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Thermal convection of viscous fluids in a faulted system: 3D benchmark for numerical codes

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Abstract

We propose a new benchmark for the simulation of thermal convection in a 3D faulted system. Linear stability analysis is adopted to estimate the critical viscous-dependent Rayleigh number. These results are used to quantify the reliability of OpenGeoSys-5, Golem and FEFLOW simulators in accounting for the onset conditions and in predicting the long-term behavior of convective flow patterns. By comparing the analytical and numerical results, we can conclude that the proposed methodology and Rayleigh expressions can be applied as benchmark case for any numerical study involving coupled hydrothermal fluid flow in fault zones.

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Keywords: Fault; Convection; Rayleigh; Simulation; OpenGeoSys; Moose

1. Introduction

Free thermal convection of viscous fluid in porous media is a process relevant for a wide variety of problems related to practical aspects of engineering processes. Examples of these applications include, but are not limited to:

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(1) fresh-salt water intrusion in coastal regions; (2) upconing of brackish water and their mixing with surface fresh water lenses; (3) flow instabilities around salt domes and their effects on the cap rock behavior of these geological barriers for geological storage; and (4) geothermal heat production near the well bore areas and along pre-existing fault zones. The main characteristic of convective flows is that they are influenced by, even small, fluid density and viscosity gradients giving rise to self-sustained (aka self-perturbing) and highly non-linear flow dynamics.

In this paper, we focus in quantifying, via analytical and numerical approaches, onset conditions and first order characteristics of the long-term behavior of convective flow instabilities across major fault zones. Despite the ubiquitous presence of faults in the subsurface and their relevance for geo-engineering applications, the dynamics of convective flows in fault zones is still relatively unexplored. Exceptions are the works from [1-3].

Indeed no analytical solution of the strongly coupled partial differential equations (PDEs) of the convective problem exists. Therefore, it is not known whether the development of the perturbation as depicted in coupled hydrothermal simulations might reflect the actual, i.e. physical instability of the fluid or whether it is caused by instability of the numerical, therefore unphysical, integration of the governing equations.

Here, an attempt to rule out unphysical disturbances on convective related studies is described. We provide an analytical solution to the problem, which we propose as a benchmark case to quantify the reliability and robustness of numerical analysis of these types of problems and test the validity of our approach by solving the proposed benchmark with three finite element software, OpenGeoSys-version5 (OGS) [4], Golem [5] and FEFLOW [6].

Nomenclature

Ra	Rayleigh number [1]
Ra_{Crit}	Critical Rayleigh number
k	Hydraulic permeability [m^2]
ρ_0	Fluid density at $T=T_c$ [kg/m^3]. In this example, ρ_0=1022.38 kg/m3
c_f	Specific fluid heat capacity [J/kg/°C]
g	Gravity [m^2/s]
β	Fluid thermal expansion [1/°C] to fit fluid density Eq.5 In this example, β=5.9e-4 $°C^{-1}$
T_h	Bottom boundary condition (hot) [°C]. In this example, T_h=170°C
T_c	Top boundary condition (cold) [°C]. In this example, T_c=20°C
T_v	Approximation temperature [°C] to fit fluid viscosity Eq.5. In this example, T_v=62.1°C
T_{init}	Initial temperature
H	Fault height [m]. In this example, H=5500m
ϕ	Fault porosity [1]
$\lambda_{f,s}$	Fluid, solid heat conductivity [J/ m/s/°C]
λ_b	Bulk heat conductivity [J/ m/s/°C]; $\lambda_b=\phi\lambda_f+(1-\phi)\ \lambda_s$
μ_0	Fluid viscosity at $T=T_c$ [Pa/s]. In this example, μ_0=1.17e-3 Pa/s
2δ	Fault width [m]. In this example, 2δ=40m
Δ	Half of aspect ratio [1], Δ=δ/H. In this example, Δ=3.64e−3
γ	Dimensionless temperature [1], $\gamma=T_h-T_c/T_v$ Eq. 4. In this example, γ=170-20/62.1=2.42

2. Methods and results

2.1. Problem description and linear stability analysis

Figure 1a illustrates the setup of the model used in this study, as adapted from [7]. The geometry of the model domain consists of a 40 m wide (2δ), 5500 m long (H) fault (half aspect ratio Δ = δ/H = 3.64e-3) surrounded by an impervious rock matrix (5500x5500x5500 m in lateral and vertical dimensions). The matrix-fault system is isothermally heated from below by an imposed constant temperature along the basal boundary (T_h=170°C). The temperature at the top surface is also kept constant and equal to T_c=20°C, thus resulting in an overall thermal gradient of 27.3°C/km.