



The effect of heterogeneity on heat extraction and transmissivity evolution in a carbonate reservoir: A thermo-hydro-chemical study



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ABSTRACT

Heterogeneous aperture distribution is very common in large faults or fracture connecting injection and production wells. Recently the effects of heterogeneity on the temperature drawdown and transmissivity alteration due to dissolution/precipitation and thermo-elastic deformation of silicate reservoir were studied. The previous results based on numerical modeling have indicated that energy production rate is affected by correlation length and standard deviation of initial heterogeneous aperture field. The formation of a preferential flow path or channel is one of the most important consequences of heterogeneity when aperture alteration due to thermo-chemical and thermo-mechanical effects is significant. Previous studies have shown significant differences between the aperture alteration patterns of initially uniform fractures in carbonate and silicate reservoirs. Retrograde solubility and fast reaction rate of calcite with water are responsible for this. This has motivated us to study the effect of heterogeneity in carbonate reservoir. We have shown that the heterogeneity has much stronger effect in carbonate reservoir than that in silicate reservoir. In some cases the nature of evolution is completely different from homogeneous case under same injection conditions.

1. Introduction

Heat energy is extracted from a geothermal reservoir by injecting relatively cold water into the high permeable zone. The heat extraction largely depends on the reservoir heterogeneity and the mineral compositions of rocks comprising the reservoir. In a heterogeneous geothermal reservoir, migration of the injected fluid through preferred paths may reduce the heat extraction from the reservoir. The effect of reservoir heterogeneity on heat extract in a doublet system has been numerically investigated by Watanabe et al. (2010), Vogt et al. (2013), Llanos et al. (2015) and Huang et al. (2017). These studies suggested that permeability distributions between the wells significantly influence the thermal drawdown and temperature at production well. Hadgu et al. (2016) studied the effects of well orientation on heat extraction in a doublet system. Their results suggested that the thermal drawdown was largely controlled by the orientation of fractures with respect to well configuration. Crooijmans et al. (2016) studied the effects of facies heterogeneity on heat extraction. They found that the lifetime of a reservoir increases with N/G (net-to-gross) ratio. At higher value of N/G ratio, the more connective flow paths inside the reservoir led to slower temperature drop at the production well. In a recent study, Willems et al. (2017) found that pumping energy loss reduced

significantly when the wells were oriented parallel to the paleo flow direction. Further, the pumping loss also decreased with increase in the N/G ratio. Few authors (Shaik et al., 2011; Koh et al., 2011; Fox et al., 2013; Gan and Elsworth, 2016; Li et al., 2016) have investigated the effects of fracture density in a discrete fracture reservoir on heat extraction. The evolution of fracture aperture also affect the heat extraction from the reservoir and have been investigated by coupled thermo-hydro-chemical (Pandey et al., 2014, 2015), thermo-hydro-mechanical (Zhao et al., 2015; Wang et al., 2016; Pandey et al., 2017) and thermo-hydro-chemical-mechanical (Ghassemi and Kumar, 2007; Izadi and Elsworth, 2015; Rawal and Ghassemi, 2014; Blaisonneau et al., 2016; Caulk et al., 2016) processes. These studies have indicated that coupled thermo-hydro-chemical-mechanical processes affect the heat extraction process throughout the injection/production period. Furthermore, heterogeneity inside the fracture may increase or decrease heat extraction. Pandey et al. (2015) studied the effect of statistical parameters such as correlation lengths, standard deviation of initial heterogeneous aperture field, and physical operating parameters such as injection temperature, concentration of dissolved silica on heat extraction performance in a doublet system for a silicate reservoir. The simulation results showed that fresh water injection was more favorable and it extract more heat from the reservoir. The impact

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of heterogeneity on heat extraction was more for longer correlation length. Guo et al. (2016) also suggested that larger correlation lengths led to flow channeling when aperture alteration was induced by the thermal contraction of the rock matrix during heat extraction. However, both studies (Pandey et al., 2015; Guo et al., 2016) showed that for smaller correlation lengths, the temperature drawdown curves were similar to those for homogeneous cases. This suggests that small scale heterogeneities are usually homogenized when the distances between the wells are much larger than the correlation length.

