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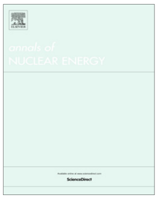

Sensitivity analysis of bentonite buffer peak temperature in a high-level waste repository

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ABSTRACT

A buffer in a geological repository minimizes groundwater inflow from the surrounding rock and protects the disposed high-level waste against any mechanical impact. As decay heat of spent fuel causes temperature variation in the buffer, which affects the mechanical performance of the system, an accurate estimation of the temperature variation is substantial. The peak temperature of the buffer, which is a critical design criterion of the repository, is affected by not only the thermal properties but also the hydraulic properties of the buffer, and these properties also affect each other. Thus, the effect of these factors should be properly evaluated during the system design. Hence, in this study, a sensitivity analysis of seven input factors was conducted using a numerical model based on a finite element method, and the model was verified using an analytical solution. In addition, a case study of the sensitivity analysis was conducted on two different property relationships of the buffer. The sensitivity indices of thermal conductivity, intrinsic permeability, and viscosity, which were determined as major factors, were 0.387, 0.215, and 0.163 in Case 1, and 0.510, 0.145, and 0.110 in Case 2, respectively, which means that these properties should be carefully considered during the design process of repositories. Furthermore, the case study shows that the relationship of the properties of a bentonite buffer has a significant effect on the design properties influencing the temperature variation.

1. Introduction

Spent fuel from nuclear energy sources release decay heat and harmful radiation for extended periods; thus, issues regarding high-level waste (HLW) disposal have constantly emerged. Among the various types of disposal systems, deep geological repositories, where HLWs are safely isolated from human society by a surrounding buffer, backfill, and near-field rock, are preferred in most countries owing to their safety and reliability. The buffer, which is an important component of a repository, minimizes groundwater inflow from the intact rock and protects the disposed HLW from any mechanical impact by filling the void between the near-field rock and the canister. Thus, buffers must possess a low hydraulic conductivity to minimize the inflow of water from the surrounding rocks that are saturated with groundwater. Furthermore, buffers must have a high thermal conductivity to release as much decay heat as possible from the spent fuel. In addition, buffers should not have negative impacts on the environment surrounding the deep geological disposal system. Most nations utilize compacted bentonite with a constant dry density as buffer material to fulfill the above requirements (Villar, 2004).

Temperature changes in engineering barriers caused by decay heat emitting from the spent fuel can be crucial for the safety of an HLW repository. In particular, as temperature changes in the buffer could cause changes in its thermal, hydraulic, and mechanical properties, nations planning to employ deep geological disposal systems have set temperature restrictions that can fulfill the basic required performance of buffers. In Korea, the maximum buffer temperature is set as 100 °C (Cho and Kim, 2016). Accordingly, it is important to accurately estimate the temperature of a bentonite buffer and design it so as not to exceed the design criterion. The thermal properties of a buffer such as thermal conductivity, specific heat capacity, and density are the crucial factors that influence its temperature variations caused by decay heat. In addition, the inflow of groundwater in the bentonite from a saturated rock can significantly affect the thermal behavior of the buffer by varying its water content. Thus, the buffer peak temperature is influenced by not only its thermal properties but also its hydraulic properties, and these properties also affect each other. Accordingly,

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many studies on the thermal behavior of bentonite buffers have been recently conducted based on coupled analyses. Lee et al. (2014) investigated the peak temperature and degree of saturation of a buffer by conducting a coupled thermo–hydraulic analysis using a numerical model. They revealed that the temperature distribution is sensitive to changes in the degree of saturation, and the degree of saturation is sensitive to variations in temperature and water viscosity. Li et al. (2013) established a numerical model using CODE_BRIGHT, and evaluated the maximum temperature of a buffer. Then, the thermo–hydraulic–mechanical processes in buffer-rock barriers of an HLW disposal system caused by temperature rise were simulated to provide design information of the repository. Nowak et al. (2011) also presented a coupled numerical model, which can accurately predict the thermal behavior of a buffer, and verified it using experimental results. Cho and Kwon (2012) assessed the effects of the re-saturation phenomenon occurring in a buffer due to the temperature distribution in the repository by considering heat and fluid flows of multiphases. However, there is a lack of research on a systematic evaluation concerning the importance of diverse factors affecting the temperature variation in bentonite buffers, although it is a relatively important information in the design process of HLW repositories.

Therefore, this study investigates the influencing factors that affect the peak temperature of a bentonite buffer by carrying out a sensitivity analysis using a numerical model which has been validated using an analytical solution. In addition, through a case study of the sensitivity analysis, we examined how the importance of the influencing factors varies with the relationships between the thermal and hydraulic properties of the buffer.

