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Numerical Modeling of Geothermal Systems

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ABSTRACT

The purpose of our study is to model a geothermal reservoir. When geothermal reservoir are assumed to be composed of pure water, the transfer of mass and energy is classically described by two balance equations: a mass balance equation and an energy balance equation. In addition to those equations, fluid velocity is classically given by the Darcy law. Thermodynamic properties are given by a set of equations from the IAPWS-IF97 thermodynamic formulation. This system is solved with pressure and enthalpy as the primary variables to increase stability of phase transition between single and two-phase states. We have chosen to use a splitting method to get rid of the complexity of coupling equations and a finite volume method for the spatial discretization. Selecting object-oriented languages, we developed a multi-language framework, combining Python, Fortran and C implementation of IAPWS (from the Freesteam project) including the supercritical regions.

We have applied this simulation model to a low temperature case in Paris basin, France, and to several one-dimensional systems and a two-dimensional system and a two-dimensional one.

1. INTRODUCTION

The purpose of our study is to model a geothermal reservoir in its natural or exploitation state. Geothermal phenomena often occur in unattainable places, in the Earth's crust, sometimes below the sub-seafloor. In such conditions data acquisition is often difficult and scientists have few measurements. Numerical modeling is often the unique way to have an idea of what happens, to explain surface observations. Numerical geothermal/hydrothermal simulators have been developed for many years now. Ingebritsen and al. (2010) give attributes of such simulators in a detailed review (see table 1 extracted from their article). Among these codes, TOUGH2 is widely used in the geothermal industry to model geothermal reservoir exploitation. HYDROTHEM is used to model hydrothermal deep high energy systems, including magmatic intrusion [Hayba and Ingebritsen,1997]. CSMP++ is a recent generic platform which has been used to model fluid-flow in mid-ocean rife hydrothermal systems [Coumou, 2008].

Name	*Tmax °C*	*Pmax MPa*	*Numerical Method*	*Reactive Transport*	*Deformation*	*CO2*	*NaCl*
CSMP++	1000	500	FE-FV				X
FEHM	1500		FE	X	X	X	
HYDROTHERM	1200	1000	FV				
NaCl-TOUGH2	620	100	IFD				X
Tough2	350	100	IFD			X	X

Table 1: Relative capabilities of selected multiphase numerical codes commonly applied in simulations of magmatic hydrothermal systems extracted from Ingebritsen and al. (2010) FE: Finite Elements, FV: Finite Volumes, IFD: Integrated Finite Differences

2. GOVERNING EQUATIONS

The flow of fluid through a porous medium is supposed to be Darcian [Bear, 1972] so that the flow rate of a fluid through a given section, that is to say the volume of water passing through the porous medium, by unit of surface of time, is written for each phase:

$$\overrightarrow{u_l} = -\frac{kk_l}{\mu_l}(\overrightarrow{\nabla} p + \rho_\varphi g \overrightarrow{\nabla} z), \quad \vec{u}_v = -\frac{kk_v}{\mu_v}(\overrightarrow{\nabla} p + \rho_v g \overrightarrow{\nabla} z) \qquad (1)$$

where subscript l represents liquid water and subscript v the vapor water, k(x) is the intrinsic permeability, k_l and k_v are relative permeabilities, μ is the fluid's dynamic viscosity, p is the fluid pressure (Pa) and ρ is the fluid's density (kg.m^3). This equation assumes that the movement of the fluid in a porous environment is the result of an instantaneous equilibrium between local pressure gradients on the one hand and external gravity forces on the other hand with the gravity acceleration given by $g = 9.81\ m.s^2$. This experimental law can be viewed as a degenerated momentum equation.

