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Laminar thermal plumes in a cavity: laboratory and numerical models

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Plumes arise from gravitational instabilities in fluids. On Earth, hot upwelling plumes that develop from thermal boundary layers deep in the mantle have been proposed to generate intraplate volcanic islands such as Hawaii and La Reunion. The instabilities are generated as non-linear Rayleigh-Bénard instabilities in a fluid with high Prandtl number ($Pr=10^{23}$). Plumes are often studied fluid dynamically in the simpler case where they start at a finite-size heater in either numerical models at infinite Pr and in the laboratory in fluids with $Pr\sim10^3$-10^6. These studies have led to a wide range of different scaling laws, diverse ideas about plume shape and size, and diverging thoughts about the role of entrainment in the plume head and tail. Some of the disagreements can be ascribed to the different experimental setups and underlying assumptions. Here, we compare laboratory experiments of a plume growing from a heater patch with numerical simulations that reproduce the laboratory conditions as closely as possible. The fluids employed constant viscosity fluids, silicone oils with weakly temperature-dependent viscosity and sugar syrups with a stronger temperature-dependent viscosity. A new laboratory visualization technique allows us to recover the temperature and velocity fields on a cross-section of the laboratory plume. The numerical methods are axisymmetric finite element simulations using the measured properties of the laboratory fluids and assuming infinite Pr and laminar flow. We find excellent quantitative agreement between the two fully independent approaches. This suggests that the laboratory experiments can be accurately described by laminar Boussinesq flow at infinite Pr, at least for finite size domains. A starting plume in a cavity develops in four main

stages: a hot pocket of fluid first grows by conduction, until it becomes buoyant enough to detach from the hot surface. The plume head grows and behaves as a thermal. As the plume head cools through time the stem starts to dominate plume dynamics. Finally, the plume reaches the top of the box and a steady state structure is established. We propose new universal scalings to describe the four stages. These depend on the aspect ratio of the box, the power input and the Prandtl number.