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PROCEEDINGS

Investigation of Pore-Scale THMC Acid Fracturing Process Considering Heat Conduction Anisotropy

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ABSTRACT

Acid fracturing is critical to improving the connectivity inside underground reservoirs, which involves a complex thermal-hydro-mechanical-chemical (THMC) coupling process, especially deep underground. Heat conduction anisotropy is one of the intrinsic properties of rock. It determines the heat response distribution inside the rock and alters the temperature evolution on the reactive surface of fractures and pores. In another way, the rock dissolution rate is closely related to the reactive surface temperature. Predictably, heat conduction anisotropy leads to different rock dissolution morphologies from that of the heat conduction isotropy situation, then the cracks distribution and permeability of rock would also be significantly changed. This work uses a pore-scale THMC coupled model recently developed by us to investigate the effect of heat conduction anisotropy on the THMC coupled acid fracturing process. The model adopts the lattice Boltzmann and discrete element methods to calculate the particle mechanical behaviors and hydro-mechanical-chemical transport processes, respectively. Particularly, the coupling phenomena of chemical damage, rock dissolution, and solute transport are covered in the simulation. A chemical damage variable based on the cohesive bond is proposed to characterize the alteration of mechanical parameters caused by local rock dissolution. The influence of the anisotropy ratio of heat conduction and Damkohler number (Da) on the THMC coupled acid fracturing process is qualitatively analyzed. Results indicate that the dissolved solid is more sensitive to the heat conduction anisotropy in the middle level of Da, where a conical area tends to generate upstream of the main fracture. However, for the large Da, it is the diffusion-controlled process, and it shows uniform dissolution around the injection hole even in large heat conduction anisotropy, and little acid reactant can flow into fractures.

KEYWORDS

THMC coupled; acid fracturing; pore-scale; heat conduction anisotropy

Methods

The intact rock is divided into discretized but bonded particles for discrete element method (DEM) simulation [1-2]. Particle motion is tracked in space and time through the Lagrangian approach. The governing equations of particle location and rotation are as follows,

$$\begin{cases} m_p \dfrac{\mathrm{d}^2 \mathbf{x}_p}{\mathrm{d}t^2} = \mathbf{F}^{\mathrm{contact}} + \mathbf{F}^{\mathrm{cohesion}} + \mathbf{F}^{\mathrm{f}\to\mathrm{s}} \\ I_p \dfrac{\mathrm{d}^2 \boldsymbol{\omega}_p}{\mathrm{d}t^2} = \mathbf{T}^{\mathrm{contact}} + \mathbf{T}^{\mathrm{cohesion}} + \mathbf{T}^{\mathrm{f}\to\mathrm{s}} \end{cases} \tag{1}$$

where $\mathbf{x}_p$ and $\boldsymbol{\omega}_p$ are the particle location and rotation, m_p and I_p are the particle mass and moment of inertia,

$\mathbf{F}^{\text{contact}}$, $\mathbf{F}^{\text{cohesion}}$, and $\mathbf{F}^{\text{f}\to\text{s}}$ are contact force, cohesion force, and hydrodynamic force exerted on the particle respectively, and $\mathbf{T}^{\text{contact}}$, $\mathbf{T}^{\text{cohesion}}$, and $\mathbf{T}^{\text{f}\to\text{s}}$ are contact torque, cohesion torque, and hydrodynamic torque respectively.

Cohesive bonds, which induce $\mathbf{F}^{\text{cohesion}}$ and $\mathbf{T}^{\text{cohesion}}$, characterize the bonding function inside rock and make the particles into an aggregate. Fractures and rock mechanical damage are arranged at the cohesive bond to form a fluid pathway. In addition, the strength of the cohesive bond is constrained by the rock strength criterion, expressed as,

$$\left(\frac{\left\langle \sigma_n^c \right\rangle}{\sigma_n^{\text{th}}}\right)^2 + \left(\frac{\sigma_t^c}{\sigma_t^{\text{th}}}\right)^2 \geq 1 \tag{1}$$

where σ_n^c and σ_t^c are the normal and tangential cohesive stress, σ_n^{th} and σ_t^{th} are the normal and shear cohesive strength following the Mohr-Coulomb criterion. A chemical damage variable based on the cohesive bond is defined, and the total rock damage variable is evaluated through this,

$$\begin{cases} d_c = 1 - \dfrac{m_c}{m_c^0} \\ d' = d_m + d_c - d_m d_c \end{cases} \tag{2}$$

where d_c is the chemical damage variable, m_c is the solid mass inside the region of the cohesive bond, m_c^0 is the value at the initial time, and d' is the total rock damage variable under the coupling effect of mechanical damage and chemical damage.

