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Numerical study on internal structure and turbulent mixing of overpressured jets

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During explosive volcanic eruptions, the eruption clouds form buoyant plumes or dense pyroclastic flows. The critical condition that separates these two eruption styles is primarily governed by entrainment of ambient air into the eruption clouds by turbulent mixing. When turbulent mixing is efficient, the eruption clouds form buoyant plumes, whereas, when it is inefficient, the eruption clouds form dense pyroclastic flows. Recently, it has been pointed out that compressibility of the eruption clouds also influences on the critical condition (e.g., Koyaguchi et al., 2010). When the compressible ejected material is released from the vent at higher pressures than atmospheric pressure (under overpressured conditions), it forms a jet with complex internal structure including rarefaction waves and shock waves. This internal structure affects turbulent mixing between the ejected material and ambient air. Here, we focus on the overpressured eruptions at sonic velocities, and analyze their fluid dynamical features, particularly those of turbulent mixing just above the vent using a three-dimensional numerical model (Suzuki et al., 2005).

In general, as fluid flows from a nozzle at sonic velocities with an overpressure, the fluid undergoes Prandtl-Meyer expansion, rapidly accelerating to high Mach numbers and decreasing in pressure and density. This supersonic flow forms a standing shock wave called a Mach disk perpendicular to the flow just above the nozzle. The high Mach number fluid crossing the Mach disk undergoes an abrupt decrease in velocity to subsonic speeds and increases in pressure and density. A barrel shock is formed surrounding the jet axis and a jet flow boundary is formed outside the barrel shock. An annular supersonic up-flow develops between the barrel shock and the jet flow boundary and maintains its supersonic flow above the Mach disk (e.g., Ogden et al., 2008). According to experimental results by Solovitz et al. (2011), the efficiency of the entrainment of overpressured jets falls to approximately 60% of those in turbulent jets issuing from the nozzle as subsonic flows.

We performed the numerical simulations under the same conditions as those of the experiments by Solovitz et al. (2011): air is issuing from the nozzle into the atmosphere at sonic velocities for an initial temperature of 258 K and for an initial pressure of 2.55 atm. Our results reproduced the complex internal structure with the barrel shock, the Mach disk, the jet flow boundary and the annular supersonic up-flow. As the fluid crosses the Mach disk, its Mach number is reduced from 2.5 to 0.5. The annular supersonic up-flow has a Mach number of about 2.0 and this region with high Mach number is maintained up to ten diameters downstream of the exit.

We also carried out a detailed analysis of our numerical experiment obtained here. We found that eddy structure is formed along the jet flow boundary and these eddies remarkably enhance mixing between the ejected material and ambient air. Solovitz et al. (2011) concluded that the efficiency of entrainment of overpressured jets is reduced on the basis of the properties estimated from averaged values of the column at a given height. However they do not evaluate the effect of local mixing along the annular supersonic up-flow observed in our numerical results. We suggest that the buoyant region generated by the local mixing in the annular supersonic up-flow may stabilize eruption columns.

Keywords: volcano, eruption cloud, numerical simulation, pyroclastic flow