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Converging gravity currents of power-law fluids in the subsurface

Wednesday, 2 June 2021 09:00 (1 hour)

Gravity currents are primarily horizontal flows driven by a density contrast between the current and the ambient fluid. Viscous gravity currents propagate under a viscous-buoyancy balance, inertial forces being negligible except at the very beginning of motion. Non-Newtonian currents arise in several environmental and industrial applications when the fluid has a nonlinear stress-strain relationship. The power-law rheology is the simplest model that approximates the behaviour of a non-Newtonian fluid, in which the strain rate is scaled non-linearly with applied stress. The possibility to have reliable solutions to adopt as benchmarks for the asymptotic behaviour of numerical solutions, and to extract relevant scalings for the front speed and depth of gravity currents, justifies the extension of the analyses already available in literature for a Newtonian case.
We hence study gravity currents of power-law fluids of rheological index *n* for a particular category of 1-D transient free-surface flow fields that admit self-similar solutions of the second kind. Two different setups in plane (x) and radial (r) coordinates are examined: i) converging flow toward the origin in a channel of gap thickness $b(x) \propto x^k$ and $k < 1$ and ii) converging flow toward the centre in a cylinder. Under the classical viscous-buoyancy balance, the current propagation is described by a differential problem amenable to a self-similar solution. In both configurations, self-similarity requires a transformation identified as a 1-parameter Lie group for which the parameter identification is part of the solution, i.e. an incomplete self-similarity. The time is mapped as $t_r = t_c – t$, where t_c is the touch down time when the converging current reaches the origin. The transformation group is $U' = U$, $H' = H$, $x' = cx$, $t_r' = c^{1/\delta} t_r$, where U and H are the cross-section averaged velocity and the current depth, respectively. The unknown element of the parameter c is the exponent δ, which is a function of fluid rheology n and of channel geometry k for the first setup; it is a function only of n for the second setup.
For both configurations a single eigenvalue δ_c is computed, showing a modest dependency on n. The theoretical formulation is validated through experiments conducted during both pre- and post-closure phases and aimed at measuring the front position and the profile of the current. Experimental results are in fairly good agreement with theory and allow quantitative determination of the time interval of validity of the intermediate asymptotics regime, when self-similarity is achieved and when is lost.
Both configurations are relevant in subsurface flow in fractures and macropores, and the Hele-Shaw cell with power-law varying gap, configuration i), is directly representative of a porous medium with horizontally varying permeability and porosity, in accordance with the existing analogies valid for power-law fluids. The general layout is also amenable for extension to Herschel-Bulkley fluids and brings to an autonomous system of three variables admitting a spectrum of eigenvalues; this extension is presently under investigation.

Time Block Preference

Time Block A (09:00-12:00 CET)

References

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