In general fluids, solute diffusivity is smaller than kinematic viscosity and thermal diffusion coefficient, making the relaxation parameter of solute transport smaller. The LBM will lose numerical stability if the relaxation parameter is too small. Fortunately, the lattice kinematic scheme (LKS) provides a greater range of acceptable diffusivity because it adds a modifiable factor for the conversion between the diffusivity and relaxation parameter [3-4]. Its evolution and equilibrium distribution equations are written as,

$$h_i^k(\mathbf{x} + \mathbf{c}_i\delta_t, t + \delta_t) = h_i^k(\mathbf{x}, t) - \frac{1}{\tau_h^k}\left[h_i^k(\mathbf{x}, t) - h_i^{k,\text{eq}}(\mathbf{x}, t)\right] \tag{3}$$

$$h_i^{k,\text{eq}} = w_i H^k \left[1 + \frac{\mathbf{c}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_i \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}^2}{2c_s^2}\right] + w_i \tau_B^k \delta_t \left(\mathbf{c}_i \cdot \nabla H^k\right) \tag{4}$$

where h_i^k is the concentration distribution function with discrete velocity $\mathbf{c}_i$ at the location $\mathbf{x}$ and time t for the solute k (k =$L1$ or $L2$), τ_h^k is the relaxation parameter, τ_B^k is the modifiable factor, $h_i^{k,\text{eq}}$ is the equilibrium distribution function, w_i is the weight coefficient, H^k is the lattice concentration, $\mathbf{u}$ is the lattice velocity of the fluid, c_s is the lattice speed of sound, δ_t is the lattice time step, $\mathbf{c}_i$ is the discrete velocity and w_i is the weight coefficient based on the two-dimensional nine-velocity model.

In summary, the THMC coupled phenomena considered in our pore-scale model are summarized in Fig. 1.

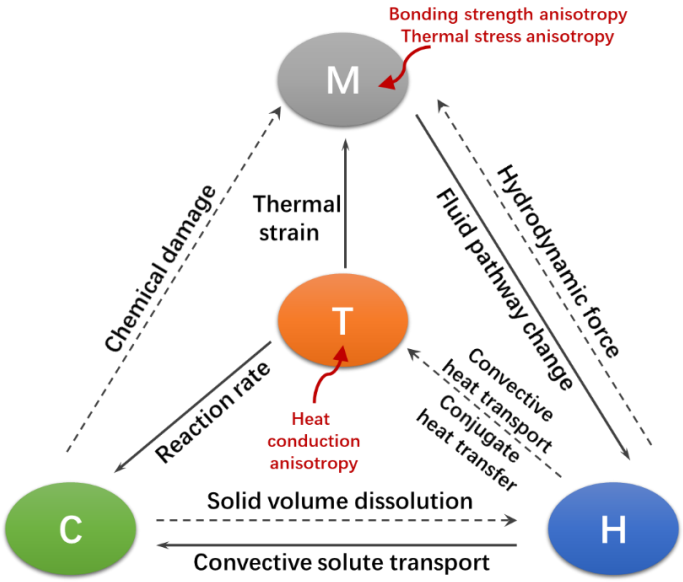
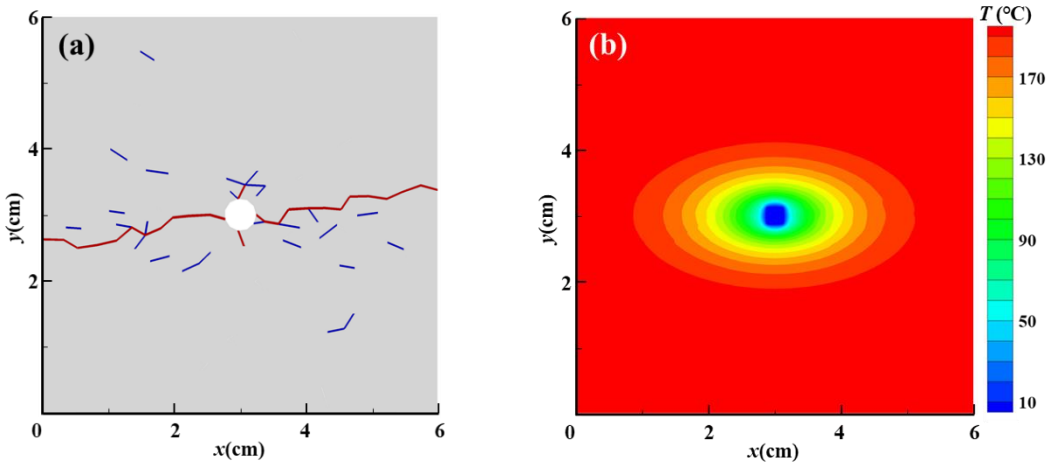


