International Journal of Coal Geology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Coal Geology

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

# Modelling flow and heat transfer in flooded mines for geothermal energy use: A review

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ARTICLE INFO

*Article history:*
Received 31 October 2015
Received in revised form 23 March 2016
Accepted 26 April 2016
Available online xxxx

*Keywords:*
Mine closure
Geothermal energy
Mine water
Analytical modelling
Numerical modelling
Ground source heat pump

ABSTRACT

In the last decades numerous coal mines have been closed. One way to overtake the costs associated to the mine closure is the geothermal use of the water stored in the closed and flooded mine workings. The temperature of the water flooding from the mine voids, in some cases reaching depths of several hundreds of meters, is suitable for space heating and cooling by means of the use of ground source (geothermal) heat pumps (low-enthalpy geothermal systems).

Flooded mine voids constitute new-created pseudokarstic aquifers or reservoirs, which can store significant volumes of groundwater. However, the recharge and the heat capacity of these systems are finite, and this is the main concern when using mine water as a heat source or sink. These reservoirs can be regulated by means of flow extraction and injection depending on the use demands; notwithstanding, these flows have to be limited to a sustainable value, in order to avoid the exhaustion of the capacity of the aquifer to provide or store heat. Several numerical and analytical models have been created with this aim, with the shortage of hydrogeological and thermal data as main drawback.

A literature review of the existent flow and heat transfer models applied to geothermal use of mine water has been undertaken, both analytical and numerical models are considered. The main parameters that have influence in the flow and heat exchange processes, have been analysed. The present paper can be used as basic guidelines to aid when selecting a modelling method for a specific scenario.

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## 1. Introduction

Issues related to the closure of mines, along with the growing interest in renewable energy utilization make the geothermal use of the abandoned mines an interesting option (Bajtos, 2001; Peralta Ramos et al., 2015; Raymond and Therrien, 2007; Verhoeven et al., 2014). Lund and Boyd, 2016 demonstrates that using low-to-moderate temperature geothermal resources in heat applications, given the right conditions, is an economically feasible business. Major costs associated with conventional geothermal systems are drilling and well maintenance, the use of mine voids provides an opportunity to decrease these costs (Ghoreishi et al., 2012). The most cost-effective systems are those already being pumped for dewatering or treatment purposes (Renz et al., 2009). In this mine context coal mines are considered the best candidates for geothermal exploitation due to their broad-based accessibility (Rühaak and Renz, 2010; Watzlaf and Ackman, 2006). According to the literature (Banks et al., 2003; Malolepszy et al., 2005; Peralta Ramos et al., 2015; Preene and Younger, 2014; Younger, 2013) the majority of mine water geothermal systems were implemented at underground mines (96%) and particularly in collieries (Fig. 1). Countries including a greater number of these systems are: USA (Hall et al., 2011; Michael C. Korb, 2012), Canada (Raymond et al., 2008), Germany (Kranz and Dillenardt, 2010; Wieber and Pohl, 2008) and UK (British Geological Survey, 2013).

The use of mine water as a geothermal fluid can be done by means of an open or a closed loop, the choice between one or the other will be made according to the characteristics of the mine system to be exploited (Banks, 2009a; Ghomshei, 2007; Hall et al., 2011; Preene and Younger, 2014).

In a closed loop system (Fig. 2a) the underground water does not move but exchanges heat with a vertical or horizontal loop of water-antifreeze solution (Lund et al., 2004). At these systems ochre coating (*i.e.* ochre accretion) may occur if underground water contains iron (Banks et al., 1997), limiting the performance of the system.

In open loop systems the mine water flows from the host underground reservoir to the environment or to another underground location. Compared to closed systems, open systems have a higher efficiency of thermal exchange in subsurface as the heat carrier media is directly in contact with the surrounding ground (Luo, 2014). These systems generally require a preventive heat exchanger to avoid the contact between the mine water and the heat pump (Athresh et al., 2015; Raymond and Therrien, 2007). Ochre clogging may occur in pipes

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http://dx.doi.org/10.1016/j.coal.2016.04.013
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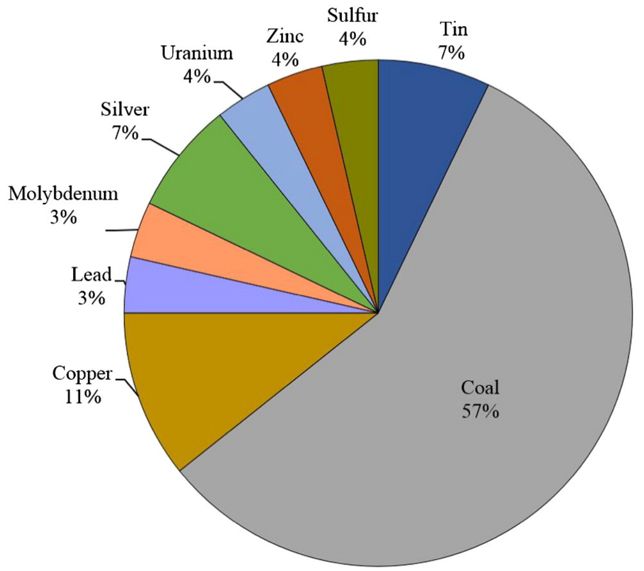