2. Numerical analysis

2.1. Description

In this study, a numerical analysis was conducted using a commercial program, COMSOL Multiphysics 5.3a, where a combined analysis of the heat and fluid fully coupled flow is possible based on a finite element method. The bentonite buffer in a HLW repository, which is composed of three phases, can be regarded as a porous medium in a situation where groundwater is permeated from the surrounding rock. Heat transfer in a porous medium mainly occurs by heat conduction as follows (Incropera et al., 2007):

$$-\lambda_i\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\rho_i c_i\frac{\partial T}{\partial t}+q_i=0 \quad (i=x,y,z) \tag{1}$$

where T is the temperature of the porous medium as a dependent variable, λ is the thermal conductivity of the medium, ρ is the density, c is the specific heat capacity, and q_i denotes the internal heat generation.

For the fluid flow in a bentonite buffer, the Richards equation can be applied to both unsaturated and saturated flows in a porous medium. The equation (Eq. (2)) defines the storage and retention models in variably saturated porous media, and it can estimate the saturation according to the time, fluid pressure, and space (COMSOL Inc., 2017).

$$\rho_f\left[\frac{C_m}{\rho_f g}+S_e S\right]\frac{\partial p}{\partial t}+\nabla\cdot\rho_f\left[-\frac{\kappa_s}{\mu}k_r\left(\nabla p+\rho_f g\nabla D\right)\right]=Q_m \tag{2}$$

where p is the pressure as a dependent variable, ρ_f is the fluid density, C_m denotes the specific moisture capacity, and g is the acceleration due to gravity. In addition, S represents the storage coefficient, S_e the effective saturation, k_r the relative permeability, k_s the intrinsic permeability, t the time, D the elevation, and Q_m the fluid source (positive) or sink (negative). The equation can be solved for the dependent variable of pressure, specifying the values of the hydraulic head or pressure head on the boundaries of a model. The specific storage is set as follows:

$$S=\rho_f\cdot g\left(\chi_p+\theta\chi_f\right) \tag{3}$$

where χ_p and χ_f are the compressibility of the solid particles and fluid, respectively, and θ is the volumetric water content defined as the volume of liquid per porous medium volume.

The relative permeability k_r is derived from the van Genuchten closed-form model as follows (van Genuchten, 1980):

$$k_r=\begin{cases} S_e^L\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 & for\ H_p<0\\ 1 & for\ H_p\geq 0\end{cases} \tag{4}$$

where m is a shape parameter for the retention curve of van Genuchten, expressed as $1-(1/\mathrm{n})$, H_p is the pressure head, and S_e is defined as follows:

$$S_e=\begin{cases} \frac{S-S_r}{S_s-S_r}=\left[\frac{1}{1+|\alpha H_P|^n}\right]^m & for\, H_p<0\\ 1 & for\, H_p\geq 0\end{cases} \tag{5}$$

where S, S_r, and S_s are the current, maximum, and residual liquid degrees of saturation, respectively. The specific moisture capacity, C, is defined as

$$C=\begin{cases} \frac{\alpha m}{1-m}(\theta_s-\theta_r)S_e^{\frac{1}{m}}\left(1-S_e^{\frac{1}{m}}\right)^m & \mathrm{for\,H}_p<0\\ 0 & \mathrm{for\,H}_p\geq 0\end{cases} \tag{6}$$

where θ_s and θ_r are the saturated and residual porosity, respectively. The parameters α, n, and L are calculated by fitting the van Genuchten equations with an experimentally measured bentonite–water retention curve.

2.2. Comparison with analytical model

To verify the suitability of the numerical model, a numerical analysis using COMSOL Multiphysics 5.3a was performed and the results were compared with those of the analytical solution. Analytical models concerning heat conduction in a medium are generally derived by considering the heat source as a constant value. However, the decay heat generated from the canister in an HLW repository exponentially decreases according to the half-life of the radioactive waste. To calculate an analytical solution for a special decaying heat source, a cylindrical heat source with exponential decay was suggested by Hodgkinson (1979). This study solved the heat conduction equation by taking a distribution of finite line sources, arranging them to form a solid cylinder, and considering the generated heat to be an exponentially decaying function of elapsed time (Gibb et al., 2008) (Fig. 1).

In the model, the temperature variation at a point away from the source and after the elapsed time caused by the heat sources can be expressed as Eq. (7).

$$T(R,z,t)=\frac{q_0e^{-kt}}{4\rho c\alpha}\int_0^t d\mu\frac{e^{-kt}}{\mu}\left\{erf\left(\frac{z+b}{2\sqrt{\alpha\mu}}\right)\right.\left.-erf\left(\frac{z+b}{2\sqrt{\alpha\mu}}\right)\right\}\int_0^r R\prime\, dR\prime\, I_0\left(\frac{RR\prime}{2\alpha\mu}\right)\cdot\exp\left\{\frac{-\left(R^2+R'^2\right)}{4\alpha\mu}\right\} \tag{7}$$

Here, R is the radial distance from the heat source, b is the cylinder half length, r is the cylinder radius, and I_0 is a modified Bessel function. Also, R' and z are the radial and axial coordinates, respectively. In addition, k is the decay constant, α is the thermal diffusivity, q_0 is the initial rate of heating per unit volume, and t is the time. To com-