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Thermal plumes in a yield-stress fluid: from laboratory experiments to geodynamical simulations

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Thermal convection in non-Newtonian fluids is important for many different fields, i.e. engineering (glass-production, food industry) but also geoscience (planetary mantles, lava lakes, icy satellites), but is still not very well understood. From a theoretical point of view, the difficulty is that the viscosity of these fluids approaches infinity when the motion amplitude vanishes. Therefore convective instabilities cannot grow from a static conductive state submitted to infinitesimal perturbations (as in the classical Rayleigh-Bénard configuration).

For this reason, we study the development of thermal plumes out of a localized heat source (peltier element) in Carbopol. Rheometry shows that this fluid presents a yield stress, is shear thinning (cf. i.e. [1]) and can be described by the Herschel-Bulkley model. Thermochromic-liquid crystals and PIV allow us to measure simultaneously temperature and velocity fields.

The results show that depending on the yield parameter Y0, defined as the ratio of the thermally induced stress and the yield stress, three different regimes can develop. For very low Y0, no motion is observed. For intermediate Y0, a slow convection cell develops around the heater. At high Y0, a finger-shape instability develops from the slowly convecting cell. The finger morphology is associated with a deformation very localized on the edges of the thermal anomaly, while the material inside the plume rises as a plug. Furthermore, depending on the experimental parameters, the instability motion can show episodicity. We have systematically studied the influence of the yield stress, the thermal power of the heat source and the fluid height on development and behavior of the instability.

In parallel, we have conducted a numerical study to compare to the experimental results,where we implemented the rheology of the fluid into a geodynamical code [2,3]. In a first step, we solve only the "liquid" problem: since a Herschel-Bulkley rheology implies infinite viscosity at zero-shear-rate, we regularize the viscosity by imposing a high cut-off value at low shear rate. Despite this regularization, the numerical simulations reproduce well a number of features observed in the laboratory experiments, such as the morphology and some episodicity. However, the plume onset time is controlled by the cut-off viscosity value and remains far from the laboratory systematics.

References

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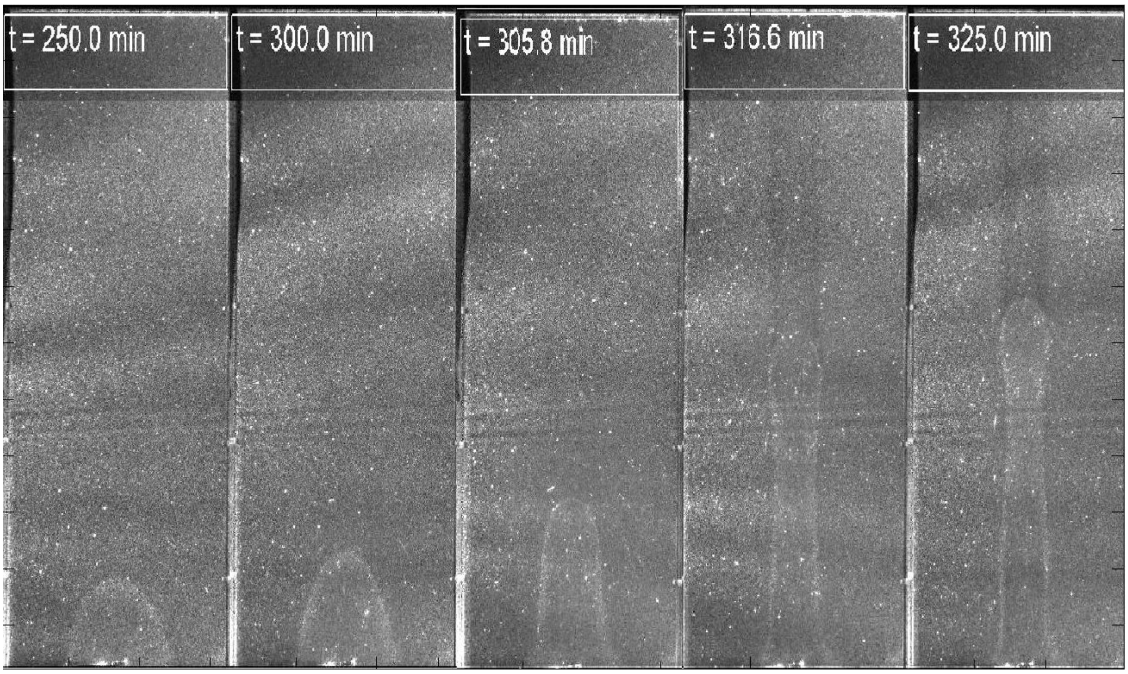

Figure 1: shows thermal instability in Carbopol for different times. Small white points: spherical particles for PIV, bright white line: isotherm at a T=24°C. The figure shows two important features: 1) it takes very long until convection starts (t_onset = 283 minutes), then it takes off comparably fast 2) plume-shape differs from normal mushroom-shape observed in Newtonian fluids.