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Gravity-driven fingers in fractures: Experimental study and dispersion analysis by moment method for a point-source injection

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ABSTRACT

In this study, we investigate the behavior of a dense contaminant injected from a point-source in a fracture. Our experimental model is a transparent Hele-Shaw cell, 0.5 mm of aperture. A saline solution is injected locally representing the point-source pollution. A Laser Induced Fluorescence (LIF) method provides concentration measurement of the pollution plume. Two propagation patterns have been observed: one and two-finger plumes. If the upper part of the plume is stable over time regardless of the second configuration, the moment when the plume separates into two fingers is highly dependent on both injection flow-rate and contaminant concentration. To further investigate the dispersion process inside the fracture, experimental results are interpreted by the spatial and time moment methods. Resulting dispersivities and plume propagation mean velocity are compared to theoretical values derived from a modified Taylor-Aris dispersion tensor. The longitudinal macro-dispersion obtained suggests an asymptotical behavior of the plume spread regardless of the studied configurations. Experimental local dispersivities derived from time and space moments proved to be close at large times to theoretical values predicted by the density-dependent dispersion tensor (Oltéan et al., 2004). Based on those observations the mechanism behind the separation of the plume into two fingers is believed to be significantly impacted by the pre-asymptotic behavior of the dispersion tensor.

1. Introduction

In case of accidental or natural groundwater contamination, faults or fractures play a key role as preferential pathways for migration of pollutants. Due to the relevance of these channels for the vulnerability assessment of aquifer systems and the specific nature (geometry, network connectivity, aperture variability and wall roughness) of these geological objects, many researchers have focused on their hydrodynamic behavior since the pioneering works of Taylor (1953) and Aris (1956) and the application of Reynolds equation to fracture flows (*e.g.:* Bear, 1972; Buès et al., 2004; Cacas et al., 1990; Witherspoon et al., 1980). A large number of analysis from a theoretical, experimental or numerical perspective have been performed to characterize concentration distribution inside the fracture and the effective dispersion associated with such mechanisms (*e.g.:* Berkowitz and Zhou, 1996; Moreno et al., 1985; Neretnieks et al., 1982; Roux et al., 1998; Suresh et al., 2006; Webster et al., 2007). Experimental measures to be compared to these numerical and theoretical forecasts are usually carried out by light transmission in transparent fractures (Detwiler et al., 1999, 2000; Nowamooz et al., 2009; Oltéan et al., 2004, 2008) and more recently, by nuclear magnetic resonance imaging (Dijk and Berkowitz, 1999; Dijk et al., 1999) or X-ray CT tomography (Zhu et al., 2007). The reader interested in the various related-scientific issues should refer to the review of Berkowitz (2002) on this topic.

Flow and transport processes in fractures can also be significantly influenced by the fluid properties (density and/or viscosity contrasts). For miscible fluids, most significant studies have employed a Hele-Shaw cell which can be considered

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Notation

α_T	Transverse dispersivity
α_L	Longitudinal dispersivity
δ_{ij}	Kronecker delta
μ	Dynamic viscosity
ρ_0	Density of the water
ρ_{inj}	Density of the saline solution
$\Delta\rho=\rho-\rho_0$	Density variation
σ_{ij}^2	Variance tensor, Eq. (9)
$\bar{\sigma}_{ij}^2$	Dimensionless variance, Eq. (13)
$(\sigma_{ij}^t)^2$	Temporal variance tensor, Eq. (12)
b	Fracture aperture
$C(x_1, x_2, t)$	Local concentration
$\bar{C}$	Ensemble mean concentration
C_{inj}	Injection concentration
$\mathbf{D}^*$	Local dispersion tensor
$\bar{\mathbf{D}}$	Macrodispersion tensor
$\bar{\mathbf{D}}^*$	Dimensionless macrodispersion, Eq. (14)
$\bar{\mathbf{D}}^t$	Time-averaged dispersion tensor
D_{mol}	Molecular diffusion
$\mathbf{g}$	Acceleration of gravity
$G=V_G/V^*$	Dimensionless number
H	Height of the fracture
L_d	Width of the plume core
L_S	Distance to the separation point
L_{total}	Total length of the plume
M_{ij}	$(\mathrm{i}+\mathrm{j})^{\mathrm{th}}$-order spatial moment
$\bar{M}_{ij}$	$(\mathrm{i}+\mathrm{j})^{\mathrm{th}}$-order spatial moment about the mean
M_n	n^{th}-order temporal moment
$\bar{M}_n$	n^{th}-order temporal moment about the mean
P	Pressure
Pe	Peclet number
Q	Flow rate
Re	Reynolds number
S	Dimensionless distance to the cross-section
t	Time
$t^* = \bar{V}_1/L_{total}$	Dimensionless time
$\bar{t}$	Dimensionless time, Eq. (13)
$\mathbf{V}$	Velocity vector
$\mathbf{V}^*$	characteristic velocity
$\mathbf{V}_G$	Gravitational velocity
$\bar{\mathbf{V}}$	Mean velocity of the mass center
$\bar{\mathbf{V}}^t$	Time-averaged velocity
$< >$	Averaged variable over the cell aperture

