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Investigation of hydrothermal activity at Campi Flegrei caldera using 3D numerical simulations: Extension to high temperature processes

Andrey Afanasyev [a,*], Antonio Costa [b], Giovanni Chiodini [c]

[a] Institute of Mechanics, Moscow State University, Moscow, Russia
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Italy

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ABSTRACT

Hydrothermal activity at Campi Flegrei caldera is simulated by using the multiphase code MUFITS. We first provide a brief description of the simulator covering the mathematical formulation and its applicability at elevated supercritical temperatures. Then we apply, for the first time, the code to hydrothermal systems investigating the Campi Flegrei caldera case. We consider both shallow subcritical regions and deep supercritical regions of the hydrothermal system. We impose sophisticated boundary conditions at the surface to provide a better description of the reservoir interactions with the atmosphere and the sea. Finally we carry out a parametric study and compare the simulation results with gas temperature and composition, gas and heat fluxes, and temperature measurements in the wells of that area. Results of the parametric study show that flow rate, composition, and temperature of the hot gas mixture injected at depth, and the initial geothermal gradient strongly control parameters monitored at Solfatara. The results suggest that the best guesses conditions for the gas mixture injected at 5 km depth correspond to a temperature of ~700 °C, a fluid mass flow rate of about 50–100 kg/s, and an initial geothermal gradient of ~120 °C/km.

Introduction

Modelling of hydrothermal activity often requires application of robust numerical techniques. The simulation of the corresponding flows in porous media must be capable of significant pressure and temperature variations, multiphase flows and phase transitions, as well as they must account for realistic geological constraints provided in a full-scale (3D) geostatic model of a hydrothermal reservoir. In case of a deep hydrothermal activity, the numerical algorithms must also be robust under near-critical thermodynamic conditions, when the density and viscosity of reservoir fluid show rapid nonlinear variations.

There are several codes that can be applied for scientific investigations of hydrothermal flows (Pruess et al., 1999; Pruess, 2004; Ingebritsen et al. 2010). One of the most popular is TOUGH2 (Pruess et al., 1999; Pruess, 2004) and its capability can be assessed through the numerous examples of its applications (e.g., Todesco, 2009; Petrillo et al., 2013). In this study we apply the MUFITS software (Afanasyev, 2013b), which we present to the volcanology community for the first time. A review of other simulators discussing their applicability and limitations can be found in Ingebritsen et al. (2010).

MUFITS simulator can be used in different applications related to subsurface exploration, we consider its particular application to modelling of CO_2–H_2O mixture convective flows in hydrothermal systems like that hosted at Campi Flegrei caldera. The CO_2–H_2O mixture flows can be simulated by TOUGH2 compiled with either EOS2, ECO2N, ECO2M or ECO2H properties module. The EOS2 and ECO2H modules (Pruess et al, 1999; Spycher and Pruess, 2011) are usually used in hydrothermal applications while the ECO2N and ECO2M modules (Pruess and Spycher, 2007; Pruess, 2011) are designed for low temperatures in carbon dioxide sequestration problems. The primary disadvantage of these modules is their incapability to simulate water flows at temperatures above its critical value for H_2O and, particularly, under near-critical conditions. Therefore, TOUGH2 (particularly EOS2 module) cannot be applied to deep hydrothermal flows where the pressure and the temperature exceed the critical parameters for H_2O.

In this work, using the MUFITS code, we consider the hydrothermal convection at Campi Flegrei caldera taking into account both shallow subcritical and deeper supercritical regions. The proposed method for CO_2–H_2O mixture properties prediction should be considered as a generalization of EOS2 and ECO2N modules, providing an extension to a wider range of pressures and temperatures. The method has already been applied to underground CO_2 storage problems (Afanasyev, 2013a, 2013b), whereas, here, we consider its application to hydrothermal systems. In particular our goals are both to demonstrate the

* Corresponding author.

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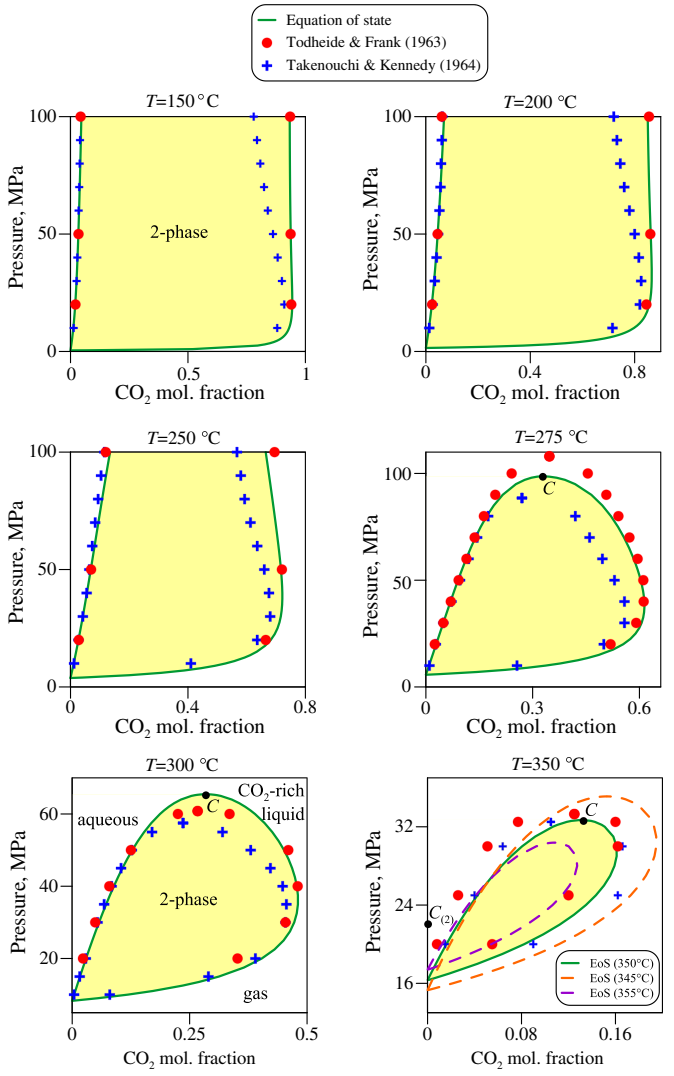

