Research Article

THERMAL TRANSPORT IN A COUPLED SINUSOIDAL FRACTURE MATRIX SYSTEM IN THE PRESENCE OF FRACTURE SKIN

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ABSTRACT

Modeling of fluid flow through fractured rock is an important aspect of many disciplines, especially in geothermal energy production. A few studies have been conducted in the coupled fracture-matrix system in the presence of fracture skin using parallel plate model. An attempt has been made to simulate thermal transport in sinusoidal fracture-skin-matrix coupled system numerically. Results suggest that the spatial variation of the fracture aperture along the fracture affects the heat transfer at the fracture-skin interface and thus enhances the heat transfer between the fracture and the rock matrix. The variation in the fracture skin thermal conductivity has marginal effect on the heat transfer mechanism in the coupled sinusoidal fracture skin matrix system due to the curvature effect of the fracture and small fracture aperture.

INTRODUCTION

The study of fractures in the subsurface is gaining importance as it is one of the major sources of geothermal energy production. The basic concept of the geothermal system is to develop a water circulation system through subsurface fracture network. Access to these resources involves injecting cold water through a vertical injection well and conveying it through a hot fractured rock, consisting of a well defined high permeability horizontal single fracture, and finally extracting the heated water through vertical extraction wells (Natarajan and Suresh Kumar 2010). Numerical modeling of heat transport in fracture-matrix coupled system using dual porosity model has already been adopted (Ghassemi and Suresh Kumar 2007). Thermal transport in the fracture matrix system has been carried out with sinusoidal fracture geometry numerically by Natarajan and Suresh Kumar (2010a). Although significant studies have been conducted in the fracture matrix system, only a few studies have been carried out in the presence of fracture skin. Fracture skin is defined as low-permeability material deposited along the fracture walls. A few studies conducted with respect to solute transport in fracture-skins have concluded that fracture-skins in the form of clay filling (Driese et al. 2001), mineral precipitation (Fu et al. 1994) and organic growth material (Robinson and Sharp 1997) have reduced the permeability in fracture-skin while some others have concluded that the presence of fracture-skins has increased the permeability in fracture-skins by developing micro-fractures (Polak et al. 2003). Analogous to solute transport, the presence of fracture-skin can significantly affect the heat conductivity in the fracture-skin-matrix system. The formation of skin during heat transport in rock fracture can be justified on the basis that certain chemicals undergo precipitation / dissolution due to high temperatures and they get deposited on the walls of the fracture as a thin layer of fracture-skin. The heat transport parameters such as thermal conductivity may significantly differ from that of the rock-matrix. It should be noted that the conductive mechanisms are different at the fracture-skin interface as well as the skin-matrix interface. Thus the presence of fracture-skin may either enhance or mitigate the heat transfer at the interface, and in turn influence the heat transport in the fractures. Natarajan and Suresh Kumar (2010b) have analysed the effect of poroelastic and thermoelastic stresses in the presence of fracture skin in a fracture matrix coupled system using the parallel plate fracture geometry. The objective of the presence study is to analyse the
heat transfer mechanism in the coupled fracture skin matrix system with sinusoidal fracture geometry.

**Physical system and Governing equations**

The conceptual model corresponding to a coupled fracture-skin-matrix system (Robinson et al. 1998) is illustrated in Fig.1, where $b$ refers to the varying half-fracture, $H$ is the half fracture spacing, $A$ is the amplitude of the sine wave, $\delta$ is the wavelength of the sine wave and $L_f$ refers to the length of the fracture.

