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Characterizing Rayleigh Taylor Instability and Convection in a Porous Medium with Geoelectric Monitoring

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Abstract

The use of geophysical tools for subsurface characterization is a common practice in environmental studies and georesources engineering. The electrical conductivity of the subsurface is strongly influenced by the different properties of the subsurface such as pore fluid chemistry, and consequently, by subsurface processes that affect the spatial distribution of that chemistry, such as the mixing dynamics of pore fluids. In the context of freshwater-saline water interaction in coastal areas, changes in solute spatial distribution are coupled to density-driven flow, which can thus be monitored via geoelectrical measurements. Here, we study the Rayleigh Taylor instability and subsequent convection occurring due to the density difference between two miscible liquids when the lighter one is positioned on top of the denser one, a configuration that is relevant for saltwater-freshwater interactions in coastal aquifers. We simulate the convective process and monitor it numerically by computing the transverse apparent conductivity of the medium in time, as the convection develops. We then look for correlations between the geoelectrical signal and a global scalar measure of the convective process' advancement, namely the variance of the solute concentration field.

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1. Introduction

The use of geophysical tools for subsurface characterization is a common practice in environmental studies and georesources engineering. The electrical conductivity of the subsurface is strongly influenced by the different properties of the subsurface such as, pore fluid chemistry, and consequently, by subsurface processes that affect the spatial distribution of that chemistry, such as the mixing dynamics of pore fluids. In the context of freshwater-saline water interaction in coastal areas, changes in solute spatial distribution are coupled to density-driven flow, which can thus be monitored via geoelectrical measurements. Here, we study the Rayleigh Taylor instability and subsequent convection occurring due to the density difference between two miscible liquids when the lighter one is positioned on top of the denser one, a configuration that is relevant for saltwater-freshwater interactions in coastal aquifers. We simulate the convective process and monitor it numerically by computing the transverse apparent conductivity of the medium in time, as the convection develops. We then look for correlations between the geoelectrical signal and a global scalar measure of the convective process' advancement, namely the variance of the solute concentration field.

2.Theoretical Background

Rayleigh Taylor instabilities

The Rayleigh Taylor (RT) Instability is an instability of the interface between two fluids when the denser fluid is positioned on top of the lighter one. It is a dynamic process whereby two fluids seek to reduce their combined potential energy.

In present case, we consider two miscible liquids, or, in other words, a single liquid phase that is initially segregated in two regions within the porous medium, with density difference due to a difference in solute (salt) concentration between the top and the bottom regions.

Governing Equations (non-dimensionalized)

Rayleigh Number: $Ra = \dfrac{k\Delta\rho g H}{\phi D \mu}$

Velocity Scale: $U = \dfrac{k\Delta\rho g}{\mu}$

Domain pressure Scale: $P = \delta\rho g H$

Time scale: $t' = \dfrac{\phi H}{U}$

k = permeability of the porous medium (m^2)
ρ = pore fluid density (kg/m^3)
μ = viscocity (Pa.s)
p = normalised pressure (p/P)
$\boldsymbol{u}$ = normalised Darcy velocity (= u/U)
ϕ = porosity
H = height of the geological formation (m).
g = acceleration due to gravity (m/s^2)
c = nondimensionalized concentration of the solute
e_z = unit vector to z-direction
D = molecular diffusion coefficient (m^2/s)
Da = Darcy number (m) = k/H
t = normalised time (=t/t')

$$-\boldsymbol{\nabla} p + Da\left(\boldsymbol{\nabla}^2 \boldsymbol{u}\right) - u + c\boldsymbol{e_z} = 0,\ \boldsymbol{\nabla}\cdot\boldsymbol{u} = 0 \longrightarrow \text{Flow Equation}$$

$$\frac{\partial c}{\partial t} = \left(\frac{1}{Ra}\right)\boldsymbol{\nabla}\cdot(\mathrm{D}\boldsymbol{\nabla}\mathrm{c}) - \boldsymbol{u}\cdot\boldsymbol{\nabla}\mathrm{c} \longrightarrow \text{Transport Equation}$$

Geoelectrical measurements:

We designed a numerical scheme to simulate the evolution of the effective electrical conductivity of the liquid saturated porous medium during the convection process. The measurement of the conductivity is based on Ohm's Law. It consists in injecting an electrical current in a geological medium and measuring the resulting electrical potential differences between the inlet and the outlet to determine the medium's electrical conductivity. In this case, the mesoscopic scale is the main focus of the geoelectric study.