**Fig. 1.** Classification of 28 documented geothermal systems using mine water, according to the exploited substance.

carrying mine water (Baier et al., 2011; Dudeney et al., 2003), so continuous surveillance and cleaning would be necessary. If there is no reinjection and used mine water is discharged into the environment (Fig. 2b), some water treatment may be required.

When the risk of fluid depletion exists or mine water characteristics are inaccurate for divert to the environment, the fluid should be reinjected back to the aquifer after heat extraction or injection (Ghoreishi et al., 2012). Due to the menace of a thermal plume (Banks, 2009b) systems with reinjection (Fig. 2c) are less stable and need to be implemented carefully in order to assure their long term performance (Macnab, 2011), here the modelling exercise plays a fundamental role.

## 2. Analysis of variables

### 2.1. Variables of interest in geothermal systems

From an energetic point of view, the main variable of a geothermal system is its thermal potential ($P_w$). The heat that can be obtained from the water/ground can be estimated using the following equation (Preene and Younger, 2014):

$$P_c = q\, \rho_w\, c_w \Delta T \tag{1}$$

with $q$ being the water flowrate, $\rho_w$ the water density (typically 1000 kg m$^{-3}$), $c_w$ the specific heat of the water (4186.8 J kg$^{-1}$ K$^{-1}$; TA Instruments, 2002) and $\Delta T$ the temperature rise of the water at the evaporator of the heat pump, about 5 K for ground source heat pumps (Jardón, 2010; Ordóñez et al., 2012).

The Coefficient Of Performance (COP) is defined as the amount of heat delivered in relation to the drive power required. The thermal potential that can be delivered from the water by means of a heat pump is (Ochsner, 2008):

$$P_w = P_c\, COP\, (COP-1)^{-1}. \tag{2}$$

And the electricity consumed per unit of time is:

$$W_e = P_w - P_c = P_c\, (COP-1)^{-1}. \tag{3}$$

If cooling exists, the final thermal potential will be lower due to the heat generated at the compressor (Preene and Younger, 2014):

$$P'_w = P_c\, COP\, (COP+1)^{-1}. \tag{4}$$

In standard geothermal heat pumps, the COP ranges between 3 and 6 (Bazargan et al., 2008). The COP will depend on the model of heat pump used but also on the temperature gap between the geothermal fluid (heat provider) and the place to be heated (heat sink). Being able to maintain a reasonable COP is the key factor in the economic feasibility of the whole geothermal system (Ghoreishi et al., 2012).

In Fig. 3 two key parameters (flowrate and COP) are analysed when assessing the efficiency of a geothermal system. It can be noted that the consumed electricity $W_e$ increases linearly with flowrate for a given COP, whereas a smaller flowrate is required for the same consumption if the COP increases (the shaded area shows the variation for COP ranging from 3 to 6). On the other hand, for a constant flowrate (in Fig. 3 $q = 10$ L s$^{-1}$ was considered), $W_e$ decreases when COP increases, particularly for COP > 3.

### 2.2. Required inputs for geothermal modelling systems

According to what was stated before, when assessing the available energy, it is crucial to determine the evolution of the geothermal fluid flowrate and temperature. In order to do so, the use of a wide range of flow and heat transfer models has been reported in the literature, being the required inputs common for the majority of employed models. These inputs include thermal conductivity ($k$), density ($\rho$) and specific heat ($c$) of the reservoir and kinematic viscosity ($\nu$) of the mine water (Cacace et al., 2012; Kranz and Dillenardt, 2010; Uhlík and Baier, 2012). The supposition of incompressible flow is typically done.