In order to model hydrodynamic systems in a porous medium, the Darcy law (1) is injected into two equations describing mass balance and energy balance. The mass balance for a two-phase fluid can be written as:

$$\sum_{\varphi\in\{l,v\}} \frac{\partial \omega x_\varphi^V \rho_\varphi}{\partial t} + \nabla \cdot \sum_{\varphi\in\{l,v\}} \rho_\varphi \overrightarrow{u_\varphi} = Q_m \tag{2}$$

where ω is the porosity of the porous medium (dimensionless), Q(x,t) a source term (kg.s^{-1}.m^{-3}) (refill of the aquifer, pumping, injection). The energy balance can be written as:

$$(1-\omega)c_V \frac{\partial T}{\partial t} + \omega \sum_{\varphi\in\{l,v\}} \frac{\partial(\rho_\varphi h_\varphi)}{\partial t} + \nabla \cdot \sum_{\varphi\in\{l,v\}} h_\varphi \rho_\varphi \overrightarrow{u_\varphi} = \nabla \cdot (K(x)\overrightarrow{\nabla} T) + Q_e \tag{3}$$

where h is the specific enthalpy (J.kg^{-3}), T the temperature (measured in Kelvin (K)) of saturated rock. We made the usual assumption of local thermal equilibrium between rock and the fluid flowing through it. $K(x)$ is the thermal conductivity and $\Phi(x,t)$ a source term (injection of cold water, source of heat because of the presence of magma). In this classic formulation, potential and kinetic energies have been neglected (see Ingebritsen and al. (2006) for further discussion).

At this step there are two ways to solve this two-equation system. The first one is to use pressure and temperature as primary variables and solve for their transient values (which is the strategy adopted in TOUGH2). The alternative option is to retain pressure and enthalpy as primary variables (HYDROTHERM, or CSMP++ [Coumou, 2008]). The pressure-temperature formulation may present some numerical difficulties when the system switches from one-phase to two-phase conditions. The reason behind this instability is that it is not possible to describe uniquely a two-phase system with only pressure and temperature and an additional variable must be introduced (vapor saturation) [Ingebritsen and al., 2006]. As we choose to work with p and h as primary variables we write partial derivatives in terms of p and h and insert (1) in (2) and (3). Considering that there are no mechanical effects and that the rock porosity does not change (i.e. solid matrix is unaffected by fluid pressure variations) (2) and (3) become:

Equation for pressure

$$\omega\alpha_p \frac{\partial p}{\partial t} + \omega\alpha_h \frac{\partial h}{\partial t} - \sum_{\varphi\in\{l,v\}} \nabla \cdot \frac{kk_\varphi}{\mu_\varphi} \rho_\varphi \overrightarrow{\nabla} p = Q_m + \sum_{\varphi\in\{l,v\}} \nabla \cdot \frac{kk_\varphi}{\mu_\varphi} {\rho_\varphi}^2 \vec{g} \tag{4}$$

where α_p measures the fluid's compressibility, and α_h is a proxy for its thermal dilatancy. Both variables are derived from the fluid's equation of state.

Equation for the enthalpy

$$\beta_p \frac{\partial p}{\partial t} + \beta_h \frac{\partial h}{\partial t} - \sum_{\varphi\in\{l,v\}} \nabla \cdot \frac{kk_\varphi}{\mu_\varphi} h_\varphi \rho_\varphi \overrightarrow{\nabla} p$$
$$= \nabla \cdot (K\overrightarrow{\nabla} T) + Q_e + \sum_{\varphi\in\{l,v\}} \nabla \cdot \frac{kk_\varphi}{\mu_\varphi} h_\varphi {\rho_\varphi}^2 \vec{g} \tag{5}$$

3. MATERIALS

We use the equation of state for pure water given by the International Association for the Properties of Water and Steam (IAPWS-97) [IAPWS] to compute all coefficients as functions of p and h. IAPWS gives a set of equations for each phase region: liquid, vapor, supercritical and two-phase. The formulation is valid from 273.15K to 1073.15K at pressures up to 100MPa, and there is a high-temperature region extending to 2273.15K at pressures up to 50MPa.

