MeMoVolc Short visit Report –L. Pioli
MODELING ANALOG EXPERIMENTS IN TWO-PHASE FLOW

Short visit to the Osservatorio Vesuviano, Naples, Italy, 3-18 July 2012, collaboration with Dr. G. Macedonio

1. Purpose of the visit:

Original project outline
The main goal of the proposed project is to model the conduit two-phase flow regimes developing at shallow depth at open conduit basaltic volcanoes. Specifically, we will analyze the evolution of the *properties of the flow and stability of flow regimes* expected for low viscosity magmatic flows in vertical conduits, and their effect on the eruption style and explosivity. The model will couple theoretical considerations and experimental evidences. The complementary expertise of the two researcher involved in the project is fundamental; in fact dr. Macedonio will provide the necessary skills in numerical modeling and dr Pioli the experimental capabilities.

2. Description of the work carried out during the visit:

We have implemented the model describing the outgassing of basaltic magma at shallow conditions developed by Pioli et al (2012) based on theoretical studies validated by experimental data, incorporating the conditions for two-phase flow regimes stability, which are essential to the calculation of the flow parameters, as explained in the project proposal.
Separated two-phase flow regimes (bubbly, slug, annular and churn) can be analyzed in terms of the size distribution of gas bubbles in the flow. The bubble size depends on the combination of coalescence and breakup processes, regulated by bubble interaction and instability. In basaltic magmas, we expect very efficient coalescence due to the dynamic interaction between the moving bubbles and the very large conduit length to bubble size ratio L/d_b. The effect of bubble breakup due to turbulence is also negligible (due to low Re), and bubble size will be mainly limited by surface instabilities. For this reason, we can expect that the bubble population will converge to the maximum stable diameter size.
This aspect in particularly relevant for bubbly and slug flow regimes stability because it can prevent the formation of Taylor bubbles (gas slugs) in large conduits.
The formation of Rayleigh –Taylor instabilities at the interface between gas and liquid was experimentally studied by Clift et al (1978). Primarily, the critical bubble diameter depends on the wavelength of the surface instability that cannot be suppressed by surface tension. The wavelength should be smaller than half of the circumference of the bubble and the growth rate of the instability should be faster than the time available for growth, which depends on the terminal velocity of the bubble. Batchelor (1987) provided a simplified mathematical solution for this problem, which has been analyzed also through numerical modeling by Suckale et al. (2010). In our work, we have adopted this model, also incorporating the corrections proposed by James et al. (2011). In fig. 1 we show the maximum bubble diameter in basaltic magmas with viscosities ranging from 1 to 2500 Pas, density of 2600 kg/m^3, surface tension of 0.4 N/m. The results can be well fitted by an exponential function, which can be used to extrapolate the maximum stable bubble diameter for larger

viscosities. This function can be directly used to calculate Eotvos number (Eo) for the flow (Fig. 2)

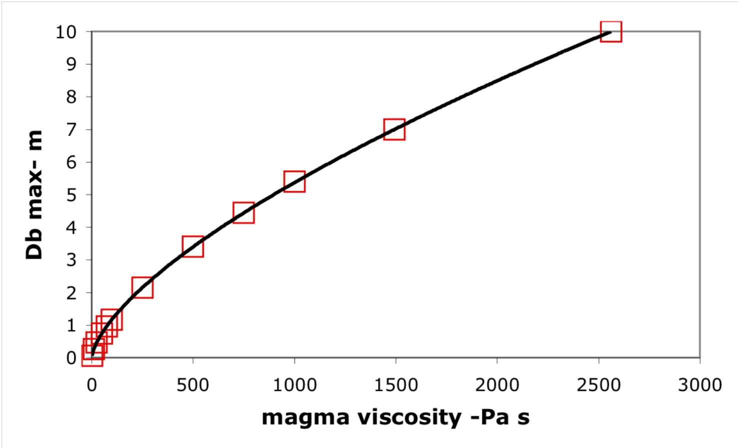

Fig. 1. Variation of the maximum bubble diameter for different basaltic magma viscosities (magma density 2600 kg/m^3, magma surface tension 0.4 N/m). The curve can be fitted with an exponential relation of the type $D_b=K\eta_l^a$ (black line).