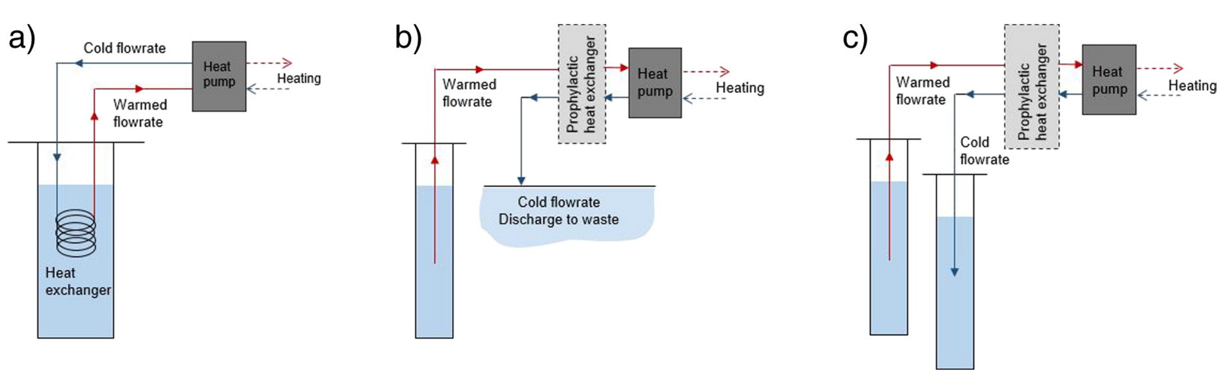


**Fig. 2.** Types of geothermal systems: a) closed loop; b) open loop without re-injection; c) open loop with re-injection.

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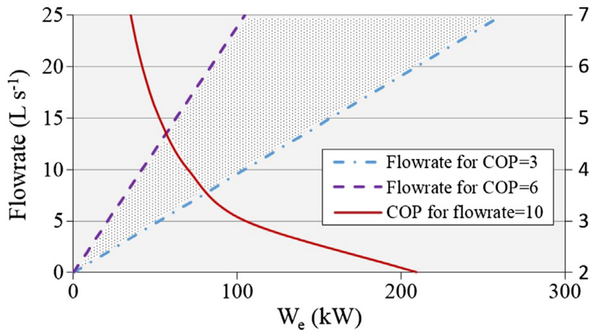


**Fig. 3.** Variation of the electricity consumed by the heat pump depending on water flowrate (in litres per second) and COP.

In open loop systems with reinjection, the porosity ($\Phi$), the length ($L$) and the radius ($r$) of the reinjection channel have to be considered, along with the flow and the temperature of the reinjected water. When the aim is not only to model the reinjection but the whole hydraulic system, then additional inputs from the particular studied area, such as average air temperature, geothermal gradient, flow and area of recharge (rainfall, river infiltration, *etc.*), are required (Pruess and Bodvarsson, 1983; Rodríguez and Díaz, 2009).

A difficulty when understanding the thermal and hydraulic system is the lateral and vertical interconnectivity of the different parts of a mine (Watzlaf and Ackman, 2006). Another complex issue is related to the lack of data regarding the reservoir characteristics (Ghoreishi et al., 2012; Raymond et al., 2008). In this cases, values consistent with previous studies are initially assumed and then adjusted with model calibrations (*e.g.* comparing simulated and measured groundwater levels or temperatures).

## 3. Flow and heat transfer modelling

Since the heat capacity of a mine is limited and should be matched with the demand, the total rate of sustainable heat extraction from the mine should be carefully assessed (Ghoreishi et al., 2012). However, the modelling of mine voids is challenging because it is necessary to simultaneously solve the heat transport in the surrounding porous medium and within the mine workings (Ferket et al., 2011; Renz et al., 2009). Two modelling approaches are considered: analytical and numerical.

Analytical models use the exact mathematical solutions of the flow and heat transport equations, and they are suitable for homogeneous systems and simple processes (Cacace et al., 2012) as they have the advantage of being easy to implement by means of simple formulae, spreadsheets or even sequences of calculations packaged up in a piece of software (McMahon et al., 2001), so they can give a first quick solution to the problem. Unfortunately, most of the real systems are in fact heterogeneous and the physical processes involved are non-linear so the role of analytical models here will be limited to feasibility studies.

Numerical models, on the other hand, utilize numerical approximations to solve the flow and heat transport equations. They constitute a more powerful tool suitable for complex systems governed by non-linear equations (Cacace et al., 2012). The time and costs involved in setting up and running a numerical model will be significantly higher than for an analytical one and a large amount of inputs and field observations are necessary to achieve a realistic representation (McMahon et al., 2001).

### 3.1. Equations governing fluid flow and heat transfer

Governing equations of flow in a conduit and matrix network have to include water flow, heat transport, and solute transport, which are in turn derived from the conservation of mass, momentum, and energy laws (Wolkersdorfer, 2008). The equations are identified below, for the sake of simplicity water has been considered as an incompressible fluid (constant density) and viscosity has been taken as a constant (Sert, 2012):

Conservation of mass (continuity equation):

$$\nabla \vec{V} = 0. \tag{5}$$

Conservation of linear momentum, Newton's second law (Navier-Stokes):

$$\frac{\partial \vec{V}}{\partial t} = \left(\vec{V} \cdot \nabla\right)\vec{V} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\vec{V} + \vec{f} \tag{6}$$

where $(\vec{V} \cdot \nabla)\vec{V}$ and $\nu\nabla^2\vec{V}$ are the convective and the diffusion terms, respectively.