Figure 1: THMC coupled relation during rock dissolution and fracturing process

Results

Fig. 2 shows the distribution of THMC physical fields at the simulation time of $1\times10^{7}\Delta t_{\mathrm{DEM}}$, where the cold acid fluid with 2.5 MPa is injected into the central hole, and Damkohler number (*Da*) for dissolution is 0.0153. The rock is shale and has a heat conduction anisotropy along the horizontal direction, as presented in Fig. 2(b). Because the thermal stress and cohesion strengths of rock have preferred direction, the fractures and rock damage tend to propagate along the horizontal direction rather than the vertical direction, as shown in Fig. 2(a). In the pore scale, fractures are the only pathway having fluid conductivity inside the rock. Therefore, the pressure gradient is only observable in horizontal fractures because they penetrate the whole rock, while high fluid pressure is accumulated in part-through cracks. On the other hand, due to the high flow velocity in horizontal fractures, the more acid reactant is carried into the horizontal fractures. The largest concentration gradient is at the inlet of horizontal fractures, as presented in Fig. 2(d) and 2(e), meaning that here has the largest dissolution rate.



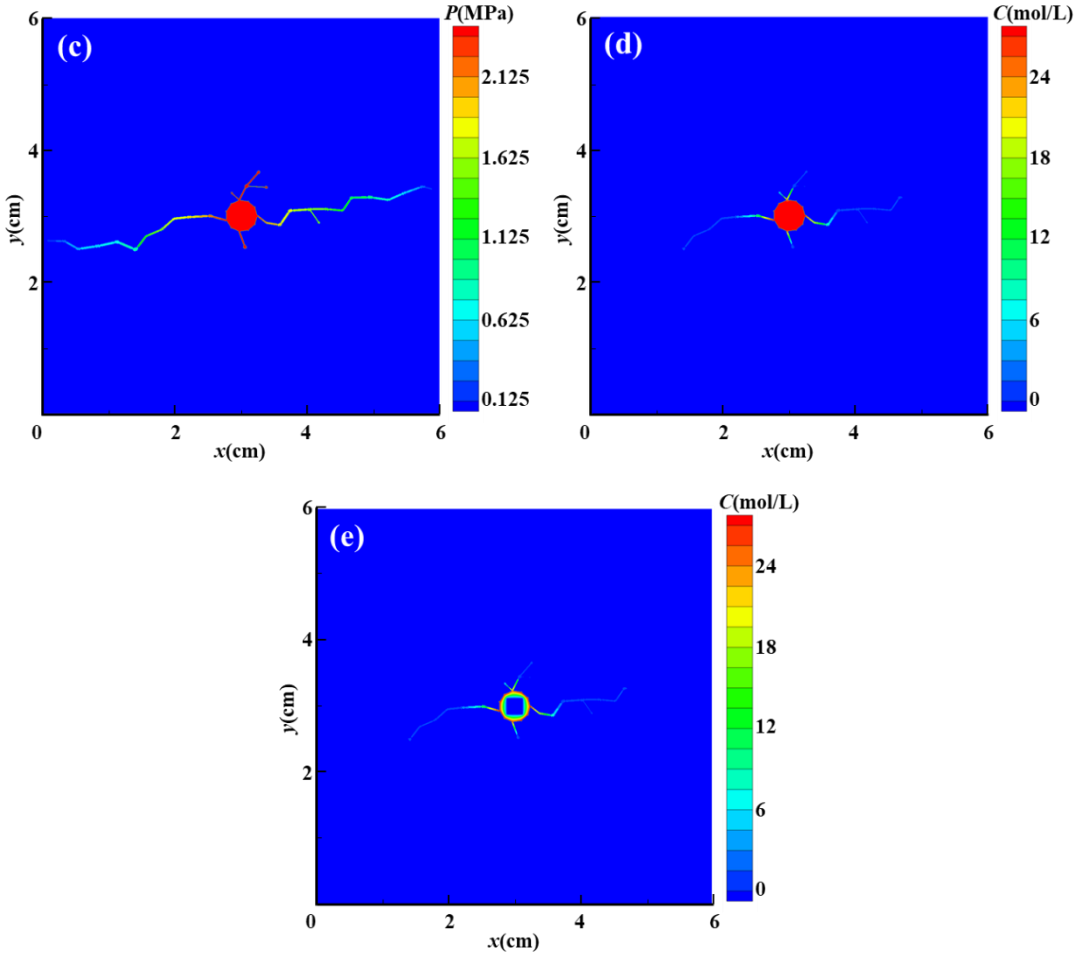


Figure 2: Physical fields with injected pressure at the central hole 2.5 MPa and *Da* 0.0153, where (a) is fracture geometry with red and blue line segments meaning the failure of cohesive bonds and cohesive bonds staying in the mechanical damage stage, respectively, (b) is temperature response, (c) is fluid pressure distribution, (d) is concentration distribution of the acid reactant, and (e) is concentration distribution of the product

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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