional flow model for the mine structure or complete 2D and 3D porous media models.

In 2004, interest in this new energy source encouraged a consortium of European entities[1] to launch a project called “Minewater”,

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[1] Municipality of Heerlen, Weller (The Netherlands), Midlothian Council, Building Research Establishment (United Kingdom), Municipality of Bönen, Wirtschaftsförderungsgesellschaft Kreis Aachen (Germany), BRGM (France).

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doi:10.1016/j.geothermics.2010.03.004

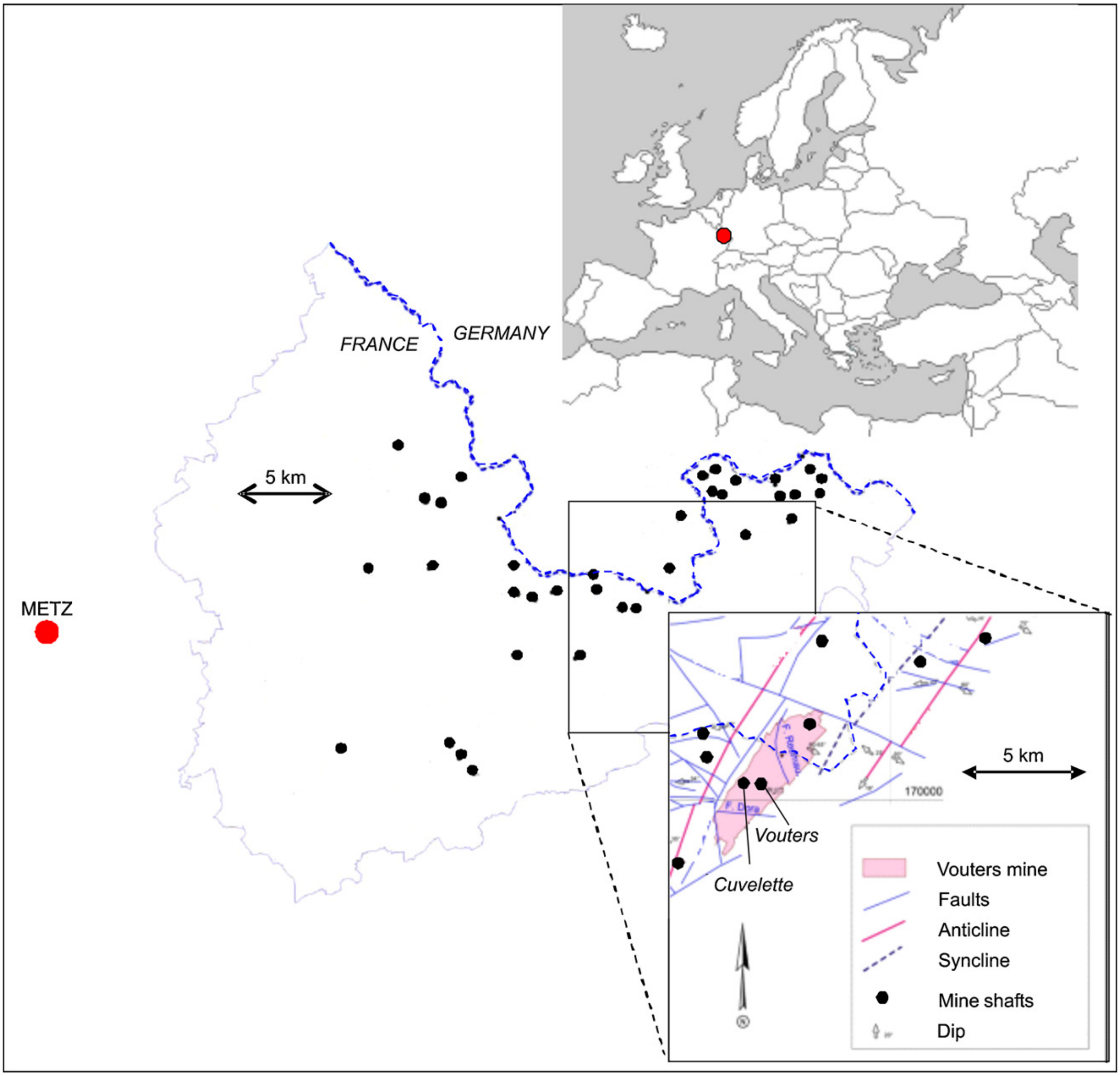

Fig. 1. Map showing the location of the Vouters mine in Lorraine, France.

funded by the EC Interreg IIIB North-West Europe program. The Minewater project, which ended in October 2008, aimed at reviving old and abandoned mining areas by exploiting the heat stored in flooded coal mines. As a part of this multinational cooperation program, the potential of the geothermal resource associated with the Lorraine coal field was studied since it was considered as a promising option for the competitive use of geothermal energy in France.

This paper presents the results of the preliminary investigations carried out on the Lorraine coal field in an area identified as the most suitable place for building a full-scale demonstration facility. The studies focus on the modelling of the hydraulic and thermal behaviour of the geothermal system associated with a flooded mine by assuming different exploitation scenarios.

2. Site description

The 490 km^2 Lorraine coal basin is located approximately 30 km east from the city of Metz and extends across the Franco-German border (Fig. 1). The SW-dipping coal seams are overlain by Permian and Triassic sandstones. Only the shallowest north-eastern part of the basin has been exploited; it has been divided into three sectors: the Houve concession in the west, the Wendel concession in the east and the Sarre and Moselle concession between them.

