ESF short visit scientific report

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Purpose of the visit

The scientific report presented hereafter involves two young scientists from institutes within in the MeMoVolc Network, both in ESF contributing countries: Matteo Cerminara from SNS–INGV (Pisa, Italy), and Sébastien Valade from LMV (Clermont-Ferrand, France). Both teams study the dynamics of volcanic ash plumes, yet with different approaches: the first develops sophisticated mathematical models to understand the physics of rising ash plumes, while the second uses a variety of remote sensing tools to monitor them.

Aim of the short visit. "Modern physical volcanology is situated between two different research approaches: multidisciplinary data acquisition in field and laboratory settings, and analytical and computer-based multi-parameter modelling", Neuberg (2006). The aim of this exchange is to bring together the two approaches outlined in the above comment, by combining the remote sensing data of LMV with the numerical codes of INGV. The recent MeMoVolc summer school held in Nicolosi has enabled us to confront our respective methods and results, and has suggested that these could readily interact to provide positive feedbacks for both parties. Let us first briefly describe the work of both parties, and the way these could interact to enhance our understanding of volcanic plumes.

The Data and Models before the short visit.
DATA (LMV): Small, short-lived, Vulcanian ash plumes were imaged at Santiaguito (Guatemala) using an infrared thermal camera. Automated algorithms were then developed to analyze the video sequences, and extract key parameters to characterize the ash plumes, such as ascent velocities, volume, spreading rate, air entrainment coefficient, heat budget, and ash mass loading. The data obtained from these algorithm now require comparison with physical models.
MODELS (INGV): Analytical mean Plume models (e.g., [7]) are intended to capture the "zero order" behavior of multiphase gas-ash Jets and Plumes (turbulence is filtered, no fluctuations are modeled). In this way the complex thermo and fluid dynamics of the 4 dimension system reduces to a 1 dimensional one. This procedure together with statistical techniques, allows us to invert the problem and to measure indirectly some plume parameters from experimental data.

The interaction to come between the Data and Models. We intend to confront the data recorded by the cameras with the data expected from mean plume models (e.g., compare the measured velocities, temperatures, densities, etc., with those predicted from the theory). This may involve inversion procedures to find the best-fit between measured and modeled data, and in turn derive crucial information such as the ash mass content within the plume, the air entrainment coefficient, the particle size distribution, etc. The end objective is to define the most efficient way to provide a quantitative assessment of key source eruptive terms (i.e. eruptive mass flux, particle size distribution, plume height and emission duration) from video data analysis. Indeed, these are crucial parameters needed by Volcanic Ash and Transport Models (VATD) to forecast the ash propagation downwind over hours to days, and thus assess the potential hazards during volcanic crisis.

Description of the work carried out during the visit

In the first couple of days we described each other our research work in order to deepen the knowledge of the tools used either to make all the measures and to write the models. Clarified our methodologies, we decided the tactics we would follow and we scheduled them in a number of key points.

We decided to focus our work on the use of the 1D mean models, and their interactions with geophysical data:

- To understand clearly the models underlying hypothesis – where and when we can use them?
- To solve the forward model in order to find analytical solutions as general as possible.
- Having the evolution of all the variables, to simulate the observed IR electromagnetic radiation.
- To compare it with IR camera data by the inversion of the model, obtaining the initial parameters, in particular:
    - total ejected mass both for the solid and gaseous phase
    - information on the particle grain size distribution

The main assumptions. The purpose of 1D plume theories is to model the mean behavior of a fluid's flow into another through an inlet, usually point or circular like. The fluid can be just one (mono-phase) or a mixture (poly-dispersed), it can be sustained by its initial inertia (jets), by its buoyancy (plumes) or by both (forced plumes). While the dynamics of these kind of phenomena is largely driven by turbulence (cf. Fig. 1a), averaging techniques allow us to find a mean solution, describing just the averaged evolution, and filtering all the turbulence fluctuations (cf. Fig. 1b). This procedure introduce an important empirical parameter, called the entrainment coefficient. It relates the axial plume velocity to the radial velocity of the entrained fluid.

