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Morphological evolution of turbulent plumes : experimental approaches

Shogo Kitamura[1]; Ikuro Sumita[2]

[1] Earth Sci., Kanazawa Univ.; [2] Nat.Sci.Tech., Kanazawa Univ.

Turbulent plumes (Reynolds number 'Re' gt 1) are ubiquitous in nature, typical examples of which are volcanic plumes. There have been many laboratory experiments on turbulent plumes, in particular at steady state. For example by Kaminski et al. (2005) conducted experiments with variable source buoyancy and flux and studied whether the plumes keep on rising or lose their buoyancy and collapse. From observational side, Patrick (2007) studied the evolution of the ascending volcanic plumes using images of Strombolian ash plumes. However, there have been few attempts to characterize the shape of evolving plumes as a function of source parameters such as Re and Froude number 'Fr'. If these relations between the shape and source parameters are clarified, it may be possible to constrain the unknown eruption parameters (e.g., the initial velocities and the temperatures) by studying the time evolutions of the shape of the volcanic plumes. Here we report the preliminary results of laboratory experiments performed in order to study the time evolution of the shape of the plumes with variable Re and Fr.

A water colored with a fluorescent dye and milk (density=1.020g/cc) or a similarly colored salt water (20wt%, density=1.158g/cc) is injected downward through an orifice (ID 1 mm) into a water contained in an acrylic tank with a cross-section of 30cmx30cm and a height of 50cm. A light sheet is used as an illumination, and video images are taken using a HD digital video camera. The injecting velocity is controlled by the height of the reservoir fluid from which the colored fluid is injected, and the density is controlled by changing fluids. The resulting Re and Fr are in the range of 250-580 and 7-42 respectively. The image analyses were performed using computers, and we calculated the downward velocity, cross sectional areas, volumes (assuming axisymmetry at each height), entrainment rates etc, and studied their time evolutions. We then studied how these calculated values changes as a function of dimensionless height 'z∗'(height of plume head/the orifice diameter).

From image analysis, 3 regimes were found as a function of the elapsed time. (I)First, plumes have round heads, which we define as the 'finger like'. (II)Next, plumes transform into a shape with a linear tails and spherical heads, which we define as the 'plume with head'. (III)Finally, plumes transform to shapes like a cone, which we define as the 'cone like'. The transition of I-II and II-III occurred when the position of plume heads were adout 3-5cm and 20cm from the orifice respectively. For high Re and low Fr, the time required for a plume to descend a given distance was shorter. For low Fr, the deceleration rates of plume heads were smaller. On the other hand, the growth rate of cross sectional area and volume were found to increase at a z∗of about 30˜50, which corresponds to the I-II transition.

We calculated the bulk entrainment rate defined as (dV/dt-Flux)/Flux, and found that it approaches a constant value at a z∗of about 200, which corresponds to the II-III transition. As a measure of the shape of the cross-section, we computed (boundary length)/(cross sectional area)$^{0.5}$ and (height of the center of mass)/(height of plume head) of plumes, and found that they increase at a z∗of about 30˜50, which clearly shows that they correspond to the I-II transition. We suggest that this result arise from the volume expansion of plume head caused by the combined effects of the rapid deceleration, and initiation of entrainment under a continuous fluid supply from the source. In addition, we calculated the variation of tail length of plumes, and found that it becomes constant at a z∗of about 100-130 and that its average value decreases with the Re. We can thus subdivide the regime II into two regimes at this height.

Our experiments suggest that it may be possible to estimate Re and Fr, from determining the height of transition of the 3 regimes from the plume images.