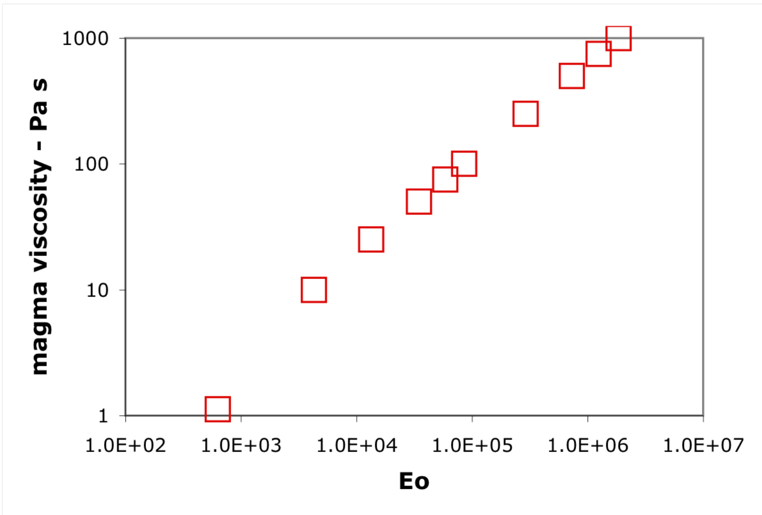

Fig. 2. Variation the Eotvos number (Eo) for different basaltic magma viscosities (magma density 2600 kg/m^3, magma surface tension 0.4 N/m).

We have then recalculated, taking into account these results, the relevant flow parameters (C_0 v_{gd} and average void fraction or vesicularity) for magma outgassing at stationary conditions, for a range of gas flow rates and viscosities, which have allowed us to define more precise stability conditions for bubbly and slug flow. We propose the same approach of Pioli et al. (2012), based on the drift flux theory and calculated the void fraction as the ratio between the gas volume flux and the average gas velocity.

$$\varepsilon_g = \frac{u_{sg}}{C_0 \cdot u_{sg} + v_{gd}} \qquad 1)$$

Where u_{sg} is the gas superficial velocity (gas volume flux normalized to the conduit cross section area), and $C_{o,}$ is a dimensionless parameter describing the shape of the velocity profile across the flow and varies with Eotvos number:

$$C_0 = 2.29\left[1 - \frac{20}{Eo}\left(1 - e^{-0.0125 Eo}\right)\right] \qquad 2)$$

and the bubble terminal velocity is

$$v_{gd} = K_1\left(\frac{\sigma\ g\ (\rho_l - \rho_g)}{\rho_l^2}\right)^{0.25} \qquad 3)$$

for bubbly suspensions, with K_1 = 1.53 (Harmathy, 1960). The terminal velocity of the gas slug varies with the square root of the conduit diameter:

$$v_{gd} = Fr\sqrt{gD_p} \qquad 4)$$

With Froude number Fr = 0.351.

We have then calculated the expected gas holdup during eruption conditions (i.e. when the liquid flow rate is >0). This requires modification of equation 1 which becomes:

$$\varepsilon_g = \frac{u_{sg} + u_{sl}}{C_0 \cdot u_{sg} + v_{gd}} \qquad 5)$$

where u_{sl} is the liquid superficial velocity.

3. Main results

The model we developed shows that the vesicularity of the degassing column is independent of magma viscosity and conduit diameter when conditions for stability of bubbly flow are met (at a first approximation, for conduit diameters larger than 10 m for low viscosity basalts, and larger than 30 m for higher viscosities, fig.3), but varies with conduit diameters for slug flow regimes, i.e. for smaller conduit diameters (fig.4).

It is also interesting to notice that the shape of the curves for the two flow regimes differ relevantly: larger vesicularities and a faster transition to churn and annular flow (predicted by the asymptotic portion of the curves) are expected for initial bubbly flow regimes. This is due to the fact that the gas rise velocity is lower for a dispersion of small bubbles than for gas slugs, resulting in a larger gas holdup.

The largest stability of slug flow (up to gas superficial velocities >10 m/s, several times larger than the expected values at passive degassing volcanoes, as shown in Pioli et al., 2012), can explain the particularly stable conditions observed at persistently active strombolian volcanoes. In particular, annular flow conditions are expected only at large conduits or very low viscosities (of the order of a few Pa s).

When we consider eruptive conditions, the effect of liquid flow is relevant to the stability of flow regimes as the curves rapidly converge to the asymptotic trend suggesting annular flow conditions (fig. 5 and 6).