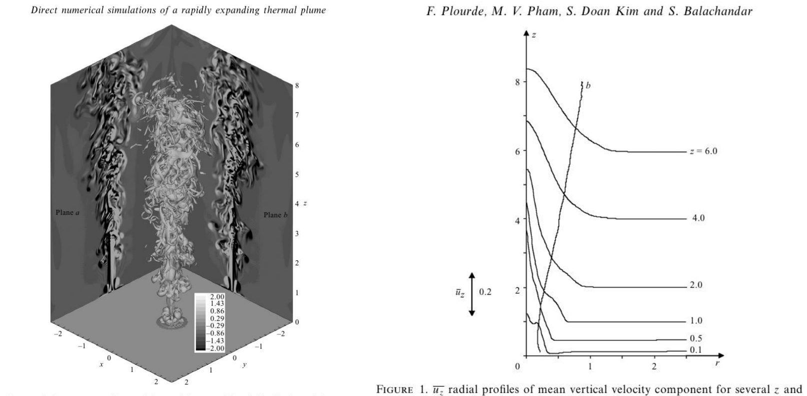

FIGURE 4. Instantaneous iso-vorticity modulus $\Omega = 3.0$ and distribution of the two components Ω_x, Ω_y in two planes at $x = 0$ (plane a) and $y = 0$ (plane b), respectively.

FIGURE 1. $\overline{u_z}$ radial profiles of mean vertical velocity component for several z and evolution of b plume radius, deduced from Gaussian fitting, with z.

Figure 1: (left) Instantaneous iso-vorticity surfaces from the plume simulation [11]. (right) Averaged vertical velocity field, where we visualize the definition of the plume radius (b) as coming out from Gaussian fits.

As a first step we ordered all the underlying hypothesis that stand behind these kind of models, by comparing the existing literature on this topic. Here we report all the assumptions needed.
We started from the Dusty Gas model (cf. [1]), i.e. the conservation laws of mass, momentum and energy for a mixture. In order to use it we have to assume:

- Local equilibrium.
- All the phases, either solid or gaseous, move with the same velocity field $u(x,t)$. [1] shows that this assumption it is valid even for the solid phase if the Stokes time $\tau_p \equiv \frac{\hat{\rho}_p}{\hat{\rho}} \frac{d^2}{18\nu}$ is small compared to the smallest time scale of the evolution problem.
- All the phases, either solid or gaseous, have the same temperature field $T(x,t)$. [1] shows that this assumption it is valid even for the solid phase if the thermal relaxation time $\tau_T = \frac{\hat{\rho}_p C}{k_p} \frac{d^2}{4}$ is small compared to the smallest time scale of the evolution problem.

Here we are interested in the mean behavior of a turbulent buoyant plume. Writing that solution we used the following assumptions (cf. [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]):

- Reynold number is big enough and turbulence is fully developed, so that will be possible to disregard thermal conduction and shear dissipation.
- Pressure is constant in horizontal section.
- The profiles of mean vertical velocity and mean density in horizontal sections are of similar form at all heights (Gaussian profiles).
- The mean velocity field outside and near the plume is horizontal. We will need to make additional assumption on the dependence of the rate of entrainment at the edge of the plume to some characteristic velocity at that height.
- Stationary flow.
- Radial symmetry around the source.

Description of the main results obtained

Having all the hypothesis allows us to start from the standard balance equations of mass, momentum and energy to get our 1D multiphase plume model, to be applied to eruption columns. We did all the steps carefully, obtaining a set of equations very similar to those obtained by [7] on his important paper. Importantly, this new set of equations obtained describes the model in a compact and non-dimensional way:

$$
\begin{aligned}
q' &= \eta \sqrt{\frac{m(\phi f + q)(q - q_1)}{q(q + (\chi - 1)q_1)}} \\
m' &= \frac{qf}{m}\left(1 - \gamma \frac{(\phi f + q)}{f[q + (\chi - 1)q_1]}\right) \\
f' &= -\lambda_\alpha(\phi f + q)\ln(h_\alpha)' + \frac{H_K}{C_\alpha T_\alpha}\frac{m^2 q'}{q^2} - \frac{H_g}{C_\alpha T_\alpha}\frac{(\phi f + q)(q - q_1)}{q + (\chi - 1)q_1}\,,
\end{aligned}
$$

where q is the mass flux, m is the momentum flux and f is a modified buoyancy flux. Then we have terms related to stratification, Kinetic energy, and gravitational potential energy. Here η is a parameter depending on the kind of entrainment assumption done.

The model in this form is derived here for the first time, it is compact and shows clearly the key parameters driving the plume behavior: ϕ represents the non-Boussinesq behavior, q_1 measures the relative flux of ejected material, χ is the relative thermal capacity, γ is the stability of the column ($0 < \gamma < 1$ the column does not collapse). These equations contain a number of famous models readable in the literature, e.g.:

- If $\phi = q_1 = \gamma = 0$ and $f = 1$ we find again the model in [2].
- If $q_1 = \gamma = 0$ and $f = 1$ we find again the model in [8].

