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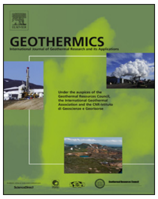

Identifying and assessing key parameters controlling heat transport in discrete rock fractures

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ABSTRACT

Numerical modeling of heat transfer in low porosity fractured rock is challenging because of the complexity associated with the interactions between fractures, bedrock matrix, groundwater, and heat sources. Possible influential parameters include the heat source configuration, the thermal conductivity of the matrix, the velocity of the fluid, the thermal dispersivity in the fracture, and the aperture of the fracture. In this investigation we use factorial analysis (2^K) to define which of the five parameters, or combinations thereof, significantly influence heat migration in a single fracture setting assuming a parallel plate condition. A 3-D numerical model based on the control-volume finite element method is used for the simulations. For the parameter ranges investigated, results indicate that the most influential factor controlling heat propagation in a single fracture setting is the velocity of the fluid in the fracture. The interaction between the thermal conductivity of the matrix and the velocity of the fluid, and between the thermal conductivity of the matrix and the aperture of the fracture, dominantly control the attenuation of the thermal front migration. Depending on the particular system, one or more of these parameters should be given better consideration during site characterization in fractured rock and in the compilation of site-specific models intended to predict heat propagation in fractured systems.

1. Introduction

Heat transport theories pertaining to fractured rock are fundamental and important components in understanding the drivers behind aquifer thermal energy storage and recovery methods (Bodvarsson and Tsang, 1982; Li, 2014), thermal enhanced oil recovery processes (AL-Hadhrami and Blunt, 2001) and thermal remediation techniques (Baston and Kueper, 2009). Heat transport in low permeability fractured rock occurs in both the fluid phase (conduction and convection) in the fractures, and the solid phase (conduction) in the matrix (Bear, 1972; Holness, 1999). Both analytical and numerical models coupling heat transport and groundwater flow can be used to predict the temperature field during thermal transport (Bodvarsson and Tsang, 1982; Doe et al., 2014; Gringarten et al., 1975; Pruess et al., 2012; Therrien et al., 2010; Yang et al., 1998). However, such heat transport models require input parameters such as the source configuration (source dimensions), fluid velocity, porosity, intrinsic permeability, thermal conductivity, fracture aperture, fracture spacing, fracture connectivity and thermal dispersivity among others. Some of these parameters are relatively easy to measure and estimate, while others are arrived at through approximations or values from literature.

Characterization and estimation methods will be influenced by time and cost constraints, the purpose of the test and sometimes environmental restrictions. Further, the relative importance and interaction of the various parameters in heat transport models for a fractured rock setting and the implication on the success of thermal energy storage and recovery, oil recovery and thermal remediation are not well understood. In this investigation we focus on five main parameters that we believe control the propagation of a thermal front in a discrete fracture setting: length of the heat source (S_L), fracture thermal dispersivity (α), matrix thermal conductivity (λ_m), fracture aperture ($2b$) and fluid velocity in the fracture (v_f).

The dimensions of the heat source are believed to significantly influence heat transport and the effect of thermal dispersion in a discrete fracture setting (Yang, 2016). When heat is applied to an isolated section of a well, thermal propagation occurs in both the fluid phase in the fracture and the solid phase in the matrix in contact with the heated source. The difficulty in handling non-point sources has led many researchers to assume a point source in solving the problem analytically and semi-analytically (Baston and Kueper, 2009; Bodvarsson and Tsang, 1982; Cheng et al., 2001; Jung and Pruess, 2012; Martínez et al., 2014; Yang et al., 1998; Yang and Yeh, 2009). Numerical models are more flexible and can accommodate a more realistic configuration that represents, for example, a nuclear waste repository or a test well

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Nomenclature

S_L	Length of heat source [L]
v_f	Velocity of fluid in the fracture [L/T]
$\lvert v \rvert$	Magnitude of the velocity of the fluid [L/T]
α	Thermal dispersivity in the fracture [L]
α_l	Longitudinal thermal dispersivity [L]
α_t	Traverse thermal dispersivity [L]
2b	Fracture aperture [L]
X	Direction
Y	Direction
Z	Direction
D	Dimensions
K	Number of factorial parameters
T	Temperature
t	Time [T]
$\overset{=}{\nabla}$	Two-dimensional gradient operator in the fracture plane
ψ_f	Pressure head in the fracture [L]
z_f	Elevations heads in the fracture [L]
S_{wf}	Saturation of water in the fracture [dimensionless]
Γ_f	Fluid source/sink term [1/T]
Γ_T	Thermal source/sink term [1/T]
k_{fr}	Relative permeability of the fracture [dimensionless]
K_f	Hydraulic conductivity of the fracture[L/T]
g	Gravitational acceleration [L^2/T]
μ	Viscosity of the fluid phase [M/LT]
q_m	Darcy's flux in the matrix [L^3/T].
D_m	Matrix thermal dispersion coefficient [L^2/T]
D_f	Fracture longitudinal/traverse thermal dispersion coefficient [L^2/T]
ρ_s	Density of the solid phase in the matrix [M/L
ρ_w	Density of the aqueous phase [M/L^3]
ρ_m	Bulk density of the matrix [M/L^3]
c_m	Bulk heat capacity of the matrix [L^2/T^2K]
c_s	Heat capacity of the solid phase in the matrix [L^2/T^2K]
c_w	Heat capacity of the aqueous phase [L^2/T^2K]
λ_s	Thermal conductivity of the solid phase in the matrix [ML/T^3K]
λ_w	Thermal conductivity of the liquid phase in the matrix [ML/T^3K]
λ_m	Bulk thermal conductivity of the matrix [ML/T^3K]
α	Longitudinal/traverse thermal dispersivity [L]
δ_{ij}	Kronecker delta unit tensor

