# Visualization of subsonic to supersonic flows processes in explosive volcanic eruptions

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**Abstract** Explosive volcanic eruptions eject in the atmosphere a gas-sustained mixture of solid rocks and molten magma fragments (pyroclasts). The physical properties of the mixture (e.g., temperature, density, gas composition, particle size distribution) and of the flow (e.g., mass flow rate, velocity, jet diameter) at the volcanic vent govern flow evolution, the distribution and sedimentation of the volcanic products, and eventually the ensuing hazards to society and environment. Recent developments in high-speed imaging allow eruptive flows to be observed with a spatial and temporal resolution suitable for the analysis of key eruption processes.

We perform high-speed imaging of explosive volcanic eruptions by using a monochrome (visible) high speed camera and a thermal infrared one. While manual analysis of the videos is still a prime tool, we also developed a specific Particle Tracking algorithm to extract flow information from highly variable videos collected during volcanic eruptions. So far, explosive eruptions have been recorded in high-speed at several active volcanoes, including Fuego (Guatemala), Stromboli and Etna (Italy), Yasur (Vanuatu), Eyjafiallajokull (Iceland), and Sakurajima (Japan).

The following key eruption processes have been observed so far and are currently under investigation:

1) Unsteadiness in the jet development. Multiple, discrete ejection pulses and sub-pulses characterize a single volcanic explosion, with ejection velocities being twice (up to 500 m/s) as high as previously recorded. Information on flow velocity and mass can be combined with analytical-experimental models to constrain the physical parameters of the gas driving individual pulses. However, sources of unsteadiness in the eruption jet at different time and spatial scales are still unclear.

2) Four-way coupling dynamics in the jet. The ejection trajectory of pyroclasts can also be used to outline the spatial and temporal development of the eruptive jet and the dynamics of gas-pyroclast coupling within it. Reduced drag zones develop at the beginning of the eruption, can increase the total travel distance of pyroclasts in the atmosphere. Also particle-particle collisions are observed, with highly variable outcomes as a function of the physical state of the particles.

3) Pyroclasts settling. High-speed videos can be used to investigate the aerodynamic settling behavior of pyroclasts from bomb to ash in size and including ash aggregates, providing key parameters such as drag coefficient as a function of Re, and particle density.

4) The generation and propagation of acoustic and shock waves. Phase condensation in volcanic and atmospheric gases is triggered by the transit of pressure waves and can be recorded in high-speed videos, allowing the speed and wavelength of the waves to be measured and compared with the corresponding infrasonic signals and theoretical predictions. Both blast waves and jet noise are produced during the eruptions, and can be parameterized from the videos.

Most of the above processes are well-studied both in theory and in experimental-mathematical models. However, their parameterization in real-scale volcanic eruptions is still challenging, and even more challenging is the assessment of their impact on the complex phenomena occurring at erupting volcanoes..
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