σ = electrical conductivity of the media (S/m)
σ_f = electrical conductivity of the fluid (S/m)
V = electric potential map in the media (Volts)
I = intensity of the current source form the electrode (Amp)
T = temperature (ºC)

$$\boldsymbol{\nabla}\cdot(\sigma\boldsymbol{\nabla}V) = -I \longrightarrow \text{Ohm's Law}$$

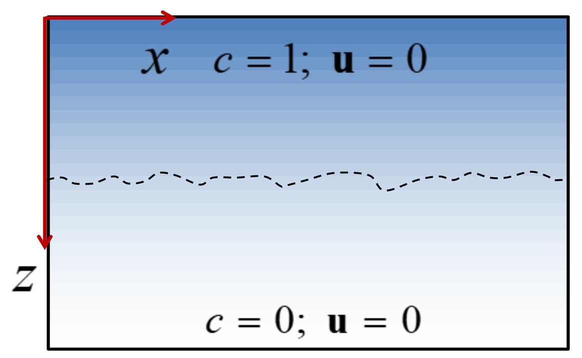
$$\sigma_f(T,c) = (d_1 + d_2 T + d_3 T^2)c - \left(\frac{d_4 + d_5\,T}{1 + d_6\sqrt{c}}\right)c^{3/2} \longrightarrow \text{empirical formula for the conductivity of an aqueous solution of NaCl [2]}$$

$$\sigma = \frac{1}{F}\sigma_f,\ F = \phi^{-m} \longrightarrow \text{Archie's laws for quantifying the net conductivity of the media to the conductivity of the pore fluid [1] (F = Formation factor, m = cementation exponent)}$$

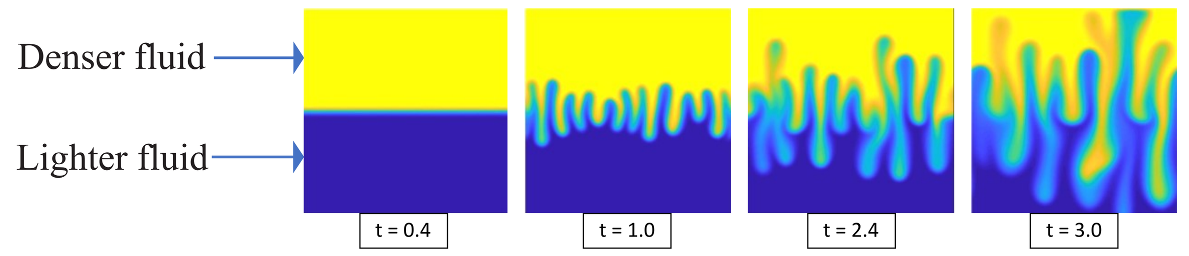
3. Numerical Simulation and Results

Initial and boundary conditions:

On lateral boundaries: $\dfrac{\partial c}{\partial z} = 0;\ \boldsymbol{u} = \boldsymbol{0}$