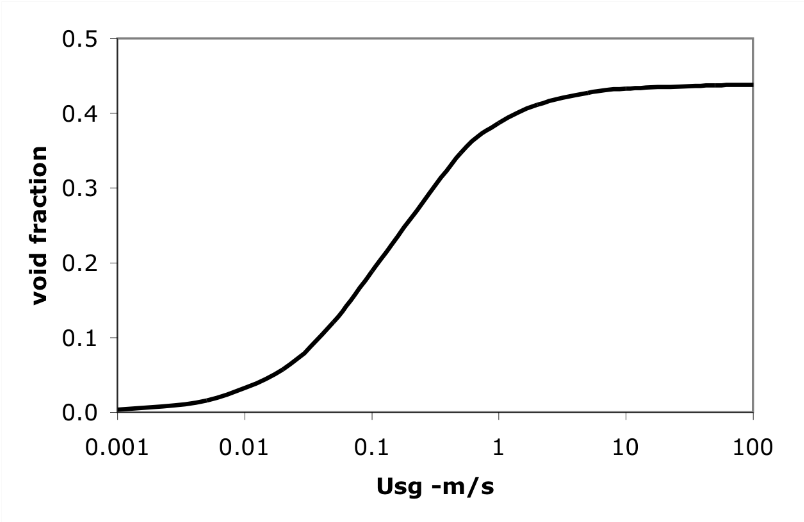

Fig. 3. Computed variation of the average void fraction with gas superficial velocity (Usg= Q_a/A) in outgassing basaltic magma column. Bubbly to annular flow conditions, conduit diameters larger than 10 m for magma viscosities of 250 Pa s or lower, and larger than 30 m for magma viscosities comprised between 250 and 1000 Pa s.

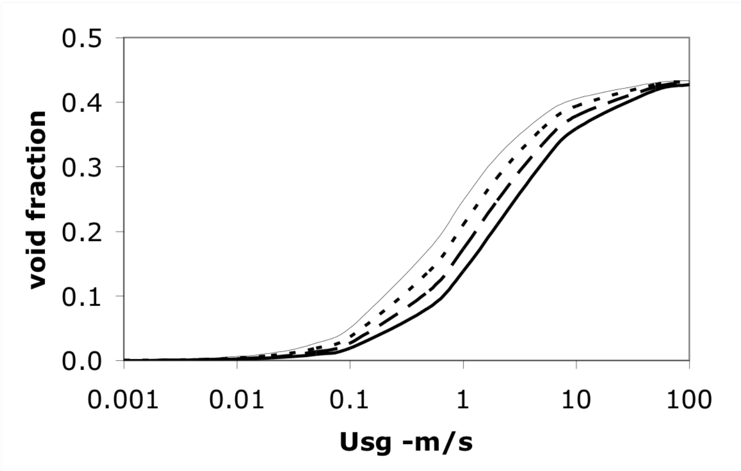

Fig. 4. Variation of average void fraction with gas superficial velocity (Usg= Q_a/A) in outgassing basaltic magma column for slug to churn flow conditions, which are assumed when the conduit diameter $>5D_{b, max}$. Thick line: D_p=20 m, long dashed line: D_p=10 m, short dashed line D_p=5 m, thin line: D_p=2.5 m.

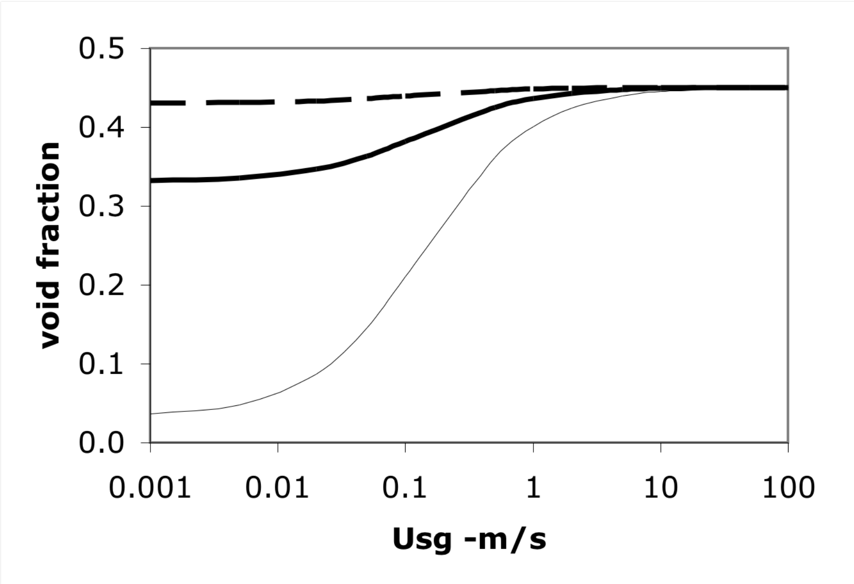

Fig. 5. Variation of average void fraction with gas superficial velocity (Usg= Q_a/A) for magma superficial velocities of 0.01 m/s (thin line), 0.1 m/s (thick line) and 0.12 m/s (dashed line) for bubbly to churn and annular flow conditions.

