Crystallization in a thermal plume

Nan He, Benoît Semin, Philippe Claudin,

PMMH, CNRS, ESPCI Paris, PSL Research University, Sorbonne Université, Université Paris Cité, F-75005, Paris, France
nan.he@espci.fr

The dynamics of multiphase reactive plumes, which govern geological and environmental processes such as cloud formation, volcanic eruption columns, and hydrothermal vent systems, rely on the interplay between fluid mixing, phase transitions, and chemical reactions [1]. To investigate these phenomena, we study experimentally the crystallization dynamics in a buoyant reactive plume using a two-dimensional tank. Butyramide is selected as the chemical due to its unique properties : its saturated solution density closely matches that of water, while its solubility exhibits strong temperature dependence [2]. To suppress interfacial crystallization at the air-water interface, the ambient solution was stratified into two layers by dissolving NaCl in the lower layer ($\rho = 1.02\ \mathrm{g\,cm^{-3}}$). A buoyant plume was generated by injecting preheated butyramide solution ($T_b = 50$–$60\,^\circ\mathrm{C}$) into the cold lower layer ($10\,^\circ\mathrm{C}$), as shown in Figure 1(a). Two cameras simultaneously capture crystal formation and concentration fields.

Crystals form within the plume in a cloud-like structure, as shown in Figure 1(b). The effects of injection temperature (T_b), injection rate (I_r), and initial ambient concentration (C_0) on crystal formation were systematically analyzed. Experimental results demonstrate that crystal count and total projected crystal area (A, sum of individual crystal areas in the plume) scale with T_b and injection rate (I_r), reaching maxima at $T_b = 60\,^\circ\mathrm{C}$ (highest tested temperature) and $I_r = 0.46\,\mathrm{mL\,s^{-1}}$. Additionally, higher initial ambient concentration (C_0) enhances the crystallization, analogue to the role of moisture in formation of cloud. To uncover universal behavior, a dimensionless analysis was performed by normalizing total crystal area (A) and growth time (t_e) against their peak values ($A_{\max}, t_{\mathrm{end}}$). The resulting curves collapse onto a single master curve across all T_b, C_0, and I_r conditions, as shown in Figure 1(c), demonstrating similar crystallization dynamics.

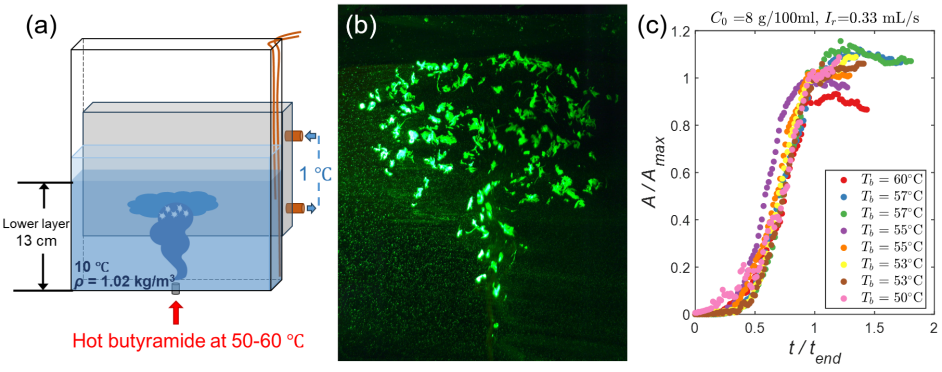

Figure 1. (a) Schematic of the experimental tank ; (b) Raw experimental image showing crystal formation ; (b) Dimensionless total area at different injection temperatures.

Références

1. Woods, Andrew W., Turbulent Plumes in Nature, *Annual Reviews*, **42**, 391–412 (2010).
2. He N.,Cui Y. et al., Sedimentation of a Single Soluble Particle at Low Reynolds and High Péclet Numbers, *Phys. Rev. Fluids*, **9**, 044502 (2024).