Conservation of energy (first law of thermodynamics):

$$\rho c_p \left[\frac{\partial T}{\partial T} + \left(\vec{V} \cdot \nabla\right)T\right] = k\nabla^2 T + D. \tag{7}$$

Note that radiative heat transfer and internal heat generation due to a possible chemical or nuclear reaction are neglected. The symbols of the parameters in the equations governing fluid flow and heat transfer are resumed in Table 1.

## 4. Review of analytical models

If the data available are insufficient there seems to be no logical reason for using a sophisticated numerical model, as simple analytical model approaches sometimes yield results which are as good as intensive CFD models (Wolkersdorfer, 2008).

Analytical models generally work with conceptual geothermal systems analogous to the one presented in Fig. 4. At this scheme two wells (injection and the abstraction) are drilled from the surface to a mine tunnel. The subsurface pathway placed between the two wells acts as a heat exchanger, being a heat source or sink, depending on whether the purpose is heating or to cooling the water. At the surface, a heat pump would be placed between both wells. At this approach water infiltration through the rock mass into the system is considered negligible, since the water will move through the lowest hydraulic resistant path *i.e.* the mine gallery (Madiseh et al., 2012).

The temperature change along the channel can be deduced from a solution proposed by Pruess and Bodvarsson (1983). This analytical approach allows simulating different flowrates for the reinjection and the abstraction. For open tunnels, the porosity of this channel is taken as 1 *i.e.* only void space, but if the water flows through mined areas, a porosity $0<\phi<1$ is considered (Bazargan et al., 2008). This analytical method assumes that the initial temperature of the abstracted flow will be constant until a certain moment when the thermal drawdown will occur. The main variables influencing this thermal drawdown are the thermohydrodynamic dispersity, the length of the pathway and the time of production. Fig. 5 shows the variation of temperature in a

**Table 1**
Parameters involved in the equations governing fluid flow and heat transfer.

| Symbol | Parameter |
|---|---|
| $\vec{V}$ | Velocity field |
| $t$ | Time |
| $\rho$ | Density |
| $p$ | Pressure |
| $\upsilon$ | Kinematic viscosity |
| $\vec{f}$ | Body force per unit mass |
| $C_p$ | Specific heat at constant pressure |
| $T$ | Temperature |
| $k$ | Thermal conductivity |
| $D$ | Dissipation function |

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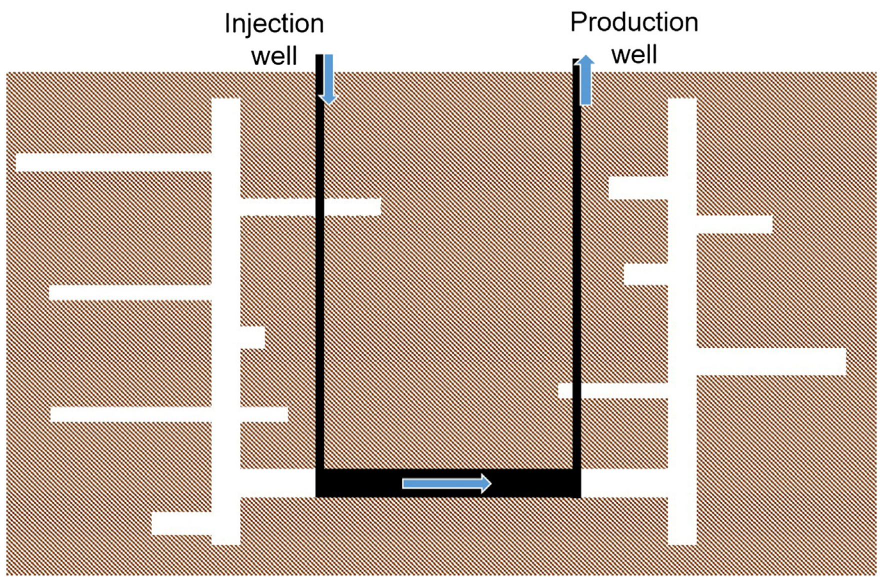


**Fig. 4.** Typical schema of water injection/production in underground mine geothermal systems.

10 km mine tunnel analogous to that shown in Fig. 4. The fluid is warmed up to an initial abstraction temperature of 30 °C and after passing through the heat pump is reinjected back at 15 °C. According to the results the initial temperature at the production well is maintained stable and then, it gradually decreases.

Rodríguez and Díaz (2009) proposed an analytical model based on a recurrent calculation algorithm which allows estimating the increment of the temperature of a fluid that runs through a mine gallery. This model is applied to a geothermal system in Springhill, Canada (Jessop et al., 1995), and the simulated results were compared to published empiric data (Caddet, 1992) which showed the same tendency. According to Rodriguez and Diaz's approach, the initial temperature of the rock mass around the channel will deplete since the very beginning depending mainly on time and on a convective coefficient. At this approach, the gallery has a circular section, and the heat exhaustion is represented as a virtual gallery wall with a constant temperature, *i.e.* initial temperature of the rock mass, which progressively moves off the gallery axis (the virtual radius of the gallery increases with time). Fig. 6 shows the temporal evolution of the temperature along the gallery according to this model, for different simulation times.

