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Model development and numerical simulation of a seasonal heat storage in a contaminated shallow aquifer

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Abstract

Seasonal heat storage in the shallow subsurface is gaining relevance due to the increasing production of energy from renewable sources. This work presents model extensions of the code OpenGeoSys for simulating impacts of heat storages on groundwater quality. Application of the non-isothermal model is demonstrated for scenarios of heat storage in a TCE contaminated aquifer. Simulation results show slightly elevated TCE emissions due to increases in flow and solubility, but also increases in contaminant biodegradation caused by widening of the plume. Further experimental and modeling work is required for a quantitative assessment of such complex systems and process interactions.

Keywords: heat storage; temperature effects; kinetic NAPL dissolution; biodegradation; numerical simulations; OpenGeoSys

1. Introduction

Seasonal heat storage in the shallow subsurface is becoming an important key stone in the transition of the German energy market from nuclear power and fossil fuels towards an increased production of energy from renewable resources. In 2012, e.g., more than 80 % of the total energy consumption in German households were spent for room heating and hot water production [1]. Especially in urban regions with high population densities and thus a high energy and heat demand, the temporary storage of large amounts of heat, e.g. in combination with district heating, is feasible. In Germany a number of large-scale seasonal subsurface heat storages were built over the last years. In combination with solar thermal systems these storages contribute to the heating demand of residential areas and large office or commercial complexes [2-4]. Depending on the operation of these heat storages, subsurface temperatures of up to 70°C may be reached during the main loading periods in summer [3,4].

Concerns about influences of such temperature increases on groundwater chemistry [5,6] and microbiology [7,8] lead to a rather restrictive approval of such high temperature heat storages [9,10]. For the same reason, approval of geothermal use of aquifers for heat storage or disposal is usually precluded directly so far at or close to groundwater

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contaminated sites, which are numerous especially in urban regions [10]. Detailed studies on the impacts of high temperature heat storage on aquifers and groundwater quality, however, are scarce. Therefore, one aim of the ANGUS+ joint research project [11] is to evaluate the general impacts of heat storages on shallow subsurface aquifers and to assess the potentially induced thermal, hydraulic, mechanical and biogeochemical effects at such storage sites by experimental work and numerical scenario simulations. For this reason, coupled and process based numerical models of non-isothermal groundwater flow, heat and reactive mass transport are required. Such model extensions of the open-source simulator OpenGeoSys (OGS) are presented in this work. Application of the code is demonstrated for a first simplified scenario, which investigates the principal impacts of a periodic high temperature heat storage by borehole heat exchangers (BHEs) in the presence of a chlorinated hydrocarbon (CHC) groundwater contamination.

2. Model development

Simulating temperature influences on flow, transport and reactive processes requires the consideration of the interactions between the individual processes. The OGS code is used here, which employs a fully coupled model of thermal, hydraulic and biogeochemical (THC) process interactions in porous media [12]. In the following subsections the relevant processes and their extensions for temperature dependencies are summarized.

2.1. Groundwater flow

OGS provides a pressure based formulation of the groundwater flow equation [13]

$$nS_w\frac{\partial p_w}{\partial t} - \frac{1}{\rho_w}\nabla\left(n\rho_w\frac{k_{rw}}{\mu_w}\mathbf{K}\left(\nabla p_w - \rho_w \cdot \mathbf{g}\right)\right) - Q_w = 0 \tag{1}$$

where n [-] is the porosity, S_w [-] the water phase saturation, p_w [Pa] the water pressure, t [s] the time and ρ_w [kg/m^3] and μ_w [Pa·s] the water density and viscosity, respectively. k_{rw} [-] is the relative permeability of the water phase, $\mathbf{K}$ [m^2] the permeability tensor, $\mathbf{g}$ [m/s^2] the gravitational acceleration and Q_w [kg/(m^3·s)] the source/sink term for the water phase. In a fully water saturated case $S_w = 1.0$, while in the presence of an immobile non-aqueous-phase-liquid (NAPL) $S_w < 1.0$, which reduces the available pore space for the mobile water. In this case, $k_{rw} < 1$ and decreases with S_w, which can be described e.g. with Brooks-Corey or van Genuchten type models [14].

In the non-isothermal case, ρ_w and μ_w become functions of temperature and can be described fairly well with simple empirical models such as presented by Yaws [15] (Fig. 1a). Decrease of ρ_w and μ_w with temperature effectively results in an increase of hydraulic conductivity k_f [m/s] of the aquifer by a factor of approximately 4 between 283.15 and 363.15 K (Fig. 1a). Increase of k_f, e.g. in a heat plume, will accordingly increase local flow and transport velocities, while a cold plume will result in the opposite effect. Such thermally induced local velocity perturbations were shown in tracer experiments by Krol et al. [16] as well as in numerical simulations by Popp et al. [17].

2.2. Heat transport

Heat transport in a fluid saturated porous medium is governed by heat convection and heat conduction [13]

$$c\rho\frac{\partial T}{\partial t} + \nabla\left(nc_w\rho_w\mathbf{v}T\right) - \nabla\left(\mathbf{D_H}\nabla T\right) + Q_T = 0 \tag{2}$$

where T [K] is the temperature, $\mathbf{v}$ [m/s] the transport velocity, $\mathbf{D_H}$ [W/(m·K)] the heat conduction-dispersion tensor and Q_H [J/(m^3·s)] the heat source/sink term. c and c_w [(J/(kg·K)] are the specific heat capacities and ρ and ρ_w [kg/m^3] the densities of the water phase and the porous medium, respectively. In the presence of water and NAPL phases the porous medium volumetric heat capacity is quantified as

$$c\rho = nS_wc_w\rho_w + nS_nc_n\rho_n + (1-n)c_s\rho_s \tag{3}$$

with S_n [-] as the NAPL phase saturation, c_s and c_n [(J/(kg·K)] as the specific heat capacities and ρ_s and ρ_n [kg/m^3] as the densities of the solid matrix and NAPL phase, respectively. Eq. 2 is coupled to Eq. 1 via the flow velocity $\mathbf{v}$ in the convection term and the heat dispersion tensor $\mathbf{D_H}$

$$\mathbf{D_H} = nS_w\lambda_w + nS_n\lambda_n + (1-n)\lambda_s + nc_w\rho_w\left(\gamma_t\mathbf{v}\delta_{i,j} + (\gamma_l - \gamma_t)\frac{v_iv_j}{\mathbf{v}}\right) \tag{4}$$