Numerical Simulation of Coupled Multiphase Fluid Flow and Elastic-viscous Mechanics for Gas Migration in Bentonite Considering Heterogeneous Distributions

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Date: 2024/04/12

Abstract

The final disposal method for high-level waste is Deep Geological Disposal. This is where nuclear waste is buried in geological formations at depths greater than 300 meters, where canister and buffer materials are used to cover and secure it. By the principles of isolation and retardation, the waste decays harmlessly, thus isolating it from the biosphere and ensuring human health and environmental safety. However, after hundreds of years of disposal, gas may be generated due to the corrosion of metallic materials under anoxic conditions, the radiolysis of water or microbial degradation. With continuous gas pressure accumulation, the stress on buffer materials can no longer withstand it, leading to pathway dilation and fractures, allowing gas to escape. This gas degrades the barrier's capability, endangering the safety of the repository. Therefore, buffer materials play a crucial role in the repository, with bentonite being commonly chosen as the buffer materials. In practical situations, bentonite exhibits different particle arrangements, porosity, and permeability, presenting heterogeneous distributions. This heterogeneity may lead to the formation of preferential pathways, particularly in regions with high porosity and loose particle arrangements, making gas flow more accessible and consequently influencing the gas migration behavior. Therefore, this study employs the THMC7.1 numerical model to simulate the heterogeneous distributions of bentonite. The results successfully demonstrate variations in gas pressure accumulation and breakthrough events, and also demonstrate that the preferential gas pathways formed by heterogeneity indeed affect gas velocity and pressure.

Keywords: Deep Geological Disposal, Bentonite, Gas migration, Multiphase fluid flow, Elastic-viscous mechanics.

考慮異質性膨潤土內氣體遷移之多相流與黏彈性力學耦合數值模擬

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報告日期：2024/04/12

摘要

高階放射性廢棄物最終處置方式為深層地質處置，以多重障壁概念，將廢棄物包覆在處置罐中，並運至地層至少三百公尺以下的岩體中，再填滿緩衝材料，藉由隔離和遲滯原理以確保廢棄物衰變到無害程度，與生物圈隔離，保護民眾健康及環境安全。然而，經處置數百年後，廢棄物自身衰變產生熱，處置系統溫度隨之上升，熱膨脹使應力改變，進而造成水力及化學效應產生。在低氧環境下金屬廢棄物罐腐蝕、輻解作用、微生物降解均可能產生氣體，隨著氣體持續累積，一旦作用在緩衝材料上的應力無法承受氣體壓力，孔隙將逐漸擴張並產生裂隙，氣體藉此流出至岩體，影響處置系統之能力，造成安全性的危險。因此，緩衝材料在系統中扮演著極為關鍵的角色，膨潤土為常見的緩衝材料選擇，在實際情況下，膨潤土含有不同的顆粒排列、孔隙率和滲透率，呈現異質性的空間分佈，這種異質性可能在高孔隙率及疏鬆顆粒排列之區域，形成優先通道，使氣體更容易流通，進而影響氣體的遷移行為。因此，本研究以膨潤土的異質性空間分佈利用 THMC7.1 數值模式模擬，結果成功地顯示氣體壓力累積和突破事件之變化，並發現異質性分佈所產生的氣體優先通道確實會影響氣體速度和氣體壓力。

關鍵字： 深層地質處置、膨潤土、氣體遷移、多相流、黏彈性力學