In order to select the best location(s) for the pilot project, the mine workings situated in these three sectors were examined in the light of five criteria: (i) depth of the deepest gallery, (ii) expected temperature in the deepest gallery, (iii) reservoir volume, (iv) accessibility from the surface, and (v) presence of a district heating system in the vicinity of the mine. As a result of this investigation the “Vouters” mine, located in the Moselle concession, was identified as a potential site for further studies. It has the following characteristics:

(i) Deepest gallery at 1250 m depth
(ii) Expected temperature of about 55 °C at the deepest level
(iii) A total reservoir (mine workings) volume of about 40.2×10^6 m^3

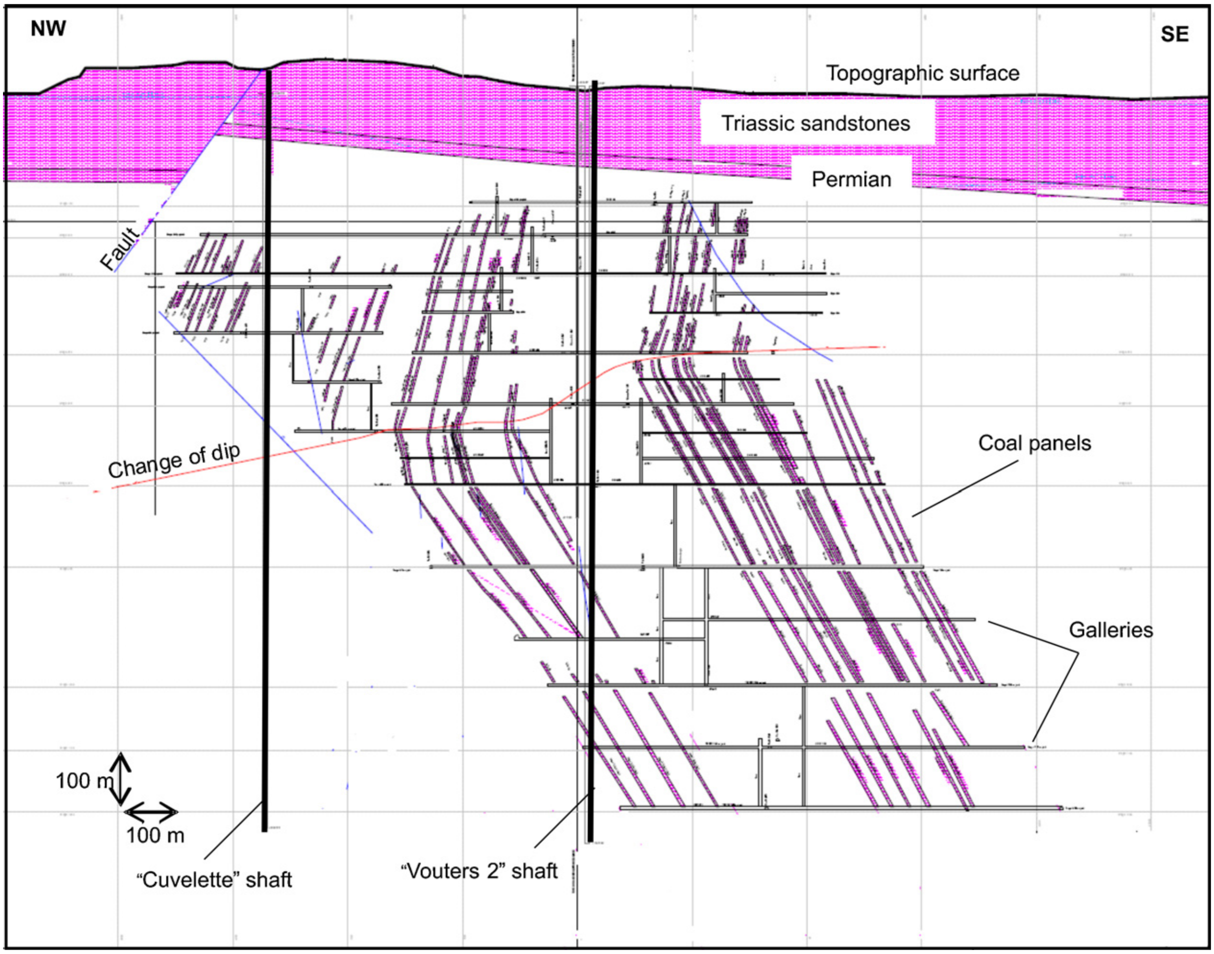

Fig. 2. Vertical section through the levels of galleries and coal panels in the Vouters mine (the Cuvelette and Vouters shafts are projected on the vertical section).

(iv) Accessibility through two shafts intersecting the deepest gallery
(v) A district heating plant 500 m from the main shaft.

The Vouters coal mine covers an area about 6 km long and 1.5 km wide. It is located in the city of Freyming-Merlebach and extends beyond the French–German border (Sarre region). Flooding began in 2006 and should end by 2013. The "reservoir" is made up of a dense network of interconnected sub-horizontal galleries between 153 m and 1250 m depth, cut by vertical "pipes" providing hydraulic links between different mine levels.

Coal seams 2–5 m thick were mined in oblique panels with a regular dip of 38°N–60°SE. Fig. 2 shows a vertical cut through the levels of galleries and coal panels. Two shafts give access to the deepest level. The "Cuvelette Nord" (Fig. 1) is an entirely cement-sealed shaft, 6 m in diameter, equipped with individual 150–250 mm diameter pipes connecting 12 galleries situated between 420 m and 1250 m below surface. This shaft is presently used for gas extraction during the flooding. The "Vouters 2" shaft (Fig. 2), 7.5 m in diameter and intersecting 10 galleries from 249 m to 1250 m deep, is sealed at its top by a 20 m thick concrete plug. An 800 mm diameter hole is drilled through the cement plug to allow monitoring the water level. Either of these shafts could be used as the production well for pumping the warm water from the deepest accessible gallery (i.e. at 1250 m) where the water temperature is expected to be highest.

3. Modelling the water temperature in the production shaft

3.1. Model and principles

The water temperature in the reservoir is assumed to be in local thermal equilibrium with the surrounding rocks. However, the water temperature inside a vertical shaft could evolve differently due to convection produced by buoyancy forces created by the difference of density between warm water (lower density) overlain by colder water (higher density). This suggests that the geothermal gradient may be a significant driver for mixing within the shaft, which is not desirable since it can induce a temperature drop at the production zone.

The parameters that can mitigate convection are viscous friction and thermal diffusion. If the density gradient induced by differences in water temperature is not sufficient to produce significant water displacement, the heat transfer in the shaft will remain mainly conductive.