Ferket et al. (2011) describes the modelling-approach followed in Heerlen, Netherlands, at a mine with numerous interconnections between levels. They combined a hybrid node-loop approach, based on the EPANET code from United States Environmental Protection Agency (EPA), to integrate the complex geometry and advective flows, with a semi-empirical approach based on Rodríguez and Díaz (2009), to simulate the heat transfer between water and pipe walls. Premature short-circuiting and thermal breakthrough caused by high flow rates is investigated.

## 5. Review of numerical models

When the abstraction-injection system is more complex than the one presented in Fig. 4, or the whole hydrogeological system is to be modelled, analytical models are not powerful enough and numerical models need to be used. These models require the discretization or transformation of the governing equations (Section 3) to be turned into a set of algebraic equations. Three of the most popular discretization methods are compared in Table 2 and described in the following paragraphs:

i) The finite difference method (FDM) is historically the oldest of the three methods (Bakker, 2006), it divides the space and time coordinates on a rectangular grid, and model parameters are specified for each model grid cell (McMahon et al., 2001). The flow and transport equations are solved by direct approximation. The grid spacing represents the degree of accuracy of the model in representing lateral or vertical changes in the property values that describes the system (Wels et al., 2012). Finite difference methods have the advantage of being relatively simple to use, but have the disadvantage of not accurately representing irregular boundaries as they are not optimised for unstructured meshes (Kuzmin, 2010), *e.g.* MODFLOW, developed by the US Geological Survey (USGS).

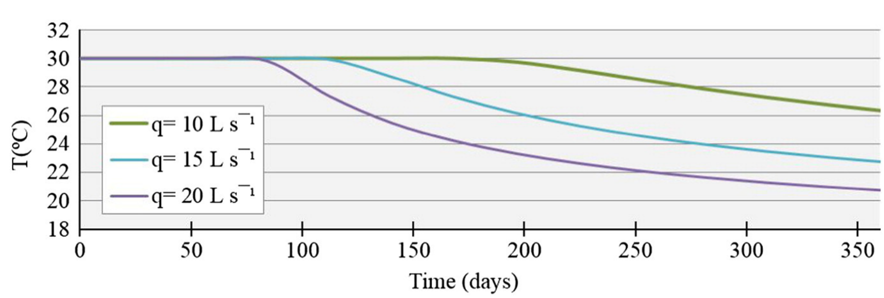


**Fig. 5.** Analytical simulation of temperature in a system analogous to that shown in Fig. 3, according to Pruess and Bodvarsson (1983). For a channel length: 10 km; initial abstraction temperature: 30 °C; temperature of reinjected flow: 15 °C.

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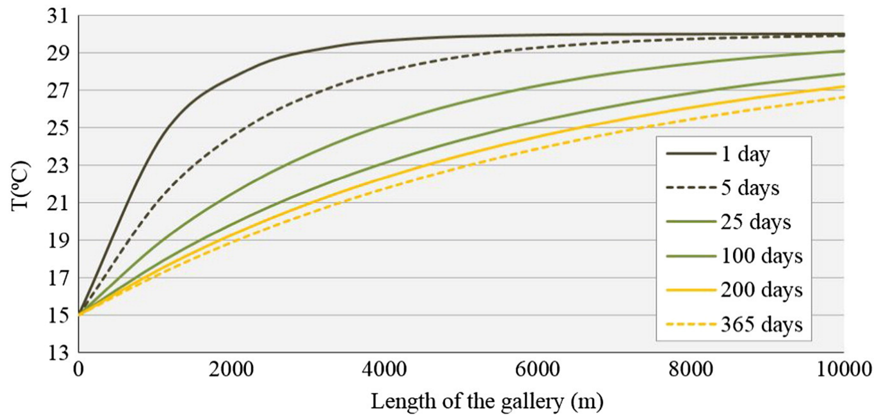


**Fig. 6.** Example of analytical model approach: variation of the temperature along a gallery of circular section for different simulation times, according to Rodríguez and Díaz (2009).

ii) In finite element method (FEM) the spatial domain is divided into a mesh of elements, generally of triangular or quadrilateral shape, it projects the continuous problem into a finite dimensional space (R. Heinzl, 2016). FEM deals with low Peclet numbers *i.e.* diffusion dominated problems (Kuzmin, 2010) and free surface problems (Bakker, 2006). It assures greater flexibility than finite difference methods in representing the model domain, particularly complex geological boundaries. The model mesh can be easily modified to provide greater precision in areas of interest (Wels et al., 2012). Finite element models are less susceptible to numerical dispersion than finite difference models, but for the same number of elements/cells the computing cost is higher (McMahon et al., 2001), *e.g.* FEFLOW, developed by DHI-WASY GmbH and COMSOL Multiphysics, developed by COMSOL.

iii) The finite volume method (FVM) uses a volume integral formulation of the problem with a finite partitioning set of volumes to discretize the equations. This method, which is based on the approximation of the conservation laws (R. Heinzl, 2016), is particularly interesting for turbulent and source term dominated flows. FVM is the most common method used in computational fluid dynamics engineering (CFD). In a geothermal modelling context it is, therefore, recommended for pumping shaft analyses or in case a piping-type scheme is to be evaluated, *e.g.* FLUENT (developed by ANSYS, Inc.).