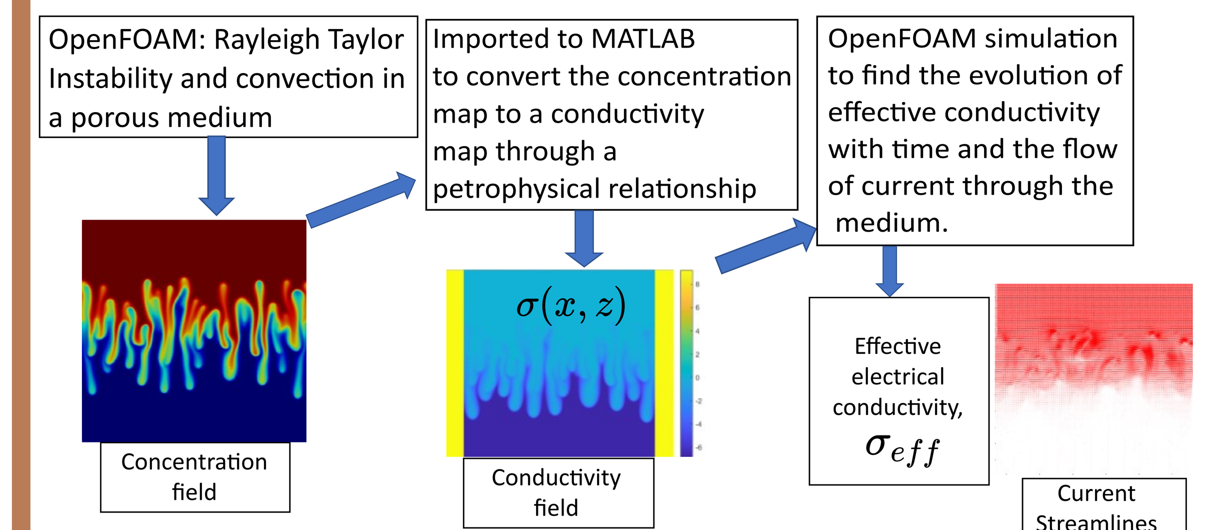


Schematic diagram for boundary conditions



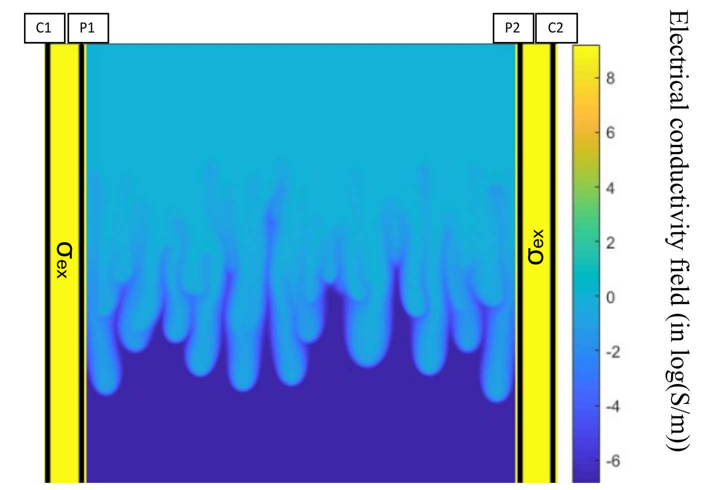
Propagation of Rayleigh Taylor instability in OpenFOAM

Flowchart of the simulation:



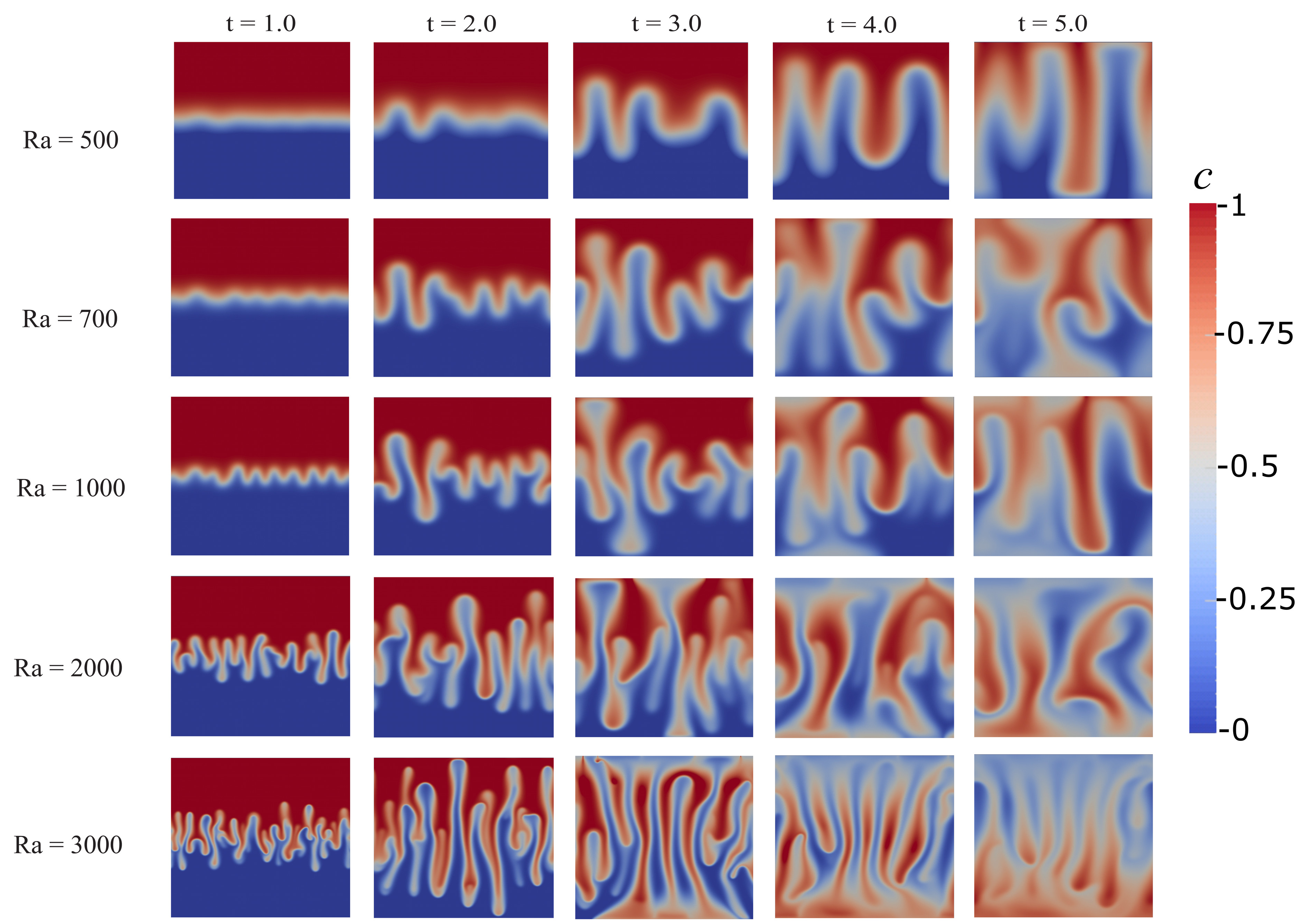
Flowchart of the simulation procedure to couple flow properties and geoelectric properties

Geoelectrical modeling in OpenFOAM:

