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Combined inter- and intra-fracture free convection in fracture networks embedded in a low-permeability matrix

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ABSTRACT

Density-driven, haline free convection in fractured porous rock is studied in a 3-dimensional numerical model to evaluate the onset and interdependence of intra- and interfracture convection. When the rock matrix allows for solute diffusion, the most likely mode of convection in a regular fracture circuit is interfracture convection along the circuit such that regular fracture circuits can be modeled in a reduced dimensionality (2D) model. The critical Rayleigh number for the onset of interfracture convection in a regular fracture circuit is determined to be half of the critical Rayleigh number for convection in a single vertical fracture. In more complex fracture networks, vertical "dead-end fractures" and additional fracture intersections complicate convective patterns. Combined inter- and intrafracture convection is possible, such that convection is hard to predict.

1. Introduction

In many deep groundwater aquifers, density-driven free convection is an important process for solute transport [11,35] . Free convection has to be considered when solute or heat influence groundwater density [30,52]. When dense brine is overlying less dense fresh water, this potentially unstable fluid stratification may be dissipated by diffusion, or may lead to free convection in case of dominating buoyancy forces [11,23,30,52]. A number of authors emphasize the widespread importance of density-driven flow, as density-driven flow transports solutes faster and farther into the aquifer then diffusion alone [32,36,45]. Therefore, neglecting free convection will lead to a considerable underestimation of solute and/or heat transport.

In low-permeability geological formations, such as shales or granites, fractures may enable free convective flow even if the matrix is virtually impermeable to flow. Therefore, fracture networks are conjointly considered to play an important role in solute and heat transport in low-permeability strata and in determining the onset and patterns of free convection in such systems [19,20,25,32,33,36,41,42]. Understanding the onset conditions of free convection in fractured rock is increasingly important because fractured rocks are widespread and gain importance as potential hosts for hazardous waste disposal, heat and CO_2 storage, natural gas extraction by fracking, and are used for thermal energy exploitation. Furthermore, density-driven flow in fractures and fault systems is known to play an important role in the formation of ore deposits [1,8,16,47,51,53].

Convection in fractured low-permeability strata is possible along a circuit of connected fractures (interfracture convection, "mode 1" as shown in Fig. 1a) or within a single fracture (intrafracture convection, "mode 2" as shown in Fig. 1b) [36,41]. Both types of convection have been examined separately in a couple of theoretical studies with different considerations of fracture–matrix interactions as discussed below.

Early studies on (thermal) convection within a single fracture approximated the fracture by a 3-dimensional fluid-filled vertical slab or by a saturated porous box heated from below. Fracture walls were assumed to be impermeable to flow and non-conducting, such that any fracture–matrix interaction was neglected [7,54]. In these cases, the onset of convection can be predicted using the classical Rayleigh number Ra which compares buoyancy to diffusivity. If the critical Rayleigh number of $Ra_c = 4\pi^2$ is exceeded, convection with streamlines parallel to the fracture plane (mode 2B) is expected to establish [3,9,15,29,54].

Some studies accounted for heat-conducting fracture walls and applied a constant vertical temperature gradient to the lateral fracture walls [22,24,48,50]. This boundary condition corresponds to assuming perfectly conducting fracture wall and has a stabilizing effect on thermal convection [26]. Thus, higher vertical temperature differences are required to initiate free convection and the critical Rayleigh