Another parameter that can modify the mine water density is its salinity.[2] In general, the salinity of a typical mine water increases with the depth (fresh water overlaying salty water) and as a consequence decreases the buoyancy contrast due to water temperature

[2] Salinity is the general term used here and includes all chemical components dissolved in the mine water.

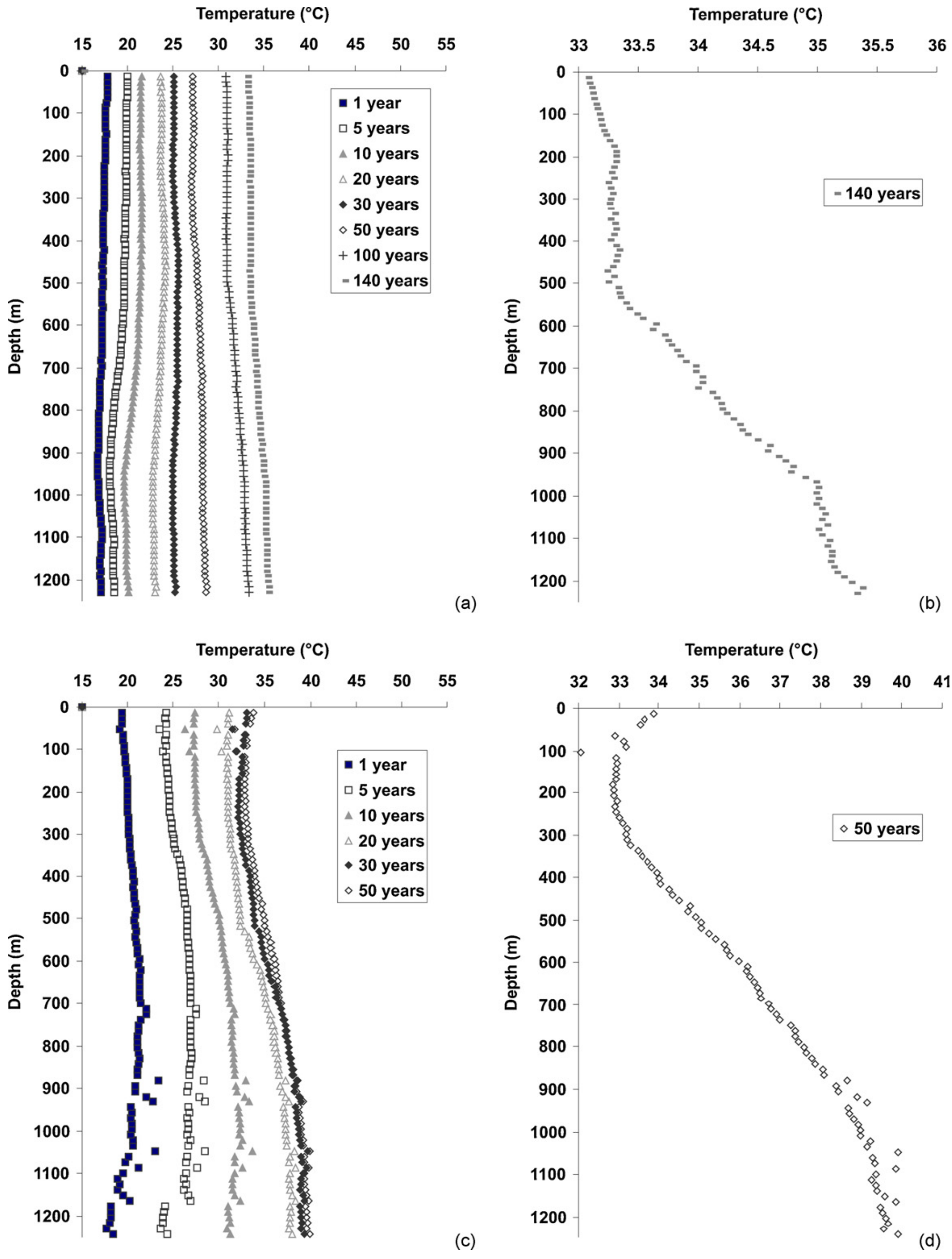

Fig. 3. Computed temperature profiles. (a) For case 1 at different times; (b) for case 1 after 140 years; (c) for case 2 at different times; (d) for case 2 after 50 years.

differences. However, in this paper we neglect the changes in water chemistry. Only thermal effects are considered corresponding to the more critical case for the onset of free convection that is triggered for a critical value of the fluid thermal Rayleigh number defined by:

$$\mathrm{Ra} = \frac{\alpha g h^3 \Delta T}{\upsilon \kappa} \quad (1)$$

where α is the thermal expansion coefficient (K^{-1}), g is the gravity acceleration ($\mathrm{m\,s^{-2}}$), h is the height of water column (m), ΔT is the difference of temperature (°C) between the bottom and top of the system (in this case a vertical shaft), υ is the fluid kinematic viscosity ($\mathrm{m^2\,s^{-1}}$) and κ is the thermal diffusivity ($\mathrm{m^2\,s^{-1}}$).

For a cylindrical well the critical Rayleigh number depends mainly on its aspect ratio i.e. the ratio of cylinder radius to its height ($\delta = r/h$). The criterion for the onset of convection in a vertical well (or shaft) has been studied by Love et al. (2007) and is expressed by:

$$Ra_c = \frac{215.6}{\delta^4}(1 + 3.84\delta^2) \quad (2)$$

This expression has been obtained for the case of a vertical channel with rigid walls and infinite hydraulic conductivity. Its value would be lower for less restrictive boundary conditions such as a porous medium with finite hydraulic conductivity. However, according to Love et al. (2007), the reduction in the value of the critical Rayleigh number by replacing the solid wall by a porous medium is expected to be small.