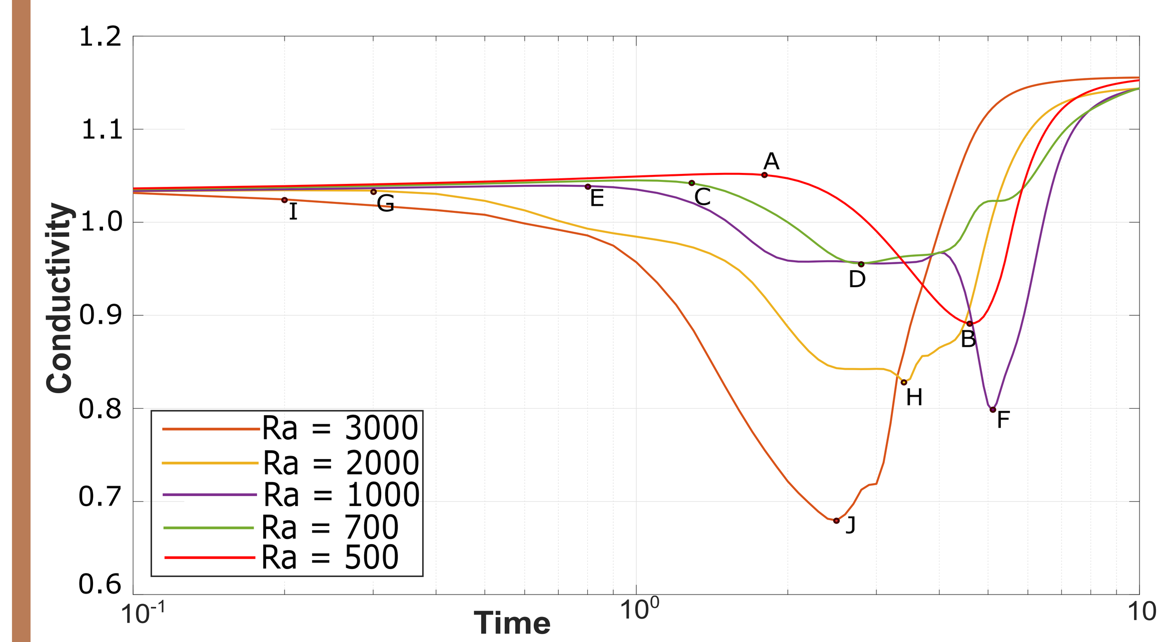


Geoelectrical simulation configuration.
C1 and C2 are the current electrodes, while P1, and P2 are the potential electrodes. C1 and C2 inject current in the medium. P1 and P2 measure the potential at the selected positions.

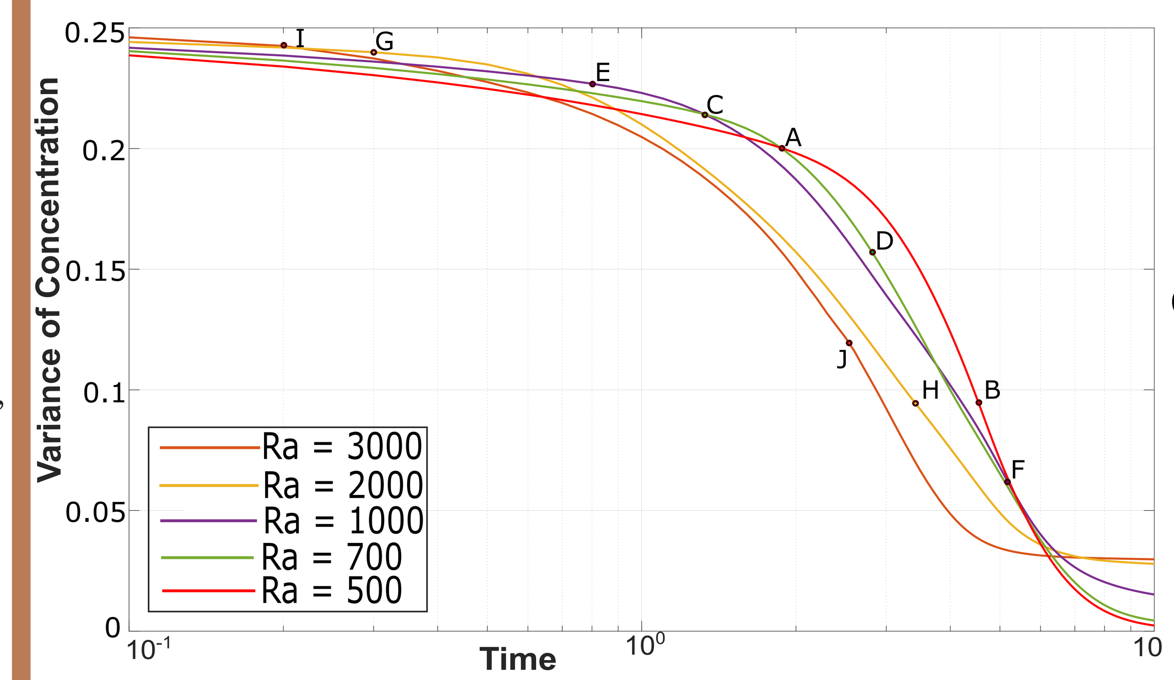
Simulated maps of concentration field for different Rayleigh numbers:



