Nonlinear mushy-layer convection with chimneys: stability and optimal solute fluxes

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We model buoyancy-driven convection with chimneys -- channels of zero solid fraction -- in a mushy layer formed during directional solidification of a binary alloy in two-dimensions. A large suite of numerical simulations is combined with scaling analysis in order to study the parametric dependence of the flow. Stability boundaries are calculated for states of finite-amplitude convection with chimneys, which for a narrow domain can be interpreted in terms of a modified Rayleigh number criterion based on the domain width and mushy-layer permeability. For solidification in a wide domain with multiple chimneys, it has previously been hypothesised that the chimney spacing will adjust to optimise the rate of removal of potential energy from the system. For a wide variety of initial liquid concentration conditions, we consider the detailed flow structure in this optimal state and derive scaling laws for how the flow evolves as the strength of convection increases. For moderate mushy-layer Rayleigh numbers these flow properties support a solute flux that increases linearly with Rayleigh number. This behaviour does not persist indefinitely, however, with porosity-dependent flow saturation resulting in sub-linear growth of the solute flux for sufficiently large Rayleigh numbers. Finally, we consider the influence of the porosity dependence of permeability, with a cubic function and a Carmen-Kozeny permeability yielding qualitatively similar system dynamics and flow profiles for the optimal states.

Comments:	20 pages, 10 figures. Changes from previous version correct typos, expand on discussion of the method including new appendix A, and minor changes to the discussion. A modified final version has been accepted for publication in the Journal of Fluid Mechanics
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