**Table 2**
Summary of advantages and disadvantages of the numerical methods.

| | Advantages | Disadvantages |
|---|---|---|
| FDM | Conceptually simple | Difficulties representing irregular boundaries |
| | Easy to implement | Not optimised for unstructured meshes |
| | Low computational requirements | Momentum, energy and mass are not conserved |
| FEM | Very flexible | Not well suited for turbulent flow |
| | Excellent for diffusion dominated problems | Slow for large problems |
| | Good for free surface problems | |
| FVM | The conservation of mass, momentum and energy is guaranteed | Tends to be biased toward edges and one-dimensional physics |
| | Suitable for turbulent flows | |
| | Good for source term dominated flows | |

### *5.1. Model set-up*

Boundary conditions (BCs) are required components in computational fluid dynamics (CFD) and other mathematical models, and their correct definition is critical, to avoid errors and increased solving time. In order to ease the implementation of flow BCs, it is recommended to select the model domain by using physical hydrological features (Wels, 2015). Common flow BCs are a fixed hydraulic head (Dirichlet or first-type BC) at water bodies, as lakes or a groundwater level contour line, and no-flow BCs (Neumann or second-type BC) are often assumed as lateral boundaries when rivers delimit the model area (DHI WASY, 2014). A Cauchy BC (third-type) is occasionally selected to simulate the surface streams drainage (Baier et al., 2011; Uhlík and Baier, 2012). The pumping rate and the rainfall recharge need to be implemented as well but there is heterogeneity in the way each model has to deal with them.

In reference to the thermal BCs, it is common to assign at the upper boundary of the system a constant temperature (first-type BC), *i.e.* annual average soil or air temperature over a long term (Banks, 2012). Meanwhile a second-type BC is commonly assigned at the base of the system, *i.e.* geothermal heat flux.

Large gradients, grid skewness, applicability to compressible or unsteady flows and computational limitations could represent modelling constraints. Commercially available codes usually check on the model set-up to prevent errors from occurring (Bakker, 2006).

### *5.2. Review of numerical models with mine water reinjection*

Malolepszy (2003) uses TOUGH2, a general purpose fluid and heat flow simulator (Pruess et al., 1999), for assessing heat exchange processes at the flooded workings of the Nowa Ruda former mine (Poland). A planar (horizontal) model is developed being the boundary conditions set by trial and error matching of the initial temperature and pressure distribution (Malolepszy, 2003). In this model faults are neglected due to the rough geometry considered. Hypothetical production and injection of mine water, with a temperature drop of 19 °C (yield heat), is simulated for two different flowrates, with a distance between wells of 1500 m. The obtained temperature distribution in the reservoir after 40 years shows a 4 °C decrease on the final pumped water temperature when the reinjected flowrate is 10 L $s^{-1}$ and a decrease of 10 °C for a 20 L $s^{-1}$ injection flowrate (Malolepszy, 2003).

Renz et al. (2009) by means of the finite element simulator FEFLOW undertook a conceptual study of an abandoned potassium mine in Staßfurt, Germany. A 2D Darcy flow model (mine cross section) was created, with 1-D elements included for the calculation of the laminar

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flow (shafts and roadways) and the turbulent flow (drivings and caverns). In order to undertake a more exhaustive study the authors have extended the model to 3D. For a pumping rate of 3.5 L $s^{-1,}$ the simulations along 20 years predict a big drop of the temperature in the extracted water due to a short circuit effect between the injection and the extraction well: the water is flowing along the shortest way (shafts and tunnels) while the bulk of the reservoir is unused. Creating flow barriers, reinjecting cool water further away or into stopes with poor connectivity to the main pathways, or simply decrease the reinjected flowrate are, according to the authors, measures that could improve the usability of the geothermal system.

In order to assess the thermal depletion induced by the reinjection, Hamm and Bazargan Sabet (2010) use MARTHE, a FVM code developed by the BRGM (Bureau de Recherches Géologiques et Minières) (Thiery et al., 2009). Two hydraulic schemes were studied -production/injection in the same shaft and in different shafts- having the two different distribution schemes similar outputs. The warm water is collected from the bottom of a shaft and reinjected in a shallow point of it. The temperature evolution of the production zone over time was calculated, from the simulations it can be inferred that most of the temperature decrease at the extraction point occurs in the first months and then, after a few years the temperature tends to stabilize.