Fig. 1. CO_2–H_2O mixture phase diagram at different temperatures. The highlighted region is the two-phase state region, C is the critical point, and $C_{(2)}$ is the H_2O critical point. Lines are the properties predicted by the cubic equation of state (EoS), points are the laboratory data.

flexibility and the robustness of MUFITS and to highlight the parameters controlling mass and energy flows in Campi Flegrei hydrothermal system.

The numerical model

Governing equations

For modelling multiphase flows of CO_2–H_2O mixture we use the system of balance equations for mass (1) and energy (2) together with the Darcy Eq. (3):

$$\frac{\partial}{\partial t}\left(\phi\sum_{i=1}^{p}\rho_i c_{i(j)} s_i\right) + div\left(\sum_{i=1}^{p}\rho_i c_{i(j)}\mathbf{w}_i\right) = 0, \qquad j = 1,2, \tag{1}$$

$$\frac{\partial}{\partial t}\left(\phi\sum_{i=1}^{p}\rho_i e_i s_i + (1-\phi)\rho_r e_r\right) + div\left(\sum_{i=1}^{p}\rho_i h_i \mathbf{w}_i - \bar{\lambda}\mathbf{grad}T\right) = 0, \tag{2}$$

$$\mathbf{w}_i = -K\frac{f_i}{\mu_i}(\mathbf{grad}P - \rho_i \mathbf{g}), \qquad i = 1,\ldots,p. \tag{3}$$

Here, ϕ is the porosity and p is the number of phases. Subscripts i and j refer to the phase and the component of the fluid mixture, whereas the subscript r refers to the rock. Symbol $c_{i(j)}$ denotes the jth component mass fraction in the ith phase, s_i is the ith phase saturation, ρ_i is the density, $\mathbf{w}_i$ is the Darcy velocity, e_i is the internal energy, h_i is the specific enthalpy, f_i is the relative permeability, μ_i is the viscosity, $\bar{\lambda}$ is the effective heat conductivity, T is the temperature, K is the absolute permeability of the matrix, and P is the pressure.

The maximal number of binary mixture phases in the temperature range of interest is three ($p \le 3$) because we do not consider temperatures at which solid phase appears. The three-phase equilibria of CO_2–H_2O mixture are possible under relatively low temperatures and pressures (subcritical for CO_2). In this case the three phases are liquid H_2O, liquid CO_2 and gaseous CO_2. Under elevated temperatures, only two-phase equilibria, formed by H_2O-rich and CO_2-rich phase are possible. For the two-phase equilibria, we use the relative permeabilities as proposed by Brooks and Corey (1964), and the critical saturations of H_2O-rich phase and CO_2-rich phase are set to 0.3 and 0.05 respectively. The extension of the relative permeability model for the case of three-phase equilibria is given in Afanasyev (2013a). However, as we mentioned above, the three-phase equilibria are possible only in regions characterized by relatively low temperatures and pressures and, actually, they are not observed in our simulations.

We assume that the parameters of the host rock are given by the following relations:

$$\rho_r = const, \qquad e_r = C_r T, \qquad \lambda_r = const,$$

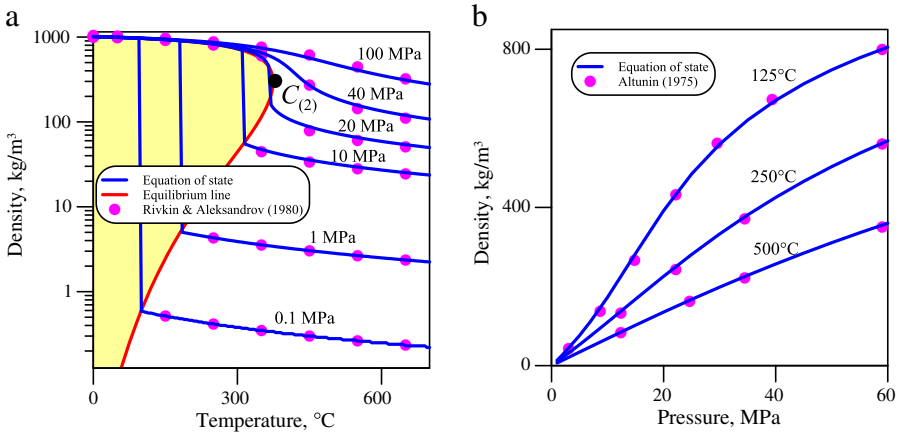

Fig. 2. Densities of pure H_2O (a) and pure CO_2 (b). $C_{(2)}$ is the H_2O critical point.