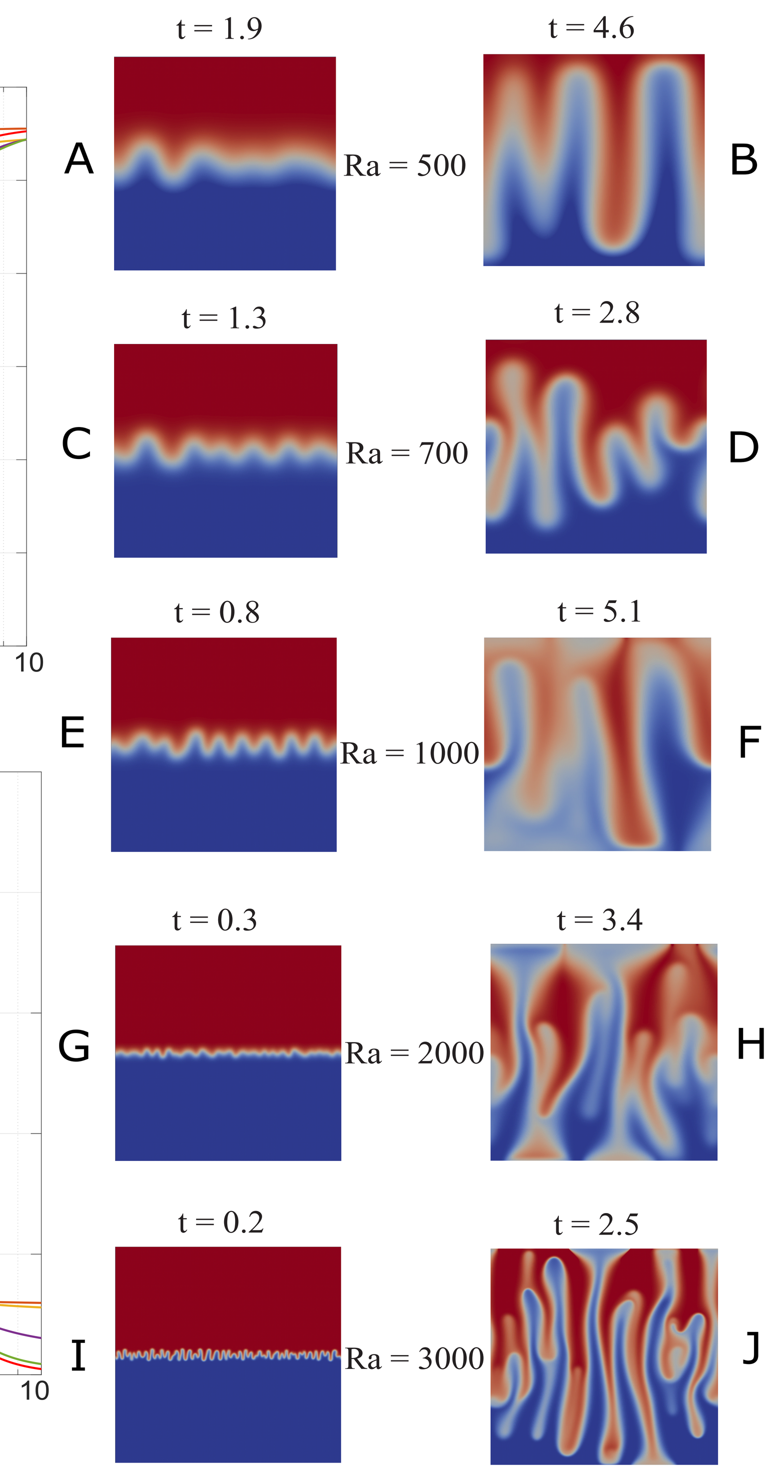
4. Analysis of the effect of Rayleigh



Variation of transverse conductivity with normalized time.



Variation of concentration variance with normalized time.



5. Conclusions

1. We developed a numerical scheme to study the geo-electrical response of Rayleigh Taylor solutal convection in a homogeneous porous media.

2. The electrical conductivity is sensitive to the changes in the spatial distribution of the charged solute (NaCl concentration) associated to the Rayleigh Taylor transport process.

3. We have investigated how various sealar global observables of the convection process vary over time, such as the concentration variance shown here, and how their evolution is correlated to that of the transverse effective conductivity of the medium.

4. We aim at monitoring the advancement of the Rayleigh Taylor instability and convection from the geoelectrical measurement.

5. It may also be possible to infer the Ra (and the medium's permeability or diffusion coefficient, other parameters in the Ra being known), form the geoelectrical measurements, *this is a work in progress*.

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