To study the establishment of the temperature profile in the Vouters mine shaft, we consider the following cases:

Case 1. The shaft has an equivalent cross-section of $44\,m^2$ (well diameter of about 7.5 m, corresponding to the Vouters 2 shaft). It connects to a single gallery of $20\,m^2$ cross-section at a depth of 1250 m. After flooding, the water column in the shaft is about 1200 m high, so that the equivalent well aspect ratio (i.e. radius/height) is about 3×10^{-3}.

Case 2. Same situation as the first case except that the shaft intercepts 10 galleries at different depths instead of only one at the bottom of the well.

Case 3. The shaft has an equivalent section of $0.5\,m^2$, corresponding to the about 0.8 m diameter open hole in the sealing plug, and the well aspect ratio is 3.3×10^{-4}. This case corresponds to installing a 0.8 m diameter pipe in the shaft and backfilling the annulus with sand and gravel; the temperature along the pipe wall is given by the geothermal gradient.

These three cases were simulated numerically. It was assumed that initially the well and gallery were filled with 15 °C water. The contact between the shaft wall and the surrounding rock is assumed to be perfect so that the Dirichlet boundary condition (i.e. specification of temperature) is applied. The geothermal gradient is assumed to be constant, equal to 0.032 °C/m. Navier Stokes and energy equations were solved using the fluid dynamics code FLUENT.[3] The geometry was meshed using 626,000–1,391,000 tetrahedral elements as appropriate for the different configurations.

3.2. Free-convection modelling results and discussion

For case 1 (configuration: r = 3.75 m, h = 1200 m, one gallery at 1250 m depth), when there is a 40 °C temperature difference between the top and bottom of the shaft the Rayleigh number is equal to 10^{21}, while its critical value is 2.5×10^{12} indicating that natural convection should occur. This is confirmed by the numerical simulations; Fig. 3(a) shows the temperature in the shaft versus axial position at different times. The results show that the water is mixed continuously in the shaft. After 140 years of simulated time the temperature along the shaft is almost constant. It reaches 35.5 °C at the bottom and 33 °C at the top (Fig. 3(b)). The expected temperature of 55 °C at the gallery level, based on the geothermal gradient, is obtained in the gallery only 600 m from the shaft connection. Therefore, in this case convection appears as the main heat transfer process inducing a very efficient intra–well mixing which fixes the temperature along the shaft close to the average of the boundary conditions at the top and the bottom of the shaft. An example of this water mixing potentially related to thermal convection was observed in a coal mine in Springhill (Canada) where water temperatures of up to 20 °C have been measured at the surface instead of the expected 7–8 °C (Jessop, 1995).

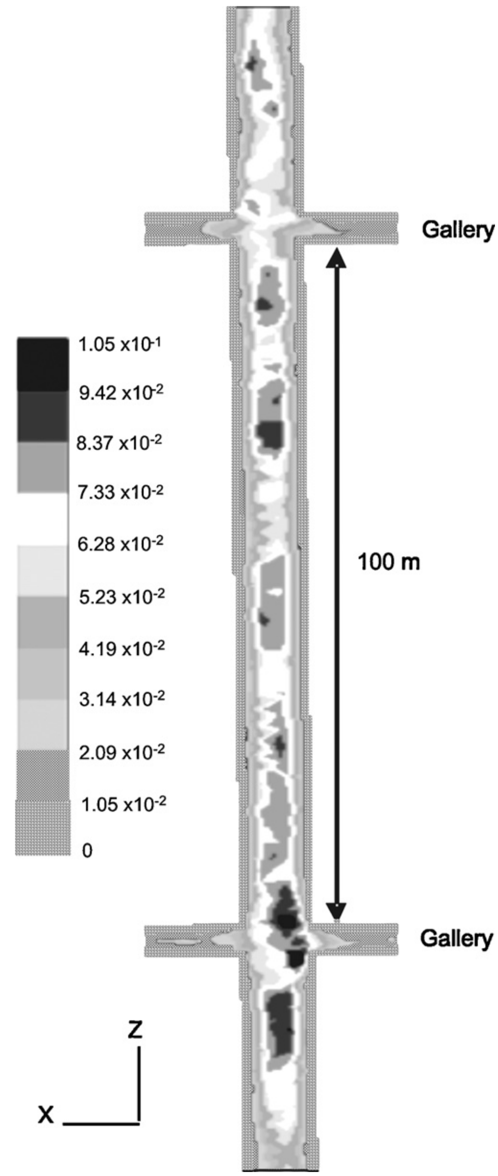

Fig. 4. Velocity field in the well intercepted by horizontal galleries. The scale corresponds to water flow velocity in m/s.

In case 2 (configuration: r = 3.75 m, h = 1200 m, one gallery at 1250 m depth and nine other galleries at higher levels), the temperature in the shaft shows greater contrast, attaining 40 °C at the bottom and 33 °C at the top after 50 years of simulation time (Fig. 3(c) and (d)). The most significant difference from the previous case appears when comparing the distribution of the water velocity along the shaft. In case 1 the convective movement is established along the entirely height of the shaft (i.e. one dominant convective loop) and the velocity ranges between 0.003 m/s and 0.03 m/s, while in this case the convective movement is subdivided into several loops situated on each side of the galleries, with velocities ranging between 0.01 m/s and 0.1 m/s (see Fig. 4). In case 2, therefore, the presence of several galleries intersecting the shaft at different levels induces local water mixing and allows the establishment of a higher temperature at the bottom of the shaft (i.e. 5 °C higher than in case 1).

For case 3 (configuration: r = 0.4 m, h = 1200 m, one gallery at 1250 m depth) the critical Rayleigh number is equal to 1.9×10^{16}. In this case there is also natural convection, but its effects are smaller than in the previous configurations. Two numerical simulations

[3] http://www.fluent.com/solutions/whatcfd.htm.

