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Sensitivity analysis on the thermal-hydraulic parameters governing the saturation of an engineered clay barrier system

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Abstract

In this paper, we study the impact a heat source makes on the thermo-hydraulic behaviour of a system composed of an engineered clay barrier and a host rock, namely an argillite. We first perform a benchmark test case with code CAST3M and code ASTER. The results of the calculations are in good agreement, except for the gas pressure. Nevertheless, gas pressure does not seem to influence the saturation process, although the saturation kinetics is governed by the darcean water flow. The saturation process is accelerated when the heat source is taken into account. More precisely, this acceleration is due to dynamic viscosity increase with heating. In a second time, five other heating sources have been tested in code ASTER. Compared with the reference calculations, some give an identical response. However, the highest heating sources provoke a desaturation phenomenon because of the air pressure increase with temperature. The liquid saturation of the engineered barrier is then delayed.

Keywords: Benchmark; Thermo-hydraulic coupling; Engineered barrier; Heating canister; Unsaturated clayed materials; Nuclear waste repository

1. Introduction

In the framework of describing the thermo-hydraulic behaviour of a High Level Waste Repository, one objective is to evaluate the influence of high temperatures on the saturation process. As a first step of simulation, the mechanical behaviour of the clay is not modelled. A first calculation was performed with the code CAST3M at the Commissariat à l'Energie Atomique (CEA). It represents an isolated canister, surrounded by an expansive clay, and placed in a cylindrical chamber (Barnel et al., 2002).

Physically, a thermo-hydraulic two-fluid model is used. It has been modelled with three nonlinear and coupled mass and energy balance equations. A special scheme to treat local complete saturation has been proposed. The results showed an acceleration of the saturation phenomenon with the temperature increase. This is due to water dynamic viscosity during a heating process. The saturation kinetic is governed by the darcean water flow.

In this paper, we first check the above-described results. Three calculations were performed both with

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the code CAST3M and the code ASTER at the Electricité de France (EDF). The code ASTER does not take into account a local complete saturation but leaves a low air–water content in the rocks.

In a second part, five different kinds of heating source are tested using the code ASTER, in order to determine whether the response of the argillaceous system submitted to heating is single or not.

2. A short comparison between the thermo-hydraulic models used in CAST3M and ASTER

The model describing the partially saturated porous materials composed of three balance equations is the same for both codes. CAST3M uses Whitaker's (1977) theory as a reference whereas ASTER employs Coussy's (1995) approach, namely, Water mass conservation:

$$\frac{\partial}{\partial t}[\rho_w\theta_w + \rho_v(\omega-\theta_w)] = -\mathrm{div}[\rho_w v_w + \rho_v v_g + j_v] \quad (1)$$

Air mass conservation:

$$\frac{\partial}{\partial t}[\rho_a\ (\omega-\theta_w)] = -\mathrm{div}[\rho_a v_g + j_a] \quad (2)$$

Energy conservation:

$$\begin{aligned}\frac{\partial}{\partial t}[h_w\rho_w\theta_w &+ h_v\rho_v\ (\omega-\theta_w) \\ &+ h_a\rho_a\ (\omega-\theta_w) + h_s\rho_s\ (1-\omega)] \\ &= \mathrm{div}\ q - \mathrm{div}[h_w\rho_w v_w + h_v\rho_v v_g + h_v j_v + h_a j_a] \quad (3)\end{aligned}$$

where ω stands for porosity, ρ_i for density of i component, θ_w for liquid content, j_i for diffusive fickian flux of i component, v_i for generalized darcean flux of i component, h_i for specific enthalpy of i component, q for thermal conduction flux, and with i = s stands for solid material, i = w for water in a liquid state, i = g for gas, i = v for vapour and i = a for dry air.The saturation is defined as follows:

$$S^* = \frac{\theta_w - \theta_{wr}}{\theta_{wsat} - \theta_{wr}} \text{ and } \theta_{gr} = \omega - \theta_{wsat} \quad (4)$$

where $\theta_{wr} = 0$, which implies no residual water content. An important difference between the two codes stays in the treatment of saturated domain. In ASTER, there always exists a slight residual gas content ($\theta_{gr} = 0.01\omega$), which prevents air mass conservation equation from degeneracy. Physically, this gas cannot be considered as trapped in the rock. Indeed, if we consider total porosity of clays, the geometry of the porous medium may keep trapped gas in small pores. However, if we consider kinematic porosity, namely the porosity fraction that is involved in flow, then the notion of residual gas content loses its pertinence. In ASTER's model, the whole porosity (ω) is involved in advective flows, ω being the kinematic porosity. As a matter of fact, the residual gas content does not correspond to trapped gas. Therefore, the value of residual gas pressure cannot be chosen by considering the gas trapped in small pores. From a mathematical point of view, in the saturated domain, the gas pressure is not determined (as can be seen in Fig. 1). We just know gas pressure should be lower than liquid pressure. Considering radioactive waste repository problems, we suppose that residual air content is in equilibrium with dissolved air present in the liquid and this one is in equilibrium with atmospheric pressure in the shafts of the repository. For these reasons, the value of 0.1 MPa is commonly chosen for residual air content. Dissolved air is not modelled in the two codes. Barnel et al. (2002) have shown it has no significant effect on liquid kinetic. In CAST3M, the model can take into account a slight residual air content, but it leads to numerical divergency problems. For this reason, a solution which allows a complete saturation has been proposed. For further details of the employed method, see Barnel et al. (2002).

Concerning the vapour content, Kelvin's law is used in both codes to express the ratio between the vapour pressure and the saturated vapour pressure. The expression of this law depends on the thermodynamical reference system chosen to determine the relationship between vapour saturated pressure and temperature (the demonstration is available in Coussy, 1995). For this reason, in CAST3M, the relative humidity is a function of suction, whereas in ASTER it depends on the difference between liquid and atmospheric pressure. Nevertheless, both expressions are equivalent, as long as the saturated vapour pressure function is chosen correctly.

In both codes, advection flows are supposed to follow Darcy's law. Therefore they are proportional to