We want to apply this model to Santiguito's eruptions (cf. Fig. 2), where the "weak plume" regime ($q \gg \phi$, q_1 and $f = 1$) holds and additional approximations are possible. In this way, we can solve the former differential problem to find an analytical solution: $q(z) = K_1(\gamma)\, z^{\frac{5}{3}}$, $m(z) = K_2(\gamma)\, z^{\frac{4}{3}}$, $f = 1$. Now we have a model as simple as the Morton's one, but which takes into account the influence of the ash particles.

This solution gives us the plume radius and the value of the velocity, temperature and density fields in all the point of the domain. We put this information into the standard Schwarzschild's equation to get the IR intensity emitted by the plume:

$$
I(L) = I_0\, e^{-\tau_L} + \int_0^L K(s)B(s)\, e^{-\tau(s)} \mathrm{d}s
$$

where

- $\tau(s)$ is the optical path, depending on the density and on the absorption coefficient of the plume

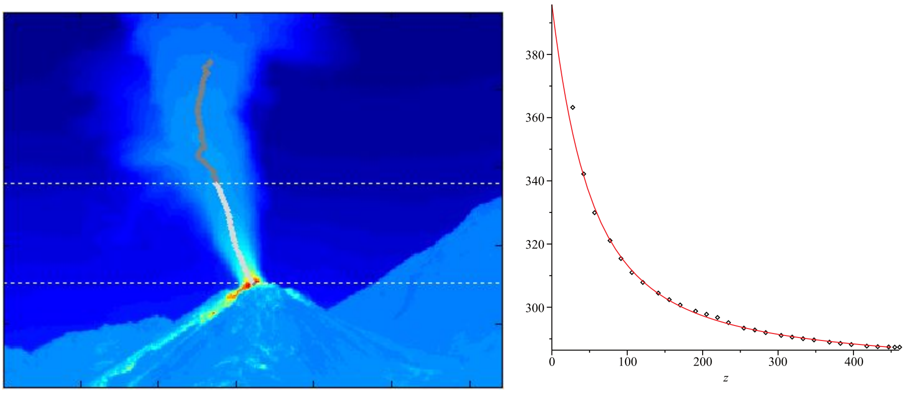

Figure 2: (left) Mean image of an eruption at Santiaguito during the stationary flow: pixel values are evaluated averaging their temperature values over the stationary period. (right) Axial temperature (°K) versus axial position (m) fitting: observation (points) versus model (line).

- $K(s)$ is the plume absorption coefficient
- I_0 is the background atmospheric radiation
- $B(s)$ is the Planck function, depending on the wavelength, on the emissivity and on the plume temperature

Now, we have the possibility to simulate the measured IR intensity (and the corresponding measured emission temperature) creating theoretical IR images of the emitting plume. The last stage of our analysis has been to compare these synthetic images with the experimental one (cf. Fig. 2a), by inversion techniques (cf. Fig. 2b).

Conclusions. To give an example, using this procedure to the eruption of Fig. 2, we get the following results:

- Ejected solid mass: $(1.3 \pm 0.2) * 10^5\,\mathrm{kg} \Rightarrow$ mass flow: $620\,\mathrm{kg/s}$ over $3.5\,\mathrm{min}$
- Particle size distribution: $r_{\text{particles}} \in [0.01,\ 1]\,\mathrm{mm}$
- Ejected gas mass: $1.9 * 10^5\,\mathrm{kg}$

Our methodology is: fast (the analytical formulation allows fast calculations $\simeq$ minutes) and robust (little sensitivity of the solid mass flow from the other parameters because of strong thermodynamics constraints). For these reasons, the developed methodology has strong potential application to real-time estimation of the solid mass flux and the particle size distribution.

Future collaboration with the host institution

We intend to continue the collaboration between our institutions working both on the model and the data part: firstly we want to improve our inversion algorithm which, at the moment, is very good in the axial direction but has some problem in the radial one. Indeed, we need a better atmospheric model in order to precisely predict the behavior of the plume edge. Secondly we want to apply our methodology to different volcanoes. For this reason, we are organizing a field campaign in the Sakurajima volcano, after the IAVCEI 2013 scientific assembly. Lastly, we intend to set up a controlled laboratory experiment to simulate a rising hot plume. In this way, we will have a precise control on the particle grain size and mass flux. When measuring this analogue experiment with IR cameras, and applying the developed methodology, we will be able to test its effectiveness.

Projected publications

We are working on three papers dealing with the different parts of the described study. The first describes the imagery data processing technique, which is made available through an open-source Matlab software. We plan on submitting this publication to Computers and Geosciences in May 2013 [16]. Another will describe the model assumptions and its development. The last one will apply the 1D plume model to the electromagnetic IR theory in order to get synthetic images to be used in the inversion algorithm. We will then apply our procedure to different eruption and we will discuss the obtained results. These results will be presented in two international conferences: [17], [18].

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