International Journal of Heat and Mass Transfer 78 (2014) 302–310

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical modelling of thermal transport and quartz precipitation/dissolution in a coupled fracture–skin–matrix system

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ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form 28 June 2014
Accepted 29 June 2014
Available online 23 July 2014

Keywords:
Fracture–skin
Fracture aperture
Reactive mineral transport
Thermal transport

ABSTRACT

This paper describes a numerical model for the analysis of chemical reactions in a coupled fracture–matrix system at the scale of a single fracture in the presence of fracture–skin. The quartz concentration is computed using simple linear reaction kinetics. Heat transfer within the fracture–skin and rock matrix is modelled as conduction, while heat transport within the fracture includes thermal advection, conduction, and dispersion in the horizontal plane. Fluid is assumed to be injected at a constant rate at the inlet of the fracture. Heat transfer at the interface of the high permeability fracture and low permeability fracture–skin is modelled on a varying grid at the interface. Sensitivity studies have been conducted using different skin thermal conductivities, fluid velocities, and half fracture apertures. We have also analysed the behaviour of the system when there is fluid loss from the fracture into the adjacent fracture skin. Results suggest that, when fluid loss is considered, the rate at which fluid is injected at the inlet of the fracture plays a major role in the heat transfer and chemical reaction within the fracture. When there is fluid loss, the effect of fracture skin formation on the heat transfer mechanism is reduced and this effect becomes much less sensitive to changes in the size of the fracture aperture. The fracture skin thickness affects the attainment of equilibrium temperature within the fracture in terms of its magnitude and distance from the fracture inlet.

1. Introduction

Hot Dry Rock (HDR) is a potential source of substantial amounts of renewable energy due to its wide-spread distribution and the extent of individual occurrences. The energy is extracted by creating a connected fracture network in the HDR heat reservoir through which fluid is circulated to extract the heat. An effective fracture network allowing sufficient fluid flow (and, thereby, sufficient heat extraction) creates an engineered (or enhanced) geothermal system (EGS). When fluid moves through a fracture it reacts with the adjacent rock–matrix resulting in precipitation–dissolution of minerals due to the high temperature gradient between the high permeability fracture and low permeability rock–matrix. Over the past 30 years there have been many publications on this precipitation–dissolution process [1–12] and many studies have been reported on fracture–matrix coupled systems.

Most studies on thermal transport in fractured formations do not consider the presence of fracture skins. Moench [13,14] defined fracture skins to be low permeability material deposited on the fracture walls which mitigates the diffusive mass transfer between the high and low permeability materials. Sharp [15] noted the formation of skins in fractured porous media. Later studies concluded that fracture skins can occur as clay filling [16], mineral precipitation [17] and organic material growth [18]. Thus, the formation of fracture–skin can affect the heat transport mechanism in fractured porous media as the properties of the fracture–skin, such as porosity and diffusion, can differ significantly from that of the surrounding rock–matrix. The differences in the properties of the fracture–skin from those of the associated rock–matrix result in different diffusive mechanisms at the fracture–skin interface from those at the skin–matrix interface. The formation of skin during thermal transport in a fracture matrix system is caused by the deposition on the fracture walls of chemicals undergoing precipitation due to high temperatures. The interchange of solutes between the fracture and the matrix causes precipitation of metal oxides [17] or calcite [19,20]. Natarajan and Suresh Kumar [21] illustrated this by using a numerical model to analyse the effect of fracture–skin formation on thermal transport in fractured porous media and concluded that the fracture–skin plays a major role in the heat transfer between

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.06.085
0017-9310/

the fracture and the associated rock–matrix. Natarajan and Suresh Kumar [22] studied the evolution of fracture permeability in a coupled fracture–matrix system in the presence of fracture–skin due to co-colloidal bacterial transport in a geothermal system. However, they did not consider the effect of fluid loss from the fracture into the adjacent fracture skin. The objective of the work presented here is to include the effect of fluid loss from the fracture in the analysis of the mineral precipitation process in fractured porous media in the presence of fracture skin for various fracture apertures, fluid velocities and skin thermal conductivities.

2. Physical system and governing equations

A conceptual model of a coupled fracture–skin–matrix system [23] is given in Fig. 1.

In Fig. 1, b is the half fracture aperture, d–b is the thickness of the fracture–skin and H is the thickness of the half fracture spacing. The following assumptions are made:

1. The fracture aperture is much smaller than the length of the fracture.
2. Thermal dispersion is analogous to dispersion of solutes in a fracture matrix system.
3. Convection within the fracture–skin and rock–matrix can be ignored.
4. Temperature at the fracture–skin interface, i.e., temperatures along the fracture wall and along the lower boundary of the fracture–skin are assumed to be equal (at $y = b$).
5. Temperature at the skin–matrix interface, i.e., temperatures along the upper boundary of the fracture–skin and the lower boundary of the rock–matrix are assumed to be equal (at $y = d$). The conductive flux in the fracture–skin is equal to the conductive flux in the rock–matrix at the skin–matrix interface as expressed in Eq. (10).
6. Specific heat capacities are not functions of temperature.
7. Assuming symmetry, the solution is restricted to one half of the fracture and its adjacent fracture–skin and its associated rock–matrix.
8. Thermal conduction is considered both in the fracture, fracture skin and the rock–matrix.
9. There is only one fluid phase.
10. Changes in fluid enthalpy with pressure are neglected.
11. Transverse diffusion and dispersion within the fracture ensure complete mixing across the fracture thickness/aperture at all times.
12. Transport along the fracture is much faster than transport within the rock matrix and fracture skin.