Subscripts

f	Fracture
m	Matrix
L	Length
w	Fluid phase
s	Solid phase
i	Direction
j	Direction

(Klepikova et al., 2016).

To the best of our knowledge, in the literature at present there are no reports of laboratory or field scale experiments performed to measure thermal dispersivity in a single fracture. When neglecting the effect of dispersion in porous media, significant impacts on the distribution of the thermal plume are observed (Metzger et al., 2004; Rau et al., 2012; Saar, 2011). Specifically, the error introduced by omitting lateral dispersion in the heat transport equation for a single fracture has been addressed by only few studies in the literature (Cheng et al., 2001; Jung and Pruess, 2012; Martínez et al., 2014; Yang, 2016). Cheng et al. (2001) analyzed the effect of thermal dispersion in a fracture with an aperture of 20,000 μm and fluid velocity ranging between 0.5 and 1 cm/s (432–864 m/day) and a fracture length of 1 km, and concluded it to be not important. These conclusions drawn from Cheng et al. (2001) were the basis for many other investigations (Ghassemi and Zhou, 2011; Wu et al., 2015; Yang and Yeh, 2009; Zeng et al., 2013). However, dispersion is a function of fluid velocity and travel distance (Ganguly and Mohan Kumar, 2014; Molina-Giraldo et al., 2011; Sauty et al., 1982) and it is influenced by the source configuration (Yang, 2016), therefore the conclusions drawn from Cheng et al. (2001) may not be valid at all aperture values, flow conditions and source configurations.

Conclusions from Cheng et al. (2001) are also limited by the assumption made for the matrix equation where heat transport is restricted to thermal conduction in the direction perpendicular to the fracture. Early work (Baston and Kueper, 2009; Cheng et al., 2001; Kolditz, 1995; Martínez et al., 2014; Metzger et al., 2004; Molson et al., 1992; Rau et al., 2012; Saar, 2011) only considered perpendicular thermal conduction in the matrix and did not consider conduction in the direction parallel to the fracture. Recent work has shown that when longitudinal thermal conduction in the matrix is integrated in the models, the heat source will affect smaller regions in the adjacent matrix (Martínez et al., 2014; Yang, 2016) and the effect of thermal dispersion in the fracture is decreased (Yang, 2016). Numerical models, considering the full thermal conductivity tensor in the matrix, will provide better results when studying thermal propagation in fractured rock.

When considering low permeability fractured rock such as dolostone, limestone and granite, with permeability values on the order of $5 \times 10^{-17}\,m^2$, thermal propagation can be dominated by conduction in the matrix (Bergman et al., 2011; Lienhard, 1981; Ozisk, 1993; Saar, 2011). A good estimation of the matrix thermal conductivity is a prerequisite for the design of effective borehole heat exchanger systems (Franco et al., 2016; Sanner et al., 2009). Errors in the estimation of the matrix thermal conductivity of up to 38% can produce an important increase of up to 43% in the performance costs of real borehole heat exchanger systems (Sanner et al., 2009). In fractured low porosity rock the heat capacity of the matrix will usually retard the progression of the thermal front in the fracture (Bodvarsson, 1969; Geiger et al., 2006; Oldenburg and Pruess, 1998). However, according to Baston and Kueper (2009), matrix thermal conductivity has a small effect on the early time temperature distribution in thermal remediation processes. The conclusions drawn by Baston and Kueper (2009) are based on a small range of matrix thermal conductivity, between limestone (2.4 W/m K) and sandstone (3.03 W/m K), which is limited and does not cover other low porosity rock types.

There has been limited research on the effect of groundwater influx on the location of the thermal front in fractured rock. Jung and Pruess (2012) showed that temperature recovery during backflow in thermal single-well injection-withdrawal tests (SWIW) is independent of flow rates towards the well, but this might not be the case for all flow rate conditions (Baston and Kueper, 2009; Gehlin and Hellström, 2003; Li et al., 2017; Liebel et al., 2012; Lu and Xiang, 2012). Target temperature for remediation purposes using in-situ thermal treatment technologies may not be reached or could be significantly delayed when the groundwater influx is large (Baston and Kueper, 2009). Similar results have been observed for borehole heat exchangers systems when fast moving groundwater in fractures occurs around the well, resulting in reduction of heat accumulation around the borehole (Gehlin and Hellström, 2003; Li et al., 2017; Liebel et al., 2012). These studies (Baston and Kueper, 2009; Lu and Xiang, 2012) suggest that with medium to low groundwater influx, discrete fracture properties