LABORATORY LAYERED LATTE

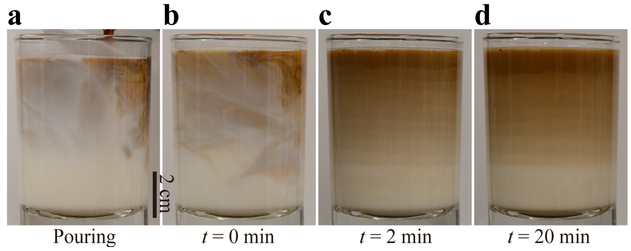

Figure 1: Pattern formation in an injection-driven system inspired by a layered latte. **a** A small volume of warm espresso is poured into a glass of warm milk. **b** Espresso and milk mix and form a mixture, which exhibits chaotic dynamics caused by the injection. The resulting espresso-milk mixture remains at the top of the container due to buoyancy. **c** As the mixture cools down to room temperature, multiple horizontal layers of different espresso concentrations are formed. **d** These horizontal layers maintain their structures over time.

Pattern forming systems are some of the intriguing and spectacular phenomena throughout science and technology[1]. In nature, patterns form in fluid media, such as the waves on the surface of deep water[2], large-scale von Kármán vortex streets in clouds[3], and the symmetric yet complex snow flakes[4], constitute some of the earliest self-organized systems, which have attracted human curiosity and initiated scientific exploration. A considerable class of spatial patterns in fluids are structured due to thermal effects, which trigger hydrodynamic instabilities[5]. For example, well-known instabilities triggered by thermal effects, such as Rayleigh-Bérnard convection[6], are often found in systems with well-defined initial conditions.

In a fluid system, when thermal gradients are introduced in the presence of an initial well-defined density gradient, distinct layered patterns are observed similar to those usually found in the ocean systems due to double-diffusive convection[7]. Surprisingly, we observe distinct horizontal layers formed after haphazardly pouring espresso into a glass of warm milk (**Fig. 1**). Pouring forces a lower density liquid (espresso) into a higher density ambient (milk). The downward liquid inertia caused by pouring is opposed by buoyancy. The dynamics are similar to the fountain effects[8] that characterize a wide range of flows driven by injecting a fluid into a second miscible phase of different density.

Here, we perform controlled model experiments injecting warm dyed water from the top into a cylindrical tank filled with warm salt solution. The mixture cools down at room temperature and multiple horizontal layers emerge over several minutes. We use the light intensity in the digital images of the fluid in the tank, after the injection, to quantify the distribution of the mixture density. We show that the formation of horizontal layers is a result of double-diffusive convection, where the salinity and temperature gradients are applied vertically and horizontally, respectively. The presence of the circulating flows within the layers are confirmed via Particle Image Velocimetry experiments and numerical simulations. Furthermore, we report that the formation of the horizontal layers is controlled by the injection velocity, i.e. layers emerge only when the injection velocity is higher than a critical value. We then identify the critical conditions of layering by a specified Rayleigh number which describes the competition between lateral thermal effect and vertical salinity effect. Finally, we propose a single-step procedure for fabricating multi-layer soft materials based on our understandings of the model system.

We are now studying the injecting and mixing problem where the dynamics in a proper dimensionless framework requires an analysis with both the Froude and Reynolds numbers.

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