Equations (4) and (5) are strongly coupled so that we use a splitting resolution method. First we start by solving (4) to obtain p then we solve (5) to obtain h. We used a finite volume method. We offer some freedom to users thanks to the implementation of several methods like explicit or implicit Euler, Runge-Kutta or BDF2 for time solvers or GMRES and BICGSTAB for the linear solver. We can handle several boundary conditions like no-flow – describing a boundary which cannot exchange matter with the exterior – or a mixed thermal condition – a Dirichlet in pressure with a Dirichlet in temperature or an outflow condition in temperature in order to describe a recharge or a discharge zone. We are developing a multi-language framework, combining Python, Fortran and the C implementation of IAPWS (from the Freesteam project). The high level part is in Python to keep all the facility and flexibility of an interpreted language. The computation part is written in Fortran to keep the efficiency of a compiled language. In this way we have

a flexible and efficient framework. Both languages (Python and Fortran 90/2003) are object languages which provide a good adaptability which is the main property needed by a research computational code.

4. BENCHMARKS

In the following section we present the results from benchmark simulations taken from literature. In all cases we get either a good agreement with the other simulators or the expected behavior.

4.1 Low energy geothermal doublet

We consider a two-dimensional horizontal problem which represents geothermal production from a low enthalpy geothermal aquifer whose size is 5km × 4km. Cold water (40°C) is injected through an injection well into a geothermal reservoir of pure water at 70°C and water is pumped from the extraction well located 1km apart. Table 2 summarizes the geometry, properties and discretization of this problem. Values correspond roughly to those encountered in the modeling of the geothermal resource of the Dogger aquifer of the Paris basin [Lopez and al., 2010].

Our test simulates the evolution of the reservoir over 10 years from an initial state, characterized by p_0 and h_0. As our model is full 3D this simulation is a pseudo-2D case with horizontal bottom and top boundaries (z sections) which are no-flow boundaries. All vertical boundaries (x and y sections) are Dirichlet boundaries held constant to their initial states. As this problem is well known it is an efficient way to validate our code. Results are compared with TOUGH2 [Pruess and al., 1999]. Comparisons are done in two cells, the injection one and the extraction one (see table 2).

Injecting cold water involves an increase in pressure and a decrease in temperature respectively due to a mass supply and the introduction of colder water. This is what the figures 1 and 2 show. In the same way, a pressure drop is expected at the extraction cell because the production well attracts mass from its neighbors (figure 1). The more intensive the pumping is the more cold water will be sucked out of the extraction well (figure 2). Figures 1-2 show that results from our code are in good agreement with those from TOUGH2. Slight differences come from the fact that we use a more recent equation of state.

initial pressure p_0	15. 10^6 Pa
initial pressure h_0	305,249J. kg^{-1}
initial temperature T_0	70 °C
permeability	2. 10^{-12} m^2
porosity	0.1
geometry of flow domain	2-D horizontal (x,y) section
gridding	51x31x1 blocks in (x,y,z)
block volume	100x100x10
injection well	50 $kg.s^{-1}$ at the position (15,15,1)
	186,776J. kg^{-1}
production well	50 $kg.s^{-1}$ at the position (30,15,1)

Table 2: Parameters corresponding to geothermal exploitation of the Dogger aquifer [Lopez and al., 2010]