![Fig. 1 Schematic diagram showing a coupled sinusoidal fracture-skin-matrix system](image)

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. Since 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 as compared with that perpendicular to the fracture plane. Heat conduction in the fracture-skin is considered to be one-dimensional perpendicular to the fracture since Ghassemi et al. (2003) has considered this to be a good assumption for relatively low injection rates. The thermal transport equations in the fracture-skin-matrix system for the present study is given below:

$$\frac{\partial T_f}{\partial t} = -\lambda_f \frac{\partial^2 T_f}{\partial x^2} + D_f \frac{\partial^2 T_f}{\partial y^2} + \frac{\lambda_f \beta_f}{\rho_f c_f} \frac{\partial T_f}{\partial y} y = b$$

(1)

$$\frac{\partial T_s}{\partial t} = \frac{\lambda_f}{\rho_f c_f} \frac{\partial^2 T_s}{\partial y^2}$$

(2)

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

(3)

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

(4)

where $T_f$, $T_s$, $T_m$ are the relative temperatures in the fracture, skin and the rock-matrix respectively. $D_f$ represents the thermal dispersion coefficient in the fracture (de Marsily 1986). $D_f$ represents the thermal conduction coefficient of the fluid in the fracture, $v$ is the velocity of the fluid in the fracture; $\beta_f$ is the thermal dispersivity; $\lambda_f$ is the thermal conductivity of the fluid in the fracture, $\lambda_f$ is the thermal conductivity of the fracture-skin and $\lambda_m$ is the thermal conductivity of the reservoir matrix; $\rho_f$, $\rho_s$ and $\rho_m$ are the density of the fracture, fracture-skin and rock-matrix; $c_f$, $c_s$ and $c_m$ are the specific heat capacities of fracture, fracture-skin and rock-matrix; $b$ represents the half fracture aperture.

Here, equation (1) represents the thermal transport in the fracture. Equations (2) and (3) represent the transport processes in the immobile zones of the fracture-skin and rock-matrix respectively. Thermal convection in the fracture is represented by the first term in equation (1) and thermal conduction by second and third terms. The last term represents the coupling between the fracture and the fracture-skin. The initial and boundary conditions associated with equations (1), (2) and (3) are as follow:

$$T_f(x, t = 0) = T_s(x, y, t = 0) = T_m(x, y, t = 0) = 1.0$$

(6)

$$T_f(x = 0, t) = 0.5$$

(7)

$$\frac{\partial T_f}{\partial t}(x = L_f, t) = 0$$

(8)

$$T_f(x, t) = T_f(x, y = b, t)$$

(9)
The following assumptions are used in the present study:

1. The fracture aperture is much smaller in comparison with the length of the fracture.
2. Thermal dispersion is analogous to dispersion of solutes in fracture matrix system.
3. Convection within the fracture-skin and rock-matrix has been ignored by assuming that there is no fluid flow within the fracture-skin and rock-matrix.
4. Temperature at the fracture-skin interface, i.e., temperature along the fracture walls and along the lower boundary of the fracture-skin is assumed to be equal (at \( y = b \)).
5. Temperature at the skin-matrix interface, i.e., temperature along the upper boundary of the fracture-skin and the lower boundary of the rock-matrix is 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 equation (10).
6. The solution is restricted to one half of the fracture and its adjacent fracture-skin and its associated rock-matrix by assuming symmetry.
7. Thermal conduction is considered both in the fracture and within the rock-matrix.
8. Only a single fluid phase exists.
9. Changes in fluid enthalpy with pressure are neglected.
10. The thermal expansion of the reservoir matrix is neglected.

**Numerical model**

In this study, the system is described by a set of three partial differential equations, containing one equation for the fracture, one for fracture-skin and the rest for the rock-matrix, formulated in a one-dimensional framework. Second-order central difference finite difference scheme is used to solve this system numerically. Solution is iterated at each time step in order to satisfy the continuity at the high and low permeability interface, i.e., fracture-skin interface. Uniform grid size is adopted in the fracture whereas a non-uniform grid size is adopted along fracture-skin as well as rock-matrix. A smaller grid size is adopted at the fracture-skin interface to accurately simulate the concentration flux at the fracture-skin interface. A wavelength of 4m and amplitude of 66µm was adopted for simulating the sinusoidal wave, using which the varying aperture values were generated for the numerical model. A fracture length of 50m and a simulation period of 10 days were adopted for the simulation.