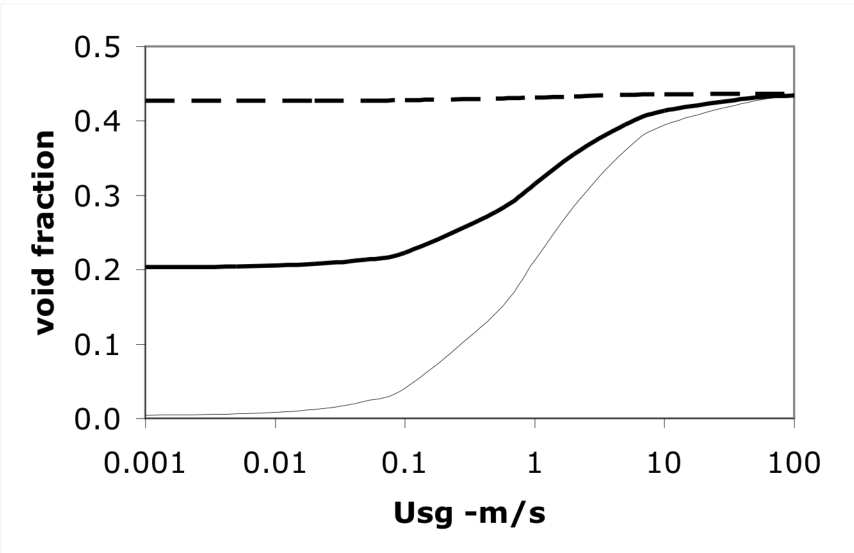

Fig. 6. Variation of average void fraction with gas superficial velocity (Usg= Q_a/A) for magma superficial velocities of 0.01 m/s (thin line), 0.5 m/s (thick line) and 1.05 m/s (dashed line) for slug to churn and annular flow conditions. D_p= 5 m.

4. Future collaboration and expected publications:

We are planning to refine the model with experimental data on the stability of large bubbles in cylindrical conduit. The experiments are essential to test the validity of the simplification adopted in the Suckale et al. (2010) model. The experiments will be done at the Fluid dynamics laboratory at the Department of Mineralogy of the University of Geneva. The results will be described in a paper whose submission is anticipated for the end of this year.

Notation

A=pipe cross section area (m^2)

C_0=distribution parameter

D_p=conduit diameter (m)

d_b=bubble diameter (m)

$d_{b,max}$=maximum stable bubble diameter (m)

Eo=Eotvos number=$g(\rho_l-\rho_g)d_b^2/\sigma$

Fr=Froude number= $v_{gd}/(gD)^{0.5}$

L= conduit lenght

Q_g= gas volume flux (m/s)

Re=Reynolds number= $\rho_l\ d_b v/\eta$

u_{sg} = superficial gas velocity (m/s)

u_{sl} = superficial liquid velocity (m/s)

v_{gd}= gas drift velocity (m/s)

ε_g= gas volume fraction

η_l= viscosity (Pa s)

ρ_g= gas density (kg/m^3)

ρ_l=liquid density (kg/m^3)

σ= surface tension (N/m)

References

- Batchelor, G.K. (1987), The stability of a large gas bubble rising through liquid, *J. Fluid Mech., 184,* 399-422.
- Clift, R., J.R. Grace, and M.E. Weber (1978), *Bubbles, drops and particles*, Academic press, New York, 380 pp.
- Harmathy, T.Z. (1960), Velocity of large drops and bubbles in media of infinite or restricted extent, *AIChE J., 6,* 281-288.
- James, M.R., E.W. Llewellin, and S.J. Lane (2001), Comment on "It takes three to tango: 2. Bubble dynamics in basaltic volcanoes and ramification for modelling normal Strombolian activity" by J. Suckale, B.H. Hager, L.T., Elkins-Tanton, J.-C. Nave, *J. Geophys. Res., 113,* B06207*,* doi:10.1029/2010JB008167, 2011.
- Pioli, L., Bonadonna, C., Azzopardi B.J., Phillips J., Ripepe, M. (2012), Experimental constraints on the outgassing dynamics of basaltic magmas. *J. Geophys. Res., 117,* B06207*,* doi:10.1029/2011JB008392.
- Suckale, J., B.H. Hager, L.T. Elkins-Tanton, and J.C. Nave (2010), It takes three to tango: 2. Bubble dynamics in basaltic volcanoes and ramifications form modelling normal Strombolian activity, *J. Geophys. Res., 115*, B07410, doi:10.1029/2009.JB006917.

ADDITIONAL COMMENTS

Please note that the visit was done on 3-18 July 2012 and not on 2-17 July 2012 as anticipated on the proposal.