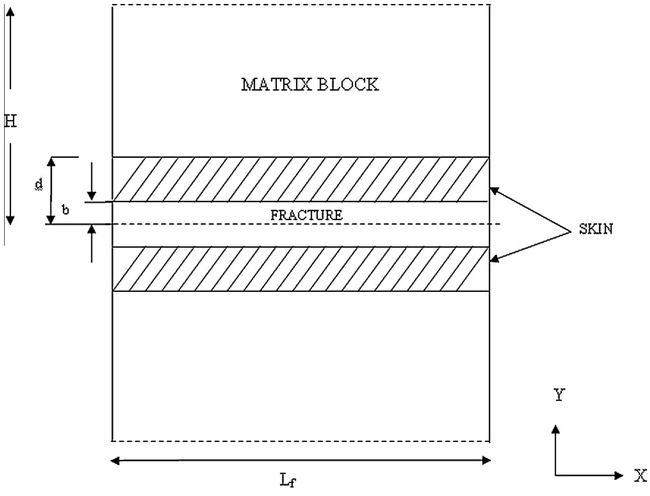

Fig. 1. Schematic diagram showing a coupled fracture–skin–matrix system.

3. Fluid flow

The momentum balance states that the flow average velocity is proportional to the pressure gradient:

$$q = \frac{b^3}{12\mu}\frac{\partial p}{\partial x} \tag{1}$$

where μ is the viscosity, b is the half fracture aperture, p is the pressure within the fracture caused by the injection, q is the volumetric flow rate per unit width of the fracture given by:

$$q = b * v \tag{2}$$

where v is the velocity of the fluid.

The continuity of the fluid considering fluid loss from the fracture wall into the fracture skin is:

$$\frac{\partial q}{\partial x} + 2q_l = 0 \tag{3}$$

where q_l is the fluid loss velocity which has been kept as constant along the fracture [24]. Rawal and Ghassemi [24] assumed that fluid loss at the interface is instantaneous and the same assumption has been used in this study.

4. Heat transport

The principal transport mechanisms in the fracture include thermal convection, conduction and dispersion, in addition to heat transfer from the fracture into the fracture–skin. As the migration of fluid is faster along the high permeability fracture, transport of heat is assumed to be one-dimensional along the fracture. The coupling between the fracture and skin is ensured by the continuity of the fluxes between them by assuming that the conductive flux from the fracture to the fracture–skin takes place in a direction perpendicular to the fracture. Conductive exchanges in the direction parallel to the fracture plane are assumed to be negligible compared with that perpendicular to the fracture plane. For relatively low injection rates it is reasonable to assume that heat conduction in the fracture–skin is one-dimensional perpendicular to the fracture [25].

The thermal transport equations for the coupled fracture matrix system provided by de Marsily [26] has been modified for the fracture–skin–matrix system.

$$\frac{\partial T_f}{\partial t} = -v\frac{\partial T_f}{\partial x} + D_f\frac{\partial^2 T_f}{\partial x^2} + D_T\frac{\partial^2 T_f}{\partial x^2} + \frac{\lambda_s}{\rho_f c_f b}\left.\frac{\partial T_s}{\partial y}\right|_{y=b} \tag{4}$$

$$\frac{\partial T_s}{\partial t} = \frac{\lambda_s}{\rho_s c_s}\frac{\partial^2 T_s}{\partial y^2} \tag{5}$$

$$\frac{\partial T_m}{\partial t} = \frac{\lambda_m}{\rho_m c_m}\frac{\partial^2 T_m}{\partial y^2} \tag{6}$$

$$D_T = v * \beta_T \tag{7}$$

$$D_f = \frac{\lambda_f}{\rho_f c_f} \tag{8}$$

where T_f, T_s, and T_m are the relative temperatures in the fracture, skin and the rock–matrix respectively. D_T is the thermal dispersion coefficient in the fracture [26]. D_f is the thermal conduction coefficient of the fluid in the fracture, v is the velocity of the fluid in the fracture; β_T is the thermal dispersivity; λ_f is the thermal conductivity of the fluid in the fracture, λ_s is the thermal conductivity of the fracture–skin and λ_m is the thermal conductivity of the reservoir matrix; ρ_f, ρ_s and ρ_m are the densities of the fracture, fracture–skin