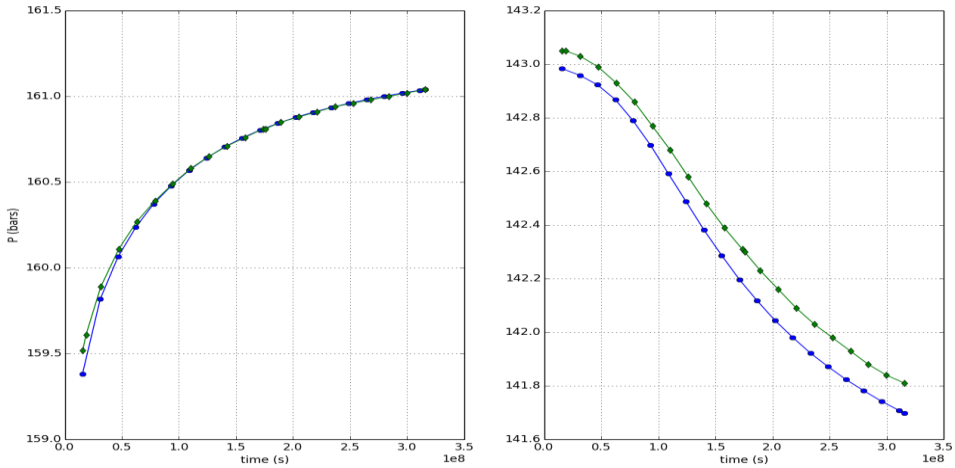


Figure 1: Comparison of pressure between TOUGH2 (diamond) and our code (circle). The left picture plots data from the injection well whereas the right picture plots data from the extraction well.

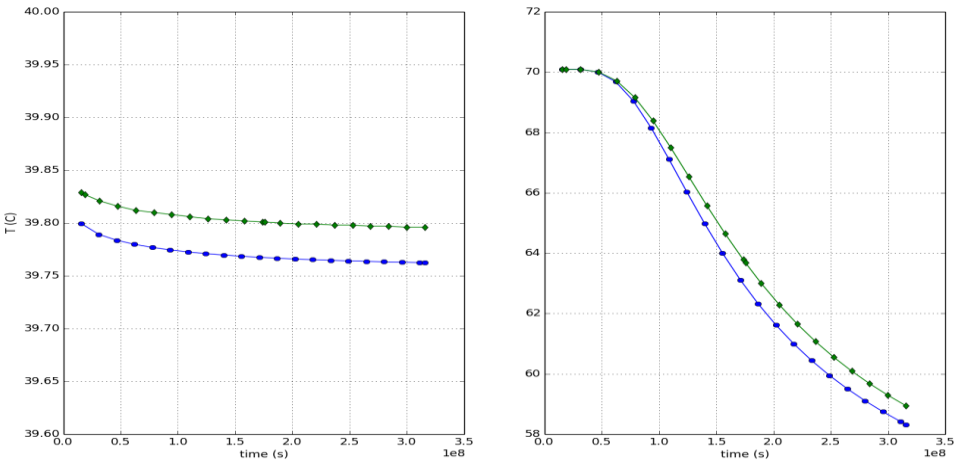


Figure 2: Comparison of temperature between TOUGH2 (diamond) and our code (circle). The left picture plots data from the injection well whereas the right picture plots data from the extraction well.

4.2 Transport of hot water in one dimensional

We performed two tests in a 1D horizontal domain showing the progress of a thermal front. Both case studies are borrowed from [Coumou, 2008] who run a comparison between CSMP++ and HYDROTHERM. Once again, our results show good agreement with the two other simulators (figure 3).

The flow is modeled along a 2 km long horizontal column assigning fixed p-h values at both ends of the column. The left limit was held at higher p-h values than the right limit resulting in the injection of hotter water in the domain from the left boundary. As the field is horizontal the flow is driven only by pressure gradients. Rock properties were uniform and constant. Porosity, rock isobaric heat and heat conductivity were respectively 0.1, 242E+4 $J.m^{-3}.s^{-1}$ and $2.25W.m^{-1}.s^{-1}$. We studied both a liquid domain – setting left boundary at p-T 35MPa-350°C and right boundary at 25MPa-170°C – and a vapor domain – setting at 10MPa-500°C and 1MPa-350°C.

Figure 3 shows p-T profiles obtained with our code on the left part and results from HYDROTHERM and Coumou/CSMP++ on the right part. Fluid pressure and temperature calculated by our code and CSMP++, HYDROTHERM show a very good match for the liquid domain. In the vapor domain our results remain consistent with the other results but they are slightly ahead of Coumou's

results.