In this paper, we have discussed the results of coupled THC simulations for carbonate reservoir. The fracture was considered with variable aperture and surrounded by three dimensional low permeable rock matrix. The effect of the spatial distribution of fracture aperture on heat extraction performance and pressure drop to circulate the fluid in the doublet system was studied. Since the dominance of dissolution or precipitation depends on the injection concentration, the simulations were performed for two injection concentrations by keeping constant injection mass flux and temperature.

2. Mathematical model

The governing equations for fluid flow, heat and reactive transport in fracture and matrix are described separately using pairs of partial differential equations.

The fluid flow in the fracture can be represented as (Ortoleva et al., 1987; Hanna and Rajaram, 1998; Chaudhuri et al., 2008):

$$\nabla \cdot \mathbf{Q}_f = f_Q \text{ and } \mathbf{Q}_f = -\frac{b^3}{12\mu F_T} (\nabla P_f - \rho \mathbf{g}) \quad (1)$$

where \mathbf{Q}_f is the aperture integrated two-dimensional flux vector, f_Q is the lateral exchange of fluid between the fracture, b is the fracture aperture, P_f is the aperture-averaged pressure, μ is the dynamic viscosity, ρ is the density of the water and \mathbf{g} is the gravitational acceleration. The additional term, F_T , in Eq. (1) accounts the non-laminar flow, which can be defined as, $F_T = 0.00838\text{Re}$ (Zimmerman et al., 2004). The flow in the low permeability porous matrix is described by the continuity equation and Darcy's law:

$$\nabla \cdot \mathbf{q}_r = 0 \text{ and } \mathbf{q}_r = -\frac{k}{\mu} (\nabla P_r - \rho \mathbf{g}), \quad (2)$$

where k is the permeability, \mathbf{q}_r is the Darcy flux and permeable rock and P_r is the fluid pressure in porous rock matrix, respectively. At fracture and rock interfaces, the coupling between flow through fracture and rock matrix is incorporated using the following relations:

$$f_Q = q_{rz}|_{z=-b/2} - q_{rz}|_{z=b/2} \text{ and } P_r|_{z=-b/2} = P_r|_{z=b/2} = P_f \quad (3)$$

where $z = -b/2$ and $z = b/2$ represent the interfaces between the fracture and rock.

The heat transport in the 2-D fracture and 3-D reservoir matrix are governed by the following advection–diffusion equations:

$$\frac{\partial(b(\rho c_p)_f T_f)}{\partial t} + \mathbf{Q}_f \cdot \nabla h_f - b \nabla \cdot (\lambda_f \nabla T_f) = f_T \quad (4)$$

and

$$\frac{\partial((\rho c_p)_r T_r)}{\partial t} + \mathbf{q}_r \cdot \nabla h_r - \nabla \cdot (\lambda_r \nabla T_r) = 0 \quad (5)$$

where T is the temperature, λ is the thermal conductivity, h is the enthalpy and c_p is the specific heat, respectively. The heat transport equations at the fracture–matrix interface are coupled through the heat flux, f_T . The temperature continuity at $z = \pm b/2$ can be expressed as:

$$f_T = \left(q_{rz} h_r - \lambda_r \frac{\partial T_r}{\partial z} \right)_{z=b/2} - \left(q_{rz} h_r - \lambda_r \frac{\partial T_r}{\partial z} \right)_{z=-b/2} \text{ and } T_r|_{z=-b/2} = T_r|_{z=b/2} = T_f \quad (6)$$