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Nomenclature

$(2b)$ [L]	fracture aperture
$(2b)_c$ [L]	critical fracture aperture in a single vertical fracture
$(2b)_{c,\,circ}$ [L]	critical fracture aperture in the fracture circuit
$(2B)$ [L]	fracture spacing
c [dimensionless]	relative solute concentration
$\mathbf{D}$ [L^2T^{-1}]	hydrodynamic dispersion tensor in the matrix
$\mathbf{D_{fr}}$ [L^2T^{-1}]	hydrodynamic dispersion tensor in the fracture
D_m [L^2T^{-1}]	effective diffusion coefficient in the matrix
D_0 [L^2T^{-1}]	free solution diffusion coefficient
$\mathbf{e_z}$ [dimensionless]	unit vector in vertical direction
g [LT^{-2}]	gravitational acceleration
h [L]	height of fracture
H [L]	domain height
h_0 [L]	equivalent fresh water head
$\mathbf{I}$ [dimensionless]	identity matrix
k [L^2]	permeability of (isotropic) porous medium
k_{fr} [L^2]	fracture permeability
k_m [L^2]	matrix permeability
$\mathbf{K_0}$ [LT^{-1}]	freshwater hydraulic conductivity tensor of porous medium
$\mathbf{K_{0,\,fr}}$ [LT^{-1}]	freshwater hydraulic conductivity tensor of porous medium
L [L]	length of the domain (y-direction)
p [$ML^{-1}T^{-2}$]	fluid pressure
$\mathbf{q}$ [LT^{-1}]	Darcy flux vector in the porous matrix
$\mathbf{q_{fr}}$ [LT^{-1}]	Darcy flux vector in the fracture
r_D [dimensionless]	diffusivity ratio between matrix and fracture
Ra [dimensionless]	Rayleigh number (homogeneous porous medium)
Ra_{fr} [dimensionless]	Rayleigh number in the fracture
Ra_c [dimensionless]	critical Rayleigh number
$Ra_{c,\,circ}$ [dimensionless]	critical Rayleigh number in a regular fracture circuit
$Ra_{c,\,fr}$ [dimensionless]	critical Rayleigh number in a single vertical fracture
S_S [L^{-1}]	specific storage of porous medium
$S_{S,\,fr}$ [L^{-1}]	specific storage of the fracture
Sh [dimensionless]	Sherwood number
t [T]	time
$\bar{j}$ [$ML^{-2}T^{-1}$]	total solute mass flux through top of the domain
W [L]	width of the domain in x-direction
x, y [L]	horizontal coordinates
z [L]	vertical coordinate
α_L [L]	longitudinal dispersion coefficient
$\alpha_{L,\,fr}$ [L]	longitudinal dispersion coefficient in the fracture
α_T [L]	transverse dispersion coefficient
$\alpha_{T,\,fr}$ [L]	transverse dispersion coefficient in the fracture
β [dimensionless]	solutal expansion coefficient
γ^{fl} [LT^2M^{-1}]	fluid compressibility
γ^{m} [LT^2M^{-1}]	matrix compressibility
θ [dimensionless]	matrix porosity
μ [$ML^{-1}T^{-1}$]	dynamic viscosity of the fluid
ρ [ML^{-3}]	fluid density
ρ_0 [ML^{-3}]	reference fluid density
τ [dimensionless]	tortuosity
φ [dimensionless]	incline of fracture (φ for a vertical fracture is 0)
Ω_{fluid} [T^{-1}]	exchange term for fluid in the porous matrix
$\Omega_{fluid,\,fr}$ [LT^{-1}]	exchange term for fluid in the fracture
Ω_{solute} [T^{-1}]	exchange term for solute in the porous matrix
$\Omega_{solute,\,fr}$ [LT^{-1}]	exchange term for solute in the fracture

number greatly exceeds $4\pi^2$ [8,22]. However, heat transport within the matrix was not considered [22,24,48,50]. In reality, this would correspond to a case where the fracture gains or looses heat along its vertical walls, but the adjacent matrix does not change temperature.

More advanced models for convection within a fracture embedded in a conducting matrix were not restricted to simulating processes within the fracture, but also accounted for heat transport in the adjacent matrix [1,21,25–27,42,51]. The stabilizing effect of the matrix is less distinct in this case, such that resulting critical Rayleigh numbers exceed $4\pi^2$, but are below those determined with vertical fracture walls at constant temperature gradient [26].

Interfracture convection within a fracture network was usually studied in 2-dimensional domains with fractures represented as 1-dimensional line elements such that convection within a fracture was neglected. Even without considering intrafracture convection (mode 2), it was shown that fracture networks considerably affect the onset, strength and patterns of free convection in fractured porous media [20,33,37,41,46]. Depending on the geometry of individual fracture networks, convection was enhanced or inhibited, such that making predictions is a complex task.

Very few studies link inter- and intrafracture convection. A theoretical comparison of the likelihood of each mode of free (haline) convection is provided by Simmons et al. [36], who considered a fracture circuit embedded in an impermeable rock matrix. A comparison of critical concentration differences (derived from critical Rayleigh numbers) led to the conclusion that intrafracture convection parallel to the fracture plane (mode 2B) is the most likely mode of convection and occurs for even very small density differences. According to Simmons et al. [36], interfracture convection around an impermeable rock matrix block (mode 1) is likely as well, while intrafracture convection normal to the fracture plane (mode 2A) requires large density differences in combination with large fracture apertures and is hence unlikely.

Ramazanov [31] analytically determined the onset of interfracture thermal convection (called transverse convection) along a fracture circuit and intrafracture convection (called longitudinal convection)

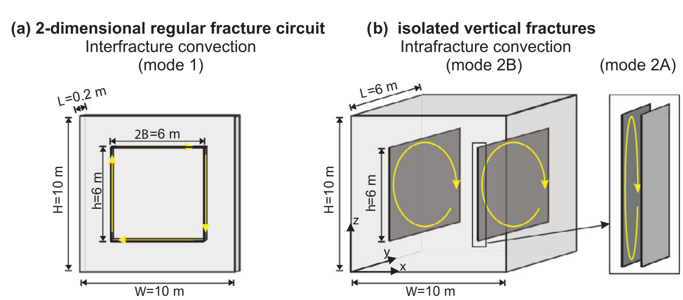

Fig. 1. Conceptual models to study (a) interfracture convection and (b) intrafracture convection. Mode 2A was not considered in this study and is just shown for completeness.