The water flow and heat transfer in the Oranje Nassau colliery, Heerlen, is modelled by Ferket et al. (2011) by means of the finite difference code SHEMAT (Clauser et al., 2012). As the extension and complexity of the studied mine workings were very high, only basic modelling exercises could be run. To simulate a complete pumping test, consisting of 10 to 20 transient periods, several weeks of computing time were required.

Madiseh et al. (2012) apply a finite volume method to a mine tunnel used as geothermal exchanger (Fig. 4) a computer FORTRAN program code, THEMUT, was created with this aim. Temperature of inlet water of the tunnel is kept at a fixed value and the rock mass and underground water are supposed to be in thermal equilibrium. Flow is assumed to be laminar (checked in the model by monitoring the Reynolds number). The authors compare their results with those from Rodríguez and Díaz (2009) approach and the curves seem similar, ratifying that the analytical model when applied to the steady state, is quite accurate.

The model is able to determine seasonal heat load variations by means of a control scheme based on a proportional differential integral scheme (PID). Therefore, the pumping flow rate may be adjusted in each time step so that the extracted heat power matches the demanded heat load (Ghoreishi et al., 2012).

### 5.3. Review of numerical models without reinjection

Even when the geothermal system has no reinjection, temperature changes could occur as pumping may induce the inflow of colder shallow groundwater into mine voids *i.e.* the natural direction of the groundwater flow is changed (Baier et al., 2011; Uhlík and Baier, 2012).

In order to investigate the water temperature evolution in a single shaft, Hamm and Bazargan Sabet (2010) apply the widely known FVM FLUENT to the Vouters coal mine at Moselle (Lorrain basin, France). It can be inferred that for free convection (no pumping) 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 than in the case of just one gallery. Forced convection is modelled for two pumping flowrates (only abstraction): for 27.8 L $s^{-1}$ there is no significant temperature change after 10 years, meanwhile for 166.7 L $s^{-1}$ a drop in temperature is observed at the bottom of the well. Here, a Dirichlet boundary condition (constant temperature) is applied at the shaft wall as the contact with the surrounding rock is assumed to be perfect.

Baier et al. (2011) evaluated the temperature changes at the Plzeňská coal basin (Czech Republic). The FDM MODFLOW (Hill et al., 2000) together with the modular solute/heat transport code MT3D (Zheng and Wang, 1998) were used. Two different groundwater extraction rates: 20 and 40 L $s^{-1}$, were simulated (steady state simulations). It was obtained that the temperature drop affects an area from 5 $km^2$ to 8 $km^2$, depending on the rate of extraction, although predicted mine water temperature changes were relatively small. The expected temperature conditions of the mine water was very stable and the temperature changes exceed the time scale of the human life.

The geothermal water resource from the uranium mines at the Příbram region (Czech Republic), was assessed by means of FEFLOW (Baier et al., 2011). A groundwater abstraction of 25 L $s^{-1}$ was simulated (steady state) for two potential locations of the production well. Model results showed a slight temperature increase under the abstraction point due to depth upward groundwater flows that were activated. The upper colliery and the abstraction point, however, became colder.

The potential for geothermal energy abstraction from the abandoned and flooded Krimich II underground coal mine was tested by using MODFLOW and MT3D (Uhlík and Baier, 2012). The authors proposed two different scenarios: an abstraction with a heat pump situated at the ground surface and heat pump exchangers installed directly in the flooded parts of mine structures. After the thermal simulation the first scenario was chosen as the most effective. A conclusion of their study is that, many abandoned mines could supply groundwater of relatively constant temperature for a long time.

Andrés et al. (2015) developed two-dimensional (transverse section) and three-dimensional numerical models (FEFLOW) for the flooded Barredo-Figaredo, coal mines, at Asturias, Spain. The aim was to predict the long-term temperature of the stored minewater which is currently supplying heating and cooling to a hospital and university buildings. In order to calibrate the model, the flooding of the reservoir (when pumping ceased) was simulated. Then, two scenarios: that currently taking place and a second one with a hypothetical reinjection, were simulated for 30, 60, and 90 years. According to the authors, the different scenarios yield similar results that envisage an optimal long-term energy use of the reservoir providing it is adequately managed and regulated.

Some details about the models reviewed in Sections 5.2 and 5.3 can be found in Table 3.