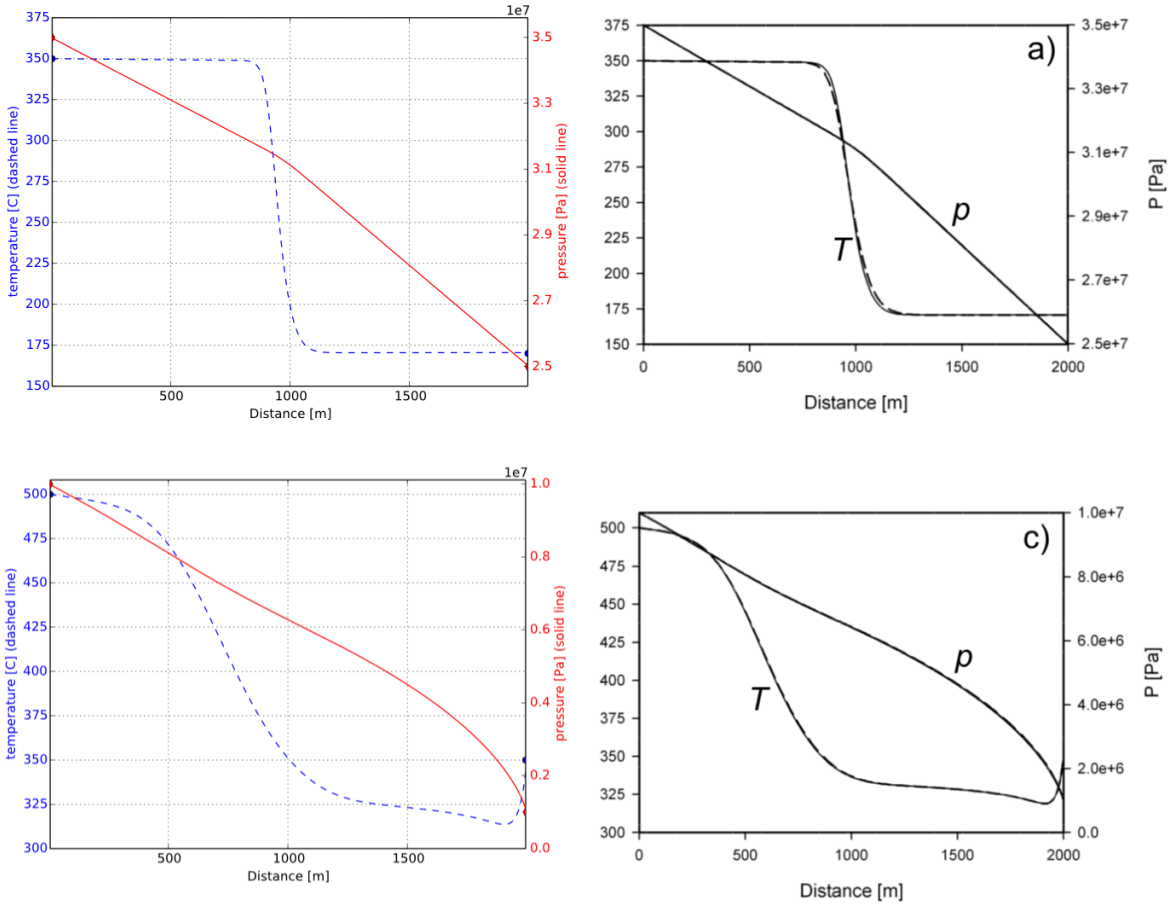
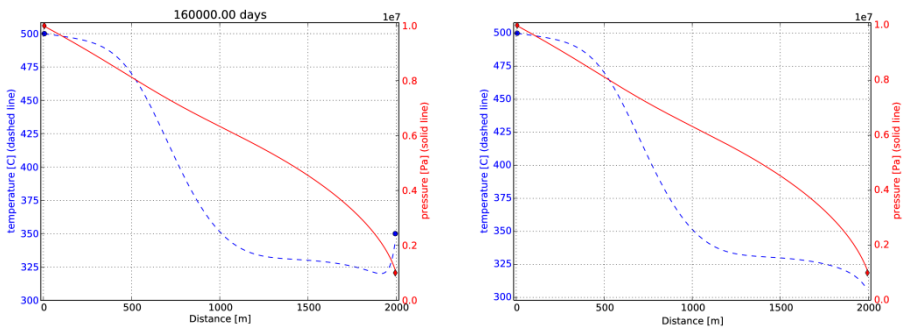