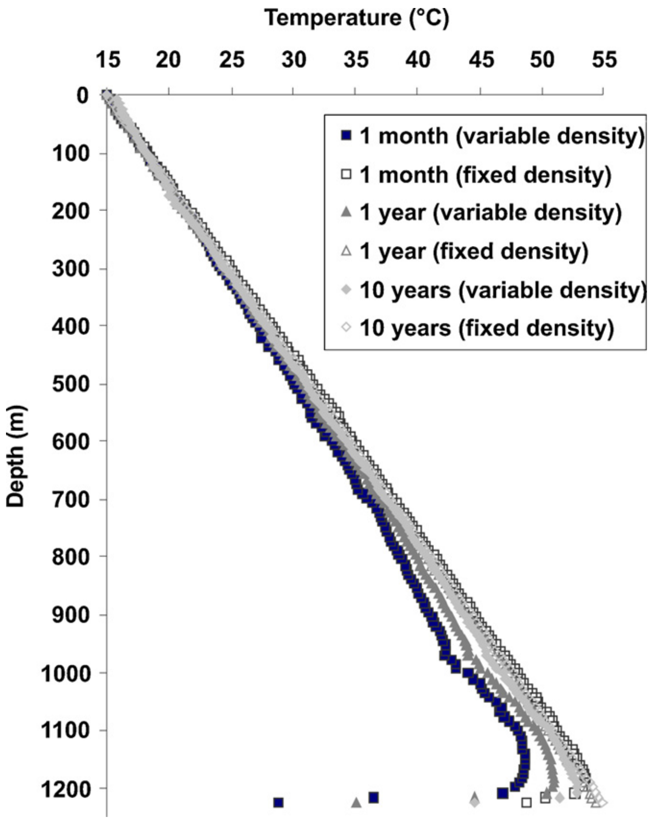

Fig. 5. Temperature profile in the 0.8 m diameter well (case 3).

were carried out, one with density defined as a function of temperature, as in cases 1 and 2, and one with a fixed density that corresponds to heat transfer by diffusion only. When the density is allowed to vary the descending movement of cold water should delay the heating of the water at the shaft bottom compared to when the density is assumed to be constant (i.e. the purely diffusive model) and was confirmed by the numerical simulation results. Fig. 5 shows the temperature along the axis of the shaft at different times. In the case of the diffusive model (fixed density) the temperature at the shaft bottom that corresponds to the local geothermal gradient (i.e. 55 °C) is reached in less than a year, whereas in the variable density model this temperature is achieved only after 10 years.

3.3. *Case of forced convection (use of pumps)*

The above results deal with the evolution of the temperature after flooding the mine, but it is important to know how the temperatures will vary when water is pumped from the bottom of the shaft. To address this question, calculations were made assuming a 0.8 m diameter well and pumping rates of 100 m^3/h and 600 m^3/h. Water was extracted at 1250 m depth where the shaft intersects the 20 m^2 cross-section gallery. In addition, it was assumed that the warm water was mobilised only at the deepest level of the mine. In other words, the water flowing into the gallery far from the well was assumed to have a temperature close to 55 °C. Of course, this is not realistic since, as shown in the next section, pumping at the production zone will induce water displacement not only at the deepest level but also from other levels of the mine where the water temperature is lower. This assumption, however, allowed distinguishing the temperature decrease due to pumping (forced convection) from that arising from other potential causes.

Fig. 6 shows the results of the calculations. For the smaller flow rate (Fig. 6(a)), there is no significant change while for the higher flow rate (Fig. 6(b)) a drop in temperature is observed, reaching a maximum of about 5 °C at the bottom of the well after a 5-year pumping period; afterwards the temperature stabilizes. It may be concluded that the temperature decrease due to forced convection is rather limited and depends mainly on the pumping rate.

4. Mine reservoir modelling

4.1. *Model and principles*

In order to evaluate the geothermal resource associated with the flooded mine waters, it is necessary to assess the temperature evolution at the production zone taking into account not only the inflow of colder waters from upper mine levels, but also the effect of injecting the waste (cooled) water after it goes through the district heating plant.

In all (or most) geothermal energy utilization projects the cooled waters are injected back into the reservoir with the main purpose of maintaining fluid pressures (Bodvarsson et al., 1985; Stefánsson, 1997). On the other hand in the case of mine waters, the main objective of the injection is deep disposal since the waters usually contains high quantities of dissolved elements (e.g. SO_4, Cl, Fe) that preclude releasing them at or near the surface.

Regardless of the objective, however, the low temperature of the injected waste water can be a problem (Bodvarsson, 1972; Horne, 1982; Kocabas, 2005). Indeed, the injected water may move through the interconnected network of galleries to the production zone in a very short time, producing an early temperature drop at the production well (early thermal breakthrough). Since the problem is site-dependent, numerical modelling that accounts for the actual geometry of the mine workings must be combined with in situ tests in order to identify the best injection location. However, the results of such tests will not be reliable before the end of the flooding process. For this reason, we have arbitrarily chosen to simulate injection into a gallery at 420 m depth that has no apparent direct connection with the production zone.

In order to estimate the mass and heat transfer in the network of interconnected galleries and shafts during the exploitation of the Vouters mine waters, numerical modelling at the mine scale has been carried out using the MARTHE computer code (Thiéry, 1990). This hydrodynamic computer program solves the fluid flow and general transport equations (solute, heat, reactive transport) in porous media. From the hydrodynamic viewpoint, two distinct transport regimes coexist in the underground mines: a high-velocity regime in the network of highly conductive galleries, and a low-velocity regime in the considerably less permeable porous rock mass. To take into account this dichotomy, we considered shafts and galleries as special porous media where the porosity is such that the section open to flow is equal to the gallery/shaft cross-section. In addition, the ratio between the gallery/shaft and rock permeabilities was fixed at 10^5.

The geometry of the Vouters mine was meshed with 1,143,450 hexahedral elements. Fig. 7 shows the dense network of high permeability galleries. A sub-set of three levels of galleries among 18 levels modelled from 193 m to 1250 m depth is also given in the figure.

4.2. *Modelling results and discussion*

Two production/injection schemes were studied (Fig. 8), i.e.