**RESULTS AND DISCUSSION**

A numerical model has been developed to analyse thermal transport in a coupled fracture-matrix coupled system with sinusoidal fracture geometry in the presence of fracture skin. The parameters used for the simulation has been tabulated below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fracture aperture</td>
<td>( b )</td>
<td>100</td>
<td>µm</td>
</tr>
<tr>
<td>Thermal dispersivity</td>
<td>( \beta )</td>
<td>0.05</td>
<td>m</td>
</tr>
<tr>
<td>Rock matrix specific heat capacity</td>
<td>( C_m )</td>
<td>800</td>
<td>J/Kg/K</td>
</tr>
<tr>
<td>Rock density</td>
<td>( \rho_m )</td>
<td>2600</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Thermal conductivity of the rock matrix</td>
<td>( \lambda_m )</td>
<td>2</td>
<td>W/m/K</td>
</tr>
<tr>
<td>Specific heat capacity of fracture fluid</td>
<td>( C_f )</td>
<td>5000</td>
<td>J/Kg/K</td>
</tr>
<tr>
<td>Fracture fluid density</td>
<td>( \rho_f )</td>
<td>1000</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Fracture skin specific heat capacity</td>
<td>( C_s )</td>
<td>1500</td>
<td>J/Kg/K</td>
</tr>
<tr>
<td>Fracture skin density</td>
<td>( \rho_s )</td>
<td>1500</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Thermal conductivity of fracture skin</td>
<td>( \lambda_s )</td>
<td>10</td>
<td>W/m/K</td>
</tr>
<tr>
<td>Length of the fracture</td>
<td>( L_f )</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Total simulation time</td>
<td>( T )</td>
<td>10</td>
<td>day</td>
</tr>
</tbody>
</table>
The results for the verification of the numerical model using the parallel plate fracture have been shown in Fig. 2. The analytical solution of Sudicky and Frind (1982) has been represented by solid lines, while the numerical results have been plotted in terms of data points. The boundary conditions in the analytical solution were modified to suit the present problem and the simulations were carried out for a period of 365 days.

Figure 3 illustrates the comparison of the results obtained from the sinusoidal model with that of the parallel plate model. Natarajan and Suresh Kumar (2010b) have concluded that the presence of fracture skin enhances the heat transfer mechanism due to the curvature of the fracture surface. Thus, the presence of sinusoidal fracture alters the rate of heat transfer in the fracture matrix system in addition to the fracture skin.

Figure 4 illustrates the comparison of the results obtained from the sinusoidal model with that of the parallel plate model. As the skin thermal conductivity is increased from 2 W/m-K to 10 W/m-K, the rate of heat transfer from the rock matrix to the fracture increases and the fracture attains the temperature of the rock matrix very close to the fracture inlet. On the other hand, the variation in the skin thermal conductivity has marginal effect on the heat transfer mechanism in the sinusoidal fracture skin matrix system as the sinusoidal curvature plays a major role and thus similar thermal profiles are obtained for all skin thermal conductivities. In addition, the small fracture aperture provides a strong coupling between the fracture and the skin which results in very low temperature in the fracture.
CONCLUSION
Numerical simulation of thermal transport in sinusoidal fracture skin matrix coupled system has been attempted. The results suggest that this model behaves differently from the common parallel plate fracture-skin matrix coupled system. The sinusoidal curvature of the fracture enhances the heat transfer from the rock matrix to the fracture in addition to the effect of the fracture skin. The variation of skin thermal conductivity has marginal effect on the heat transport mechanism in the sinusoidal fracture skin matrix system.

REFERENCES
- Ghassemi A , Suresh Kumar G (2007) Changes in fracture aperture and fluid pressure due to thermal stress and silica dissolution/precipitation induced by heat extraction from subsurface rocks. Geothermics 36(2):115-140.