as an idealized model of fracture. A particular interest was given to the evolution of the interface between two miscible fluids of different viscosities (*e.g.*, De Witt et al., 2005; Homsy, 1987; Jiao and Maxworthy, 2008; Lajeunesse et al., 1997, 1999; Maes et al., 2010; Zimmerman and Homsy, 1991) and/or densities (Fernandez et al., 2002; Gertsenshtein et al., 2008; Kneafsey and Pruess, 2010; Oltéan et al., 2004; Trevelyan et al., 2011; Wooding et al., 1997a,b). Indeed, when a denser fluid lies above a lighter one, this interface is deformed. The displacement become unstable (the so-called Rayleigh-Taylor instabilities) and results in gravity fingering which affects the spatial spreading of the plume. Note that buoyancy which drives the process is generated here by concentration (or temperature) gradients but may alternatively be induced by a combined effect of both or multiple dissolved density-affecting solutes (see for instance the double-diffusive finger convection studies of Glass and coworkers : e.g., Cooper et al., 1997; Pringle and Glass, 2002). However, very few works have considered the coupled influence of buoyancy and advection effects at the fracture scale. As representative works on this issue, we can cite Oltéan et al. (2008) or the recent study of Bouquain et al. (2011) who have investigated under the Boussinesq approximation the impact of gravity on the asymptotic Taylor-Aris dispersivity in a horizontal smooth fracture of constant aperture. Moreover, at the exception of Oltéan et al. (2008), none of these authors have focused on the case of a vertical fracture (*i.e.*, where both gravity and forced convection are oriented along the same direction) where the pollutant origin can be assimilated to a point-like source. At a large scale, this configuration may be due to leakage from waste disposal facilities (often cited as example of field problems involving variable fluid properties; e.g., Schincariol and Schwartz, 1990), CO2 injection into fractured reservoirs (Alavian and Whitson, 2010; Chen and Zhang, 2010; Farajzadeh et al., 2011; Kneafsey and Pruess, 2010) or infiltration from polluted or salt surface ponding resulting from a locally intense rainfall event (NRC, 1996). In such situations, competition between convection and gravity effects results in the formation of several gravity-driven fingers, which themselves will constitute some new multiple contaminant sources in the groundwater system (Shikaze et al., 1998).

In order to investigate these aspects, Oltéan et al. (2008) have performed experiments of density-driven flows with forced convection (here a salt solution injected in pure water) in a transparent fracture of constant aperture b and concentration measures have been obtained by light absorption. Results have been confronted to numerical simulations using a modified dispersion tensor, similar to the Taylor-Aris formulation but including buoyancy effects (Felder et al., 2004; Oltéan et al., 2004). However, a critical analysis of this comparison raises several specific issues:

(i) an experimental mass loss that seems to vary between 10% and 15%;
(ii) a finger width overestimated by numerical forecasts and, in a somehow related manner, a lower velocity of the simulated plume propagation.

The authors have initially imputed those discrepancies to the concentration measurement method and the experimental inaccuracy on the flow cell aperture. But the formulation of the dispersion tensor has never been questioned. However, the role of dispersion on the growth of fingering instability has already been clearly emphasized. Tan and Homsy (1986) have noted that transverse dispersion plays a smoothing role on the flow instability. Numerical comparison by Oltéan et al. (2008) of dense contaminant behavior using a constant molecular diffusion coefficient and a generalized Taylor dispersion tensor have suggested that an increase of the longitudinal dispersivity would slow down the fingering