Scheme 1. Water is pumped from the Vouters 2 shaft at 1250 m depth, where the temperature is close to 55 °C according to

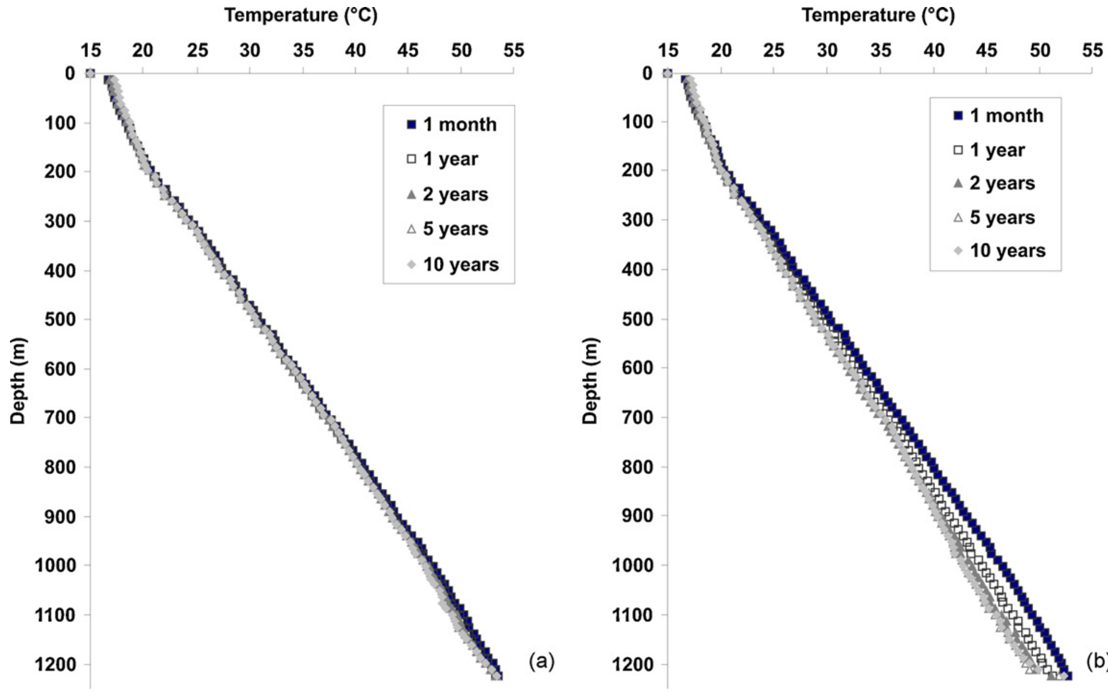

Fig. 6. Temperature profile in the 0.8 m diameter well (case 3) during production. (a) Production rate: 100 m^3/h; (b) production rate: 600 m^3/h.

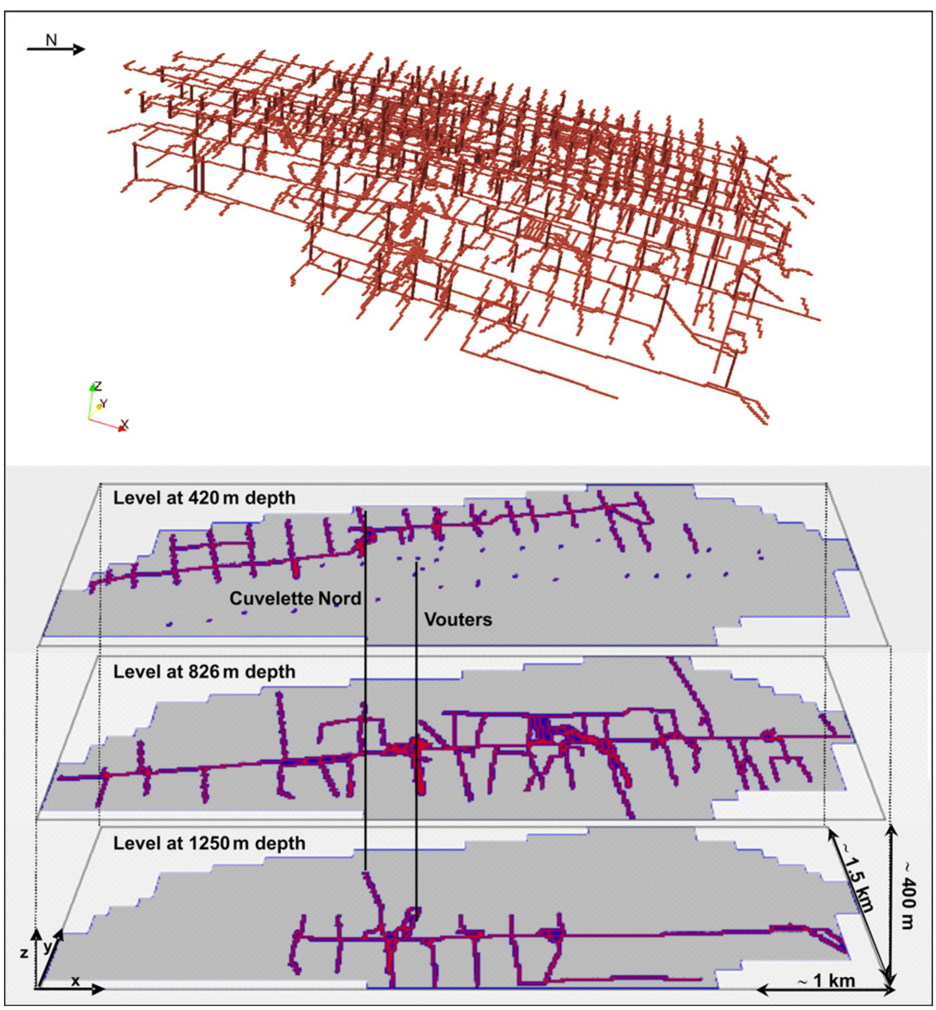

Fig. 7. View of the network of galleries in the Vouters mine (high permeability mesh used in the MARTHE code).

