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Estimation of exit velocity of a volcanic eruption column by a vortex ring model

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Exit velocity of volcanic eruption column is one of basic and important parameters for understanding of eruption dynamics because it reflects a condition of magma fragmentation and governs eruption cloud dynamics. However, it is difficult to estimate it accurately from eruption images by a simple analysis such as tracking characteristic points of the column. Most of previous imaging studies of eruption columns merely estimated rise velocity and/or surface velocity. Meanwhile, an eruption column has one characteristic feature that has scarcely been remarked; a large vortex structure at the head of the column observed in the early stage (e.g., Patrick, 2007, JGR) is similar to a vortex ring. Detailed quantitative data on vortex rings have been given by many researchers, the relation between vortex ring and exit velocity in starting jet has been investigated (e.g., Gao and Yu, 2010, JFM). In this study, we investigated whether this relation is applicable to a volcanic column, and then we estimated the exit velocity of an eruption column in Sakurajima based on the relation.

In a starting jet ejected from a circular nozzle, the boundary layer separates at the nozzle edge and rolls up to form a toroidal structure at the head of the jet, which is known as a vortex ring. The leading vortex ring is growing by absorbing the trailing jet and travels downstream. As shown in previous experimental investigations using a piston, characteristic parameters of the vortex ring (ring radius, translational velocity, circulation, and ring core radius which is radius of the section of the ring) depend on the nozzle diameter and the piston stroke tU (t: time, U: the exit velocity with the piston). Gao and Yu (2010) have derived $dC/dt=1/2U^2-Uu$, where C is circulation, U is exit velocity, and u is translational velocity of vortex ring. This equation is based on the assumptions that exit velocity is constant and that trailing jet velocity is equal to the exit velocity. This equation enables us to estimate U when dC/dt and u are known.

We used results of 3-D simulations of volcanic eruption columns, so as to ascertain whether the GY equation is applicable to the columns. We made calculations for three cases of exit velocities (67m/s, 134m/s, 201m/s) based on 3-D numerical model of Suzuki et al. (2005, JGR). Fully developed vortex structures were recognized at the head of columns up to heights of 500-1000 m in results of all cases. We measured the height of the vortex ring for each time point, and then we estimated the rise velocity as the translational velocity u. Moreover, we measured the vortex core radius and the surface velocity of the vortex ring for each time point, so as to estimate the circulation of the vortex ring C and the time variation of the circulation dC/dt. As a result, we could obtain the exit velocities within 80-125 % range of the true values from u and dC/dt by the GY equation. Therefore we confirm that exit velocity of an eruption column could be estimated by analyzing the vortex ring.

Employing the same procedures described above, we estimated exit velocity for the Feb. 15 eruption of Sakurajima in 2011. This eruption had the maximum column height of 2-2.5 km from the vent, which was a relatively larger event in Sakurajima, 2011. A vortex structure at the head of the column was clearly recognized up to 1-1.5 km over the vent. Thereafter, the vortex structure stagnated and separated from the main column, and then gradually collapsed. The exit velocity of Sakurajima eruption column was estimated at 40-60 m/s by considering some ambiguity. These exit velocities are lower among the common values in vulcanian eruption (several tens-400 m/s). This means that the pressure at the magma fragmentation was relatively low and the explosion was weak. The analysis of vortex structure is useful for discussing vulcanian eruption mechanisms.