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Estimation of exit velocity of volcanic plume from analysis of vortex structures

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ABSTRACT

We propose a simple method for estimating the exit velocities of volcanic eruptions from the observation of volcanic plumes. For this purpose, we used a model of a vortex ring of an experimental jet, which was developed in the engineering field. To validate the model for the vortex structures of volcanic plumes, we applied it to plumes generated in 3-D numerical simulations. In 11 cases where exit velocity (66.8–200.5 m/s) is given as a boundary condition, we successfully estimated it with 7% underestimation by analyzing the size and motion of the leading vortex ring that forms at the plume front. Using the same procedure, we could also estimate the exit velocity by analyzing the trailing vortices that develop behind the vortex ring (14% underestimation). From these results, we conclude that: (i) the model of the vortex ring proposed by the jet engineering studies is appropriate for the vortex ring at the front of simulated volcanic plumes, and (ii) the model is also applicable to the trailing vortices of the plumes. These conclusions indicate that we can estimate the time evolution of the exit velocity for a series of eruptions from observations of the vortex structures of the actual volcanic plumes. By applying that method to an eruption of Sakurajima volcano on February 15, 2011, we found that following an increase during the first 10 s of the eruption, the exit velocity remained constant at >40 m/s up to 80 s after the onset of the eruption. Our method will be useful in understanding the time evolution of eruptive events, such as the transitional behavior from stable column to column collapse, from observations of volcanic plumes.

1. Introduction

During explosive volcanic eruptions, a mixture of volcanic gas and magma fragments ascends in the conduit and is ejected from the volcanic vent. The exit velocity of the mixture at the vent is an important parameter that controls the dynamics of volcanic plumes and reflects the dynamics of conduit flow. In general, when the mixture exits from the vent at a high velocity, it rises easily upward to a higher level as a buoyant volcanic plume. Conversely, if the exit velocity is low, the eruption column tends to collapse and generate pyroclastic flows (Sparks, 1986). Because pyroclastic flows cause great destruction around a volcano, it is desirable to be able to estimate the exit velocity relating to a critical condition for column collapse (e.g., Suzuki and Koyaguchi, 2012). From the exit velocity, the change of conditions at magma fragmentation in the conduit, such as gas over-pressure, can be detected (e.g., Alatorre-Ibargüengoitia et al., 2011) as well as the transitional behavior of eruption columns.

Traditionally, the exit velocity has been deduced from observations of plume ascent and the trajectories of ballistic bombs. Formenti et al. (2003) derived a relation from numerical simulations, that the initial frontal velocity of a jet is approximately 0.85 times the exit velocity, and estimated the exit velocity from an analysis of momentum-dominant jets at the onset of the 1997 eruption of Soufrière Hills volcano. Fagents and Wilson (1993) proposed a model for the motions of ballistic bombs for explosive eruptions and determined a range of exit velocities of bombs as a few tens of m/s to 400 m/s for some documented eruptions at Arenal, Ngauruhoe and Ukinrek Maars volcanoes. While these methods provide the exit velocities at the onsets of eruptions, they do not provide details of the changes in velocity during the progresses of eruptions. As observed at Mt. St. Helens 1980 and Pinatubo 1991 eruptions (Carey et al., 1990; Holasek et al., 1996), transition in plume behavior from convective rise to collapse can occur during a series of eruptions. We need to develop a method to estimate exit velocity from observable features of eruption plumes during the progress of an eruption as it can be anticipated that the exit velocity changes when such transitional behavior of the columns occurs.

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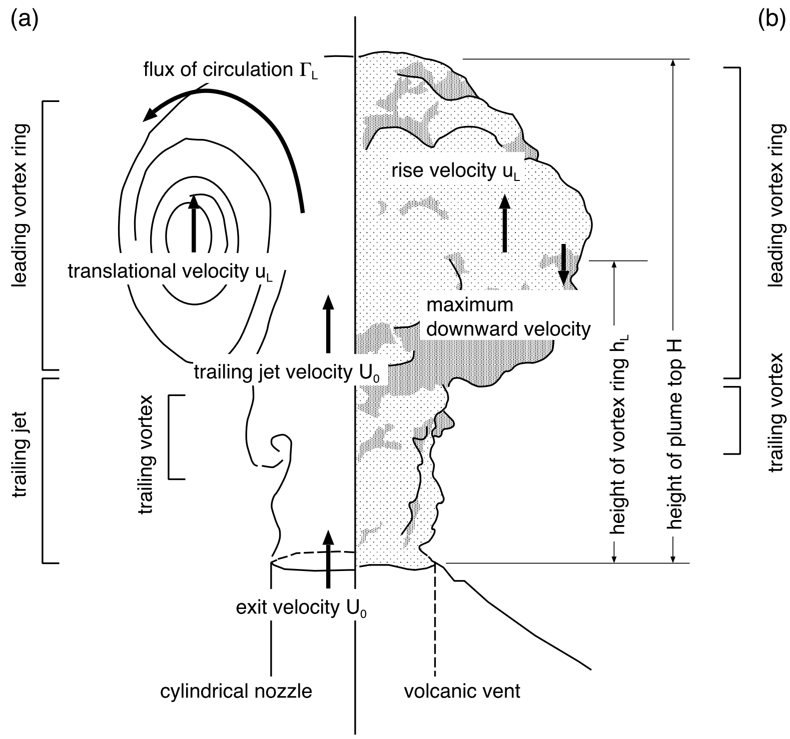