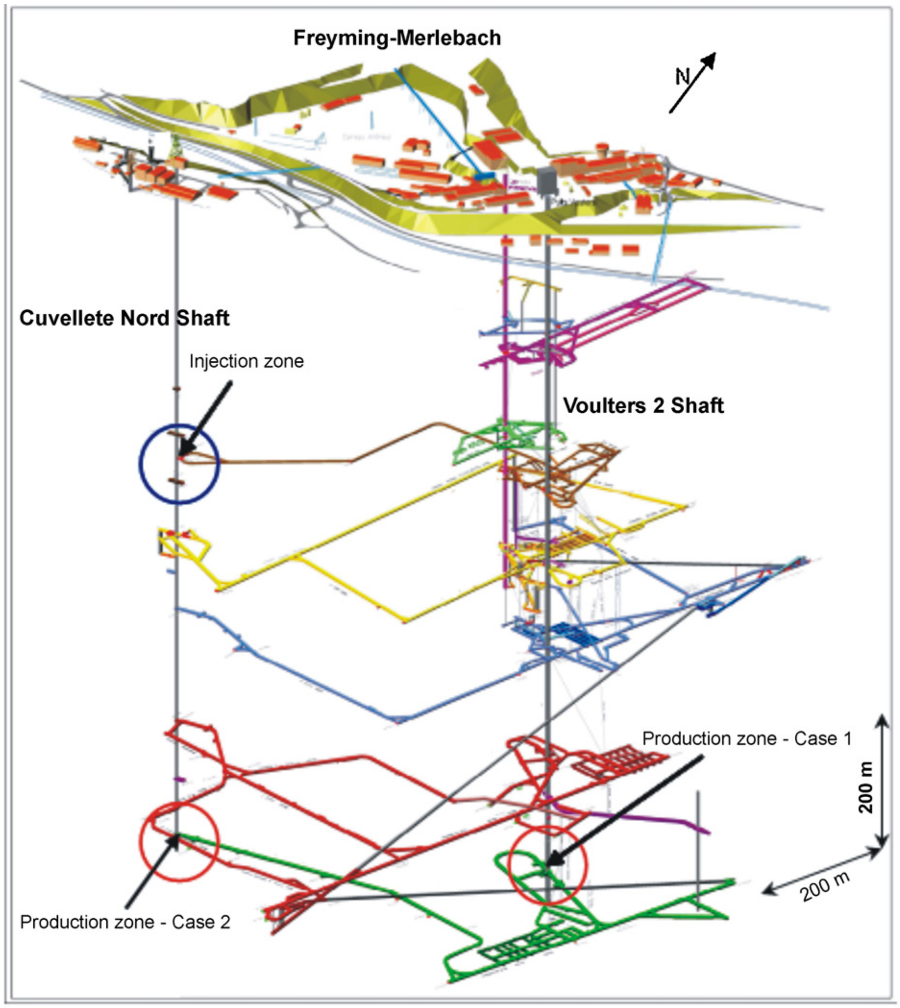

Fig. 8. Production and injection locations assumed in the model.

the geothermal gradient of 0.032 °C/m. The waste 20 °C water is injected into a gallery in the Cuvelette Nord shaft at 420 m depth; *Scheme 2*. Water is pumped from the Cuvelette Nord shaft at 1250 m depth and injected at 20° C into the same shaft at 420 m depth.

In both cases the temperature evolution of the production zone over time was calculated for production/injection rates of 100 m^3/h and 600 m^3/h. It was assumed that there is no direct hydraulic and thermal connection between the production zone and the upper galleries through the production shaft. This is indeed the case of the Cuvelette Nord shaft that is plugged with cement and where access to the galleries is made only through individual pipes. With regard to the Vouters 2 shaft, thermal and hydraulic isolation has to be considered as a technical requirement prior to exploitation. Inflatable packers could be used for isolating the gallery at 1250 m depth from inflows of water from shallower levels and to avoid premature cooling of the produced zone.

The simulation results are shown in Fig. 9 and Table 1. Most of the temperature decrease at the extraction point occurs in the first months and then, depending on the flow rate, the temperature tends to stabilize after a few years.

As the key parameter in this modelling study is the ratio between the gallery and rock permeabilities, a sensitivity analysis was carried out using a production rate of 600 m^3/h. Fig. 10 presents the results of this analysis for permeability ratios of 10^6 and 10^4 compared to the 10^5 used for the previous simulations. If the rock permeability is reduced by a factor of 10, the temperature falls about 2 °C below the reference curve. In this case (permeability ratio = 10^6) the computed temperature of the produced water mainly results from the water moving in the network of galleries with no or little contribution from the water coming from the porous rock. The heat exchange between these "two waters" is mainly diffusive. When the permeability ratio is increased by a factor of 10 compared to the reference case (i.e. rising the rock permeability 10 times), the temperature increases by about 8 °C, showing the effect of a greater inflow of warm water from the porous rock to the gallery.

The assumption of equivalent porous media for mine workings is adequate when considering large-scale modelling. Such an approach can be found in the literature (e.g. Raymond and Therrien,

Table 1
Temperature drop at the production shaft after different exploitation periods for two different production/injection schemes.

After	Temperature drop (°C)			
	Flow rate 100 m^3/h		Flow rate 600 m^3/h	
	Scheme 1	Scheme 2	Scheme 1	Scheme 2
6 months	5	4.5	13	15
1 year	7.5	8.5	16	18
60 years	13	15	18	20