Figure 3: Pressure and temperature vs distance. Results from our code are plotted of the left figures and results from CSMP++ and HYDROTHERM are plotted on the right figures. The first line of figures shows the liquid domain after 20000 days of simulation and the second line of figures shows the vapor domain after 160000 days.

As mentioned by Coumou (2008) the last test shows a non-physical behavior. In fact we observe that temperature in cells near the right boundary drop under 350°C. We propose to use an outflow boundary at the right limit (see figure 4) instead of a Dirichlet one.



(a) Condition dirichlet **(b) Condition outflow**

Figure 4: By setting an outflow boundary condition on the right (outflow) side, the enthalpy is no more constrained and drops in a more physical way.

5 NATURAL CONVECTION

In this part we have tried to model natural convection in hydrothermal systems. Jupp and Schult (2004) and Coumou (2008) show systems where plumes are constantly evolving: appearing or disappearing, dividing or merging. We did a simulation with a high intrinsic permeability $k=10^{-12}m^2$. The top represents the seafloor at 2.4km. If the fluid's flow enters in the domain we use Dirichlet conditions: $p=25MPa$ and T is held to 10 else we use an outflow boundary. All the other boundaries are impermeable and adiabatic. To model the presence of a source of heat outside of the domain we use the heat source term Q_e of equation (5). Such a discrete a

heat source is put in every bottom cell. We start with a hydrostatic pressure and a fluid at 10. The domain is a 2D domain with width 1500m and height 1000m. Figure 5 shows that vigorous convection cells develop as expected.

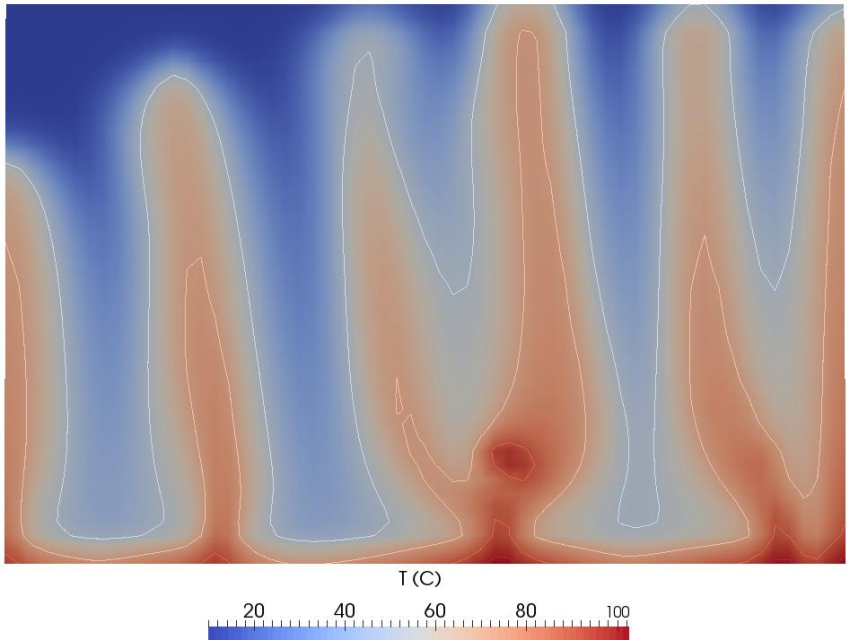


Figure 4: Natural convection

6 CONCLUSION

This paper illustrates the ability of our code to model geothermal reservoir. At this point we validated our code using benchmarks from the literature. Simulation of a real reservoir (Bouillante field, Guadeloupe) is currently a work in progress.

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