## 6. Simultaneous use of mine water for heating and cooling

Almost all the simulations found in the literature assume a continuous exploitation of the geothermal system whereas, in practice, heat production is mostly required during the coldest months and *vice versa* for the cold production. A seasonal use of the exploitation will allow a heat recovery, increasing the system lifetime (Ghoreishi et al., 2012; Hall et al., 2011; Hamm and Bazargan Sabet, 2010; Rodríguez and Díaz, 2009). If heat and cold demands co-exist, the performance of the geothermal system can be maximized acquiring the energy profile of the building (load-duration curve) and the balance between cold and heat demands (Roijen and Op, 2007). In these combined heating/cooling systems, abstraction and injection boreholes are often switched seasonally to take advantage of the heat storage capacity of the ground (Rühaak and Renz, 2010). The simultaneous use of warm and cold mine water has been successfully implemented at Heerlen, Netherlands, in one of the world's largest geothermal district heating systems sourced by mine water (Minewater project, 2011; Peralta Ramos et al., 2015). The system was developed as part of a EU-funded Project called The Minewater project and it is well documented in the literature (Verhoeven et al., 2014, among others).

Currently, the EU-funded Project LoCAL (Low-Carbon After-Life) focuses on the sustainable use of flooded coal mine voids as a thermal energy source with pilot plants in UK, Poland and Spain. The project which aims to constitute a baseline activity to minimize post-closure environmental risks, includes the analyses of models to incorporate cooling into the geothermal system (EU, 2016).

Please cite this article as: Loredo, C., et al., Modelling flow and heat transfer in flooded mines for geothermal energy use: A review, Int. J. Coal Geol. (2016), http://dx.doi.org/10.1016/j.coal.2016.04.013

**Table 3**
Summary of the revised heat and flow transfer models characteristics.

| Reference | Analytical/numerical | System with reinjection? | Code and discretization scheme (if applicable) | Mesh characteristics (if applicable) |
|---|---|---|---|---|
| Malolepszy (2003) | Numerical | Yes | FVM: TOUGH2 | 1632 grid blocks |
| Bazargan et al. (2008) | Analytical | Yes | – | – |
| Rodríguez and Díaz (2009) | Analytical | Yes | – | – |
| Renz et al. (2009) | Numerical | Yes | FEM: FEFLOW | 2D model: 114,557 triangular elements<br>3D model: 1.2E6 triangular elements |
| Hamm and Bazargan Sabet (2010) | Numerical | Yes | FVM: FLUENT | 626,000–1.39E6 tetrahedral elements |
| Hamm and Bazargan Sabet (2010) | Numerical | Yes | FVM: MARTHE | 1.14E6 hexahedral elements |
| Ferket et al. (2011) | Analytical | Yes | – | – |
| Ferket et al. (2011) | Numerical | Yes | FDM: SHEMAT | 500,000 grid cells |
| Baier et al. (2011) | Numerical | No | FEM: FEFLOW | 39,065 irregular triangular elements |
| Baier et al. (2011) | Numerical | No | FDM: MODFLOW | 40,000 $m^2$ cells, 5 layers |
| Ghoreishi et al. (2012) | Numerical | Yes | FDM: THEMUT | 160 nodes radial direction<br>120 nodes axial direction |
| Uhlík and Baier (2012) | Numerical | No | FDM: MODFLOW | 40,000 $m^2$ cells; 5 layers |
| Andrés et al. (2015) | Numerical | No[a] | FEM: FEFLOW | 2D model: 45,000 triangular elements<br>3D model: 3.9E6 triangular elements |

[a] The real system has no reinjection but the authors run a scenario considering this option.

## 7. Discussion and conclusions

The number of abandoned and flooded mines increases day by day. Flooded underground mines, as well as other water bodies linked with mining, can be considered for geothermal energy exchange; furthermore they can turn a bothersome mining waste such as the mine water into an environmentally friendly renewable energy source.

A deep understanding in the behaviour of the system's hydrogeology is required in order to acquire acknowledge for future conducts. The difficulties associated with this modelling exercise derive from the geometric complexity of the mineworkings, with lateral and vertical interconnectivities, together with the frequent lack of data about parameters involved in the processes. Different types of flow will take place *i.e.* laminar and turbulent; and the mine water will flow through fractured media, mine voids and porous media. The software/equations selected for the modelling task will need to be able to deal with this heterogeneity.

The most common outputs of the studied models are the evolution of the abstracted water temperature and flowrate. Several extraction rates are often simulated in order to determine the most performant work regime of the system and to assess the thermal power that the installations are able to provide.

Analytical models (Section 4) can be used as a starting point of the study and then, if a more detailed assessment is needed, numerical models should be applied. When selecting the most appropriated code, the capabilities and limitations of the available codes should be taken into account, as explained in Section 5.

The main factors that guaranty the success of a geothermal installation related to mine workings are the available flowrate and mine water temperature, the chemical composition of the water and the distance of the production point to the energy consumer. Intermittent heat extraction from the mine voids and seasonal use as heat source and heat sink would be the better ways to ensure the sustainably of the resource.

## Acknowledgements

This research was supported by the EU Research Fund for Coal and Steel (RFCS) LoCAL Project RFCR-CT-2014-00001.

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