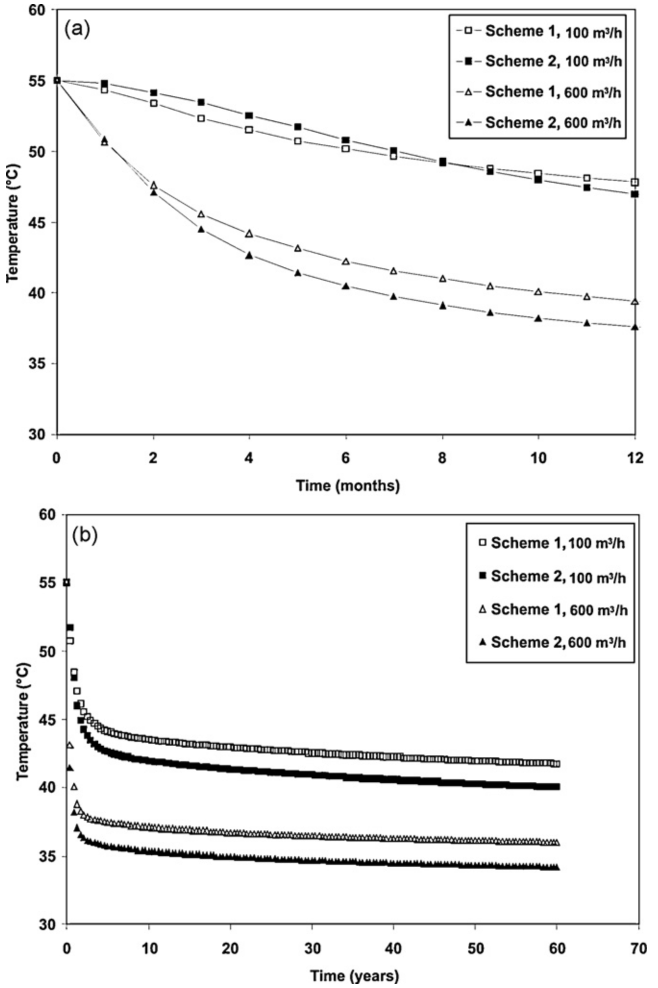

Fig. 9. Temperature decline at the production well (a) during the first year; (b) in the long term.

2008; Renz et al., 2009) and the simulation results are generally considered to be accurate enough to describe the global situation. In the case of the Vouters mine, this approach was improved by using a multi-layer model taking into account detailed digital maps of the mine's galleries and shafts that allowed a better description of the 3D geometrical and hydraulic connections. Obviously, additional tests that might be performed at the end of the flooding period could improve the accuracy of the model, particularly by calibrating reservoir parameters.

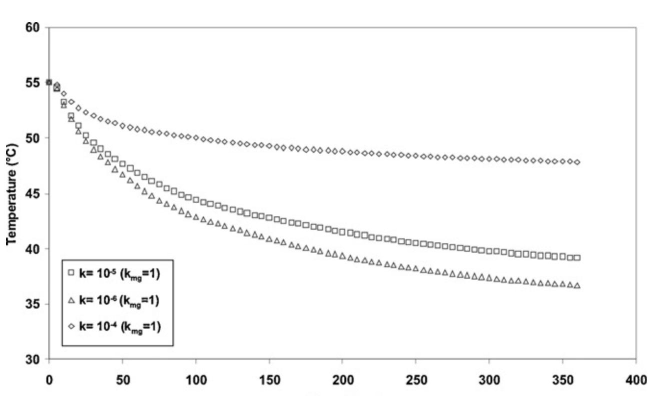

Fig. 10. Temperature decline history at the production well as a function of rock permeability (k). "k_{mg}" denotes the permeability of the mine gallery.

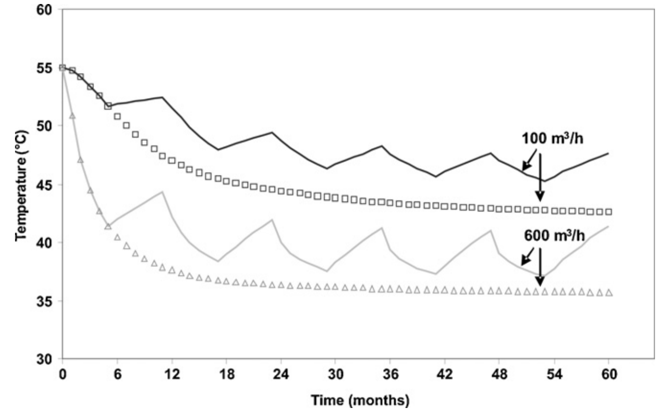

Fig. 11. Temperature decline history at the production well when mine water extraction is shutdown 6 months a year. Squares and triangles represent the case of continuous pumping and the saw-edged lines the case when pumping is shutdown for 6 months.

4.3. *Extending the lifetime of the system*

All the above simulations assumed that the mine water reservoir is exploited continuously, whereas in practice heat production is mostly required during autumn and winter. The shutdown mine water extraction during the warm season may increase the system lifetime and limit temperature drops.

Fig. 11 shows the results of numerical simulations of cyclic exploitation, where mine water is produced for 6 months per year. For a 100 m^3/h production water rate the water temperature increases by about 2 °C during the shutdown phase. More importantly, during the production period the temperature remains 3 °C higher than when the exploitation is continuous. However for a 600 m^3/h production rate, the temperature gain is only 1.5 °C.

5. Conclusions

The use of mine waters as a source of thermal energy for geothermal district heating is an attractive solution for reducing greenhouse gas emissions produced by the building sector, which accounts for 25% of the total CO_2 emissions in France. However, the exploitation of this significant resource needs appropriate studies since the geometry of the reservoir (mine galleries and shafts) is highly complex and site-dependent.

The groundwater modelling, carried out to investigate the geothermal potential of the Vouters mine, allowed to characterize some interesting aspects of such a complex underground reservoir. The study of the temperature profile in the production shaft has underlined the great influence of the aspect ratio on the occurrence of natural convection, which could lead to a lower water temperature at the pumping location than the one corresponding to the local geothermal gradient. On the other hand, modelling at the reservoir scale has shown that the temperature decline not only depends on the production flow rate, but that it is also a function of the permeability of the surrounding rocks.

Although these numerical simulations are sensitive to the assumed boundary conditions, the results show that in all cases the water temperature at the production zone remains above 30 °C. This means that the thermal energy produced from the mine water at the minimum flow rate of 100 m^3/h (i.e. production at 30 °C and re-injection at 20 °C) can effectively meet the heating demand for more than 25,000 m^2 of standard buildings.

The actual geothermal potential of the Vouters mine is probably much greater than this initial estimate and has to be refined through further investigations. In particular, in situ experiments such as pumping and tracer tests, which cannot be performed before the end of the flooding process, have to be carried out in order to obtain data for the modelling studies and improve their results.

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