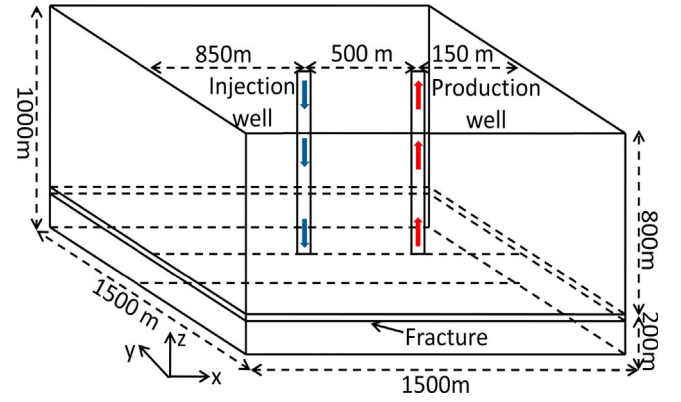


Fig. 1. Schematic of the computational domain for the geothermal heat extraction set-up.

The reactive transport equations in the 2-D fracture and 3-D reservoir matrix are:

$$\frac{\partial(b\rho_f C_f)}{\partial t} + \mathbf{Q}_f \cdot \nabla (\rho_f C_f) - b \nabla \cdot (D_f \nabla (\rho_f C_f)) = R_C + f_C \quad (7)$$

and

$$\frac{\partial(\phi\rho_f C_r)}{\partial t} + \mathbf{q}_r \cdot \nabla (\rho_f C_r) - \nabla \cdot (D_r \nabla (\rho_f C_r)) = R_C A_s \quad (8)$$

where C is the calcite concentration, D is the dispersion coefficient, ρ_f is the density of water, R_C is the reaction rate and A_s represents the specific surface area (reactive surface area per unit volume). Similar to the flow and heat transport, the lateral exchange term, f_C , at the fracture–matrix interface is:

$$f_C = \left(q_{rz} \rho_f C_r - D \frac{\partial(\rho_f C_r)}{\partial z} \right)_{z=b/2} - \left(q_{rz} \rho_f C_r - D \frac{\partial(\rho_f C_r)}{\partial z} \right)_{z=-b/2} \text{ and } C_r|_{z=-b/2} = C_r|_{z=b/2} = C_f \quad (9)$$

The saturated/equilibrium concentration in Eqs. (7) and (8) can be expressed as (Chaudhuri et al., 2013; Pandey et al., 2014):

$$C_{eq} = 1.417 \times 10^{-3} + 3.823 \times 10^{-6} P - 4.313 \times 10^{-7} T - 2.148 \times 10^{-8} P^2 + 4.304 \times 10^{-8} P T - 7.117 \times 10^{-8} T^2 \quad (10)$$

The temporal evolution of the fracture aperture due to mineral dissolution/precipitation is given as:

$$\frac{\partial b}{\partial t} = \frac{R_C}{\rho_r \omega} \quad (11)$$

where $\rho_r \omega$ is the molar density (in $\text{mol/m}^3 = \text{kg/m}^3 \text{ mol/kg}$). The reaction rate, R_C , in Eqs. (7), (8) and (11) can be written as:

$$R_C = 10^r \text{ for } \tilde{C} > 0 \\ = -10^r \text{ for } \tilde{C} < 0 \quad (12)$$

where

$r(\tilde{C}, T) = a_0 + a_1 T + a_2 \log|\tilde{C}| + a_3 T^2 + a_4 T \log|\tilde{C}| + a_5 (\log|\tilde{C}|)^2$. The coefficients of this polynomial are given in Table 2. The \tilde{C} in Eq. (12) can be written as:

$$\tilde{C} = \frac{(C_{eq} - C)}{C_{eq}} \quad (13)$$

The temporal evolution of the rock matrix porosity due to mineral dissolution/precipitation is given as:

$$\frac{\partial \phi}{\partial t} = \frac{R_C A_s}{\rho_r \omega} \quad (14)$$

where A_s is the specific surface area and $\rho_r \omega$ is the molar density (in $\text{mol/m}^3 = \text{kg/m}^3 \text{ mol/kg}$). The specific surface is given as (Koponen et al., 1997):

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