Fig. 1. Schematic images of (a) vortex ring generated by fluid ejection from the nozzle and (b) vortex structure of a volcanic plume. Details of each sign are described in the text.

Dynamics of volcanic plumes can be deduced from observations of the vortex structures of the plumes. Andrews and Gardner (2009) measured the sizes of several hundreds of vortices from still images for two periods of the Mt. St. Helens 1980 eruption, and found that the changes of the vortex structures coincided with transitions from volcanic plume to column collapse regimes. In the initial ascent stage of a plume, a mushroom-like vortex structure, which is one of the most remarkable structures of a plume, is observed at the plume front (e.g., Patrick, 2007). It is well known in engineering that this structure, called a "vortex ring," is formed in a starting jet. Many experimental studies have shown that the motion of a vortex ring depends on the exit velocity of the jet at a nozzle (Didden, 1979; Gharib et al., 1998). The plume front velocity has been proposed as relating to the mean velocity of the steady plume which follows behind the cap of the plume. Based on the theoretical and experimental study of Turner (1962), the front velocity is approximated 61% of the mean velocity v_m. Estimated mean velocities for the eruption at Soufrière volcano are in good agreement with the values calculated based on the 1-D steady model of volcanic plume dynamics (Sparks and Wilson, 1982). In order to examine the exit velocity and its time evolution, this study focuses on this vortex structure of a volcanic plume.

In this paper, we introduce a model of a vortex ring based on jet experiments in Section 2. Next, we confirm that this model is applicable to estimate exit velocity of a volcanic plume by analyzing results of 3-D numerical simulation of volcanic plumes in Section 3. In Section 4, employing the model, we estimate the exit velocity at an eruption at Sakurajima volcano. Finally, we summarize the main conclusion of this study.

2. Model of vortex ring in jet engineering

The vortex ring used in experimental studies is generated by the motion of a fluid pushed by a piston through a nozzle (e.g., Didden, 1979; Gharib et al., 1998). This generates a boundary layer at the edge of the nozzle, and the boundary layer rolls up and forms a vortex ring at the head of the fluid jet. This leading vortex ring travels downstream and grows with an increase in its circulation by absorbing vorticity from the fluid behind the vortex ring, trailing jet (Fig. 1a). The circulation is defined using Stokes' theorem for a suitable surface S bounded by the closed curve C as $\oint_C \boldsymbol{v} \cdot d\boldsymbol{l} = \iint_S \boldsymbol{\omega} \cdot d\boldsymbol{S}$, where $\boldsymbol{v}$ and $\boldsymbol{\omega}$ are the velocity field in the line element $\boldsymbol{l}$ and the vorticity field in the surface element $\boldsymbol{S}$, respectively. The leading vortex ring has a flow field characterized by streaming forward at the center, branching at the front, backward flows at the outside, and then turning back to the inside (see Fig. 1a). Similar structures of vortices to the leading vortex ring are sometimes observed in the trailing jet (Pawlak et al., 2007). These vortices, known as "trailing vortices," also travel forward with an increase in size.

Gao and Yu (2010) proposed an analytical model for a vortex ring in a starting jet. Their model (termed the GY model in this paper) assumed that: (i) the jet is ejected from a straight cylindrical nozzle with a constant velocity U_0, and (ii) a trailing jet behind the vortex ring has a velocity equaling U_0 (Fig. 1a). Under these assumptions, the flux of circulation from the trailing jet into the leading vortex ring, Γ_L, can be expressed as a function of U_0 and the translational velocity of the leading vortex ring u_L (Gao and Yu, 2010):

$$\frac{d\Gamma_L}{dt} \approx \frac{1}{2}U_0^2 - U_0 u_L. \quad (1)$$

The GY model has been proposed for the leading vortex of a starting jet in the laboratory. We need to confirm whether the GY model is applicable to the leading vortex of volcanic plumes because the characteristics of volcanic plumes are different from those of the pure fluids used in the experimental studies, such as water (e.g., Didden, 1979; Gharib et al., 1998), in terms of their higher temperature compared to that of the surrounding air. Next, in order to estimate the exit velocity during the progress of a volcanic eruption, we also need to know whether the GY model can be established for the trailing vortices that might be