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Experimental determination of the ascent velocity of bubbles in the bubble–slug transitional regime

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Gas bubbles in magma play an important role in driving volcanic eruptions and determining eruption style. In low-viscosity systems, bubbles may have an appreciable ascent velocity through the magma within the volcanic plumbing system, enhancing bubble coalescence, and driving the system towards Strombolian activity. Consequently, the dynamics of bubble ascent has been widely studied both experimentally and theoretically. In particular, the end-member cases of unconfined bubbles (bubble radius R_b is much smaller than conduit radius R_c), and conduit-filling Taylor bubbles or slugs (R_b approaches R_c) have been the focus of much recent research. However, the transitional regime of partially confined bubbles, where 0.1 < R_b/R_c < 1 remains poorly understood.

To address this knowledge gap, analogue experiments were performed to quantify the ascent velocity of bubbles through Newtonian liquids in cylindrical pipes in the transitional regime of confinement. Four transparent, Plexiglas pipes were used (R_c = 32, 66, 100, and 152 mm) filled with liquids of four different viscosities and densities: water, vegetable oil, dilute golden syrup and pure golden syrup. A syringe was used to inject a determined volume of air, forming one single bubble at a time. The bubble ascent was recorded with a digital video camera. Via image analysis techniques, the bubble's diameter as well as its ascent velocity are quantified with their uncertainties.

Scaling is achieved through four dimensionless parameters: the Froude number, which is a dimensionless velocity; the inverse viscosity, which is a buoyancy Reynolds number; the radius ratio R_b/R_c ; and the Eötvös number, which describes the balance between buoyancy and surface tension stresses. Parameter values were chosen to cover the range expected in natural volcanic systems. Results obtained are plotted as Froude number against radius ratio. In the limits of low and high radius ratio, the well-known results for unconfined and slug regimes are recovered; in the transitional regime, these asymptotic values are linked by a smooth, nonlinear relationship. A systematic dependence on inverse viscosity is observed.

Further, experiments are compared with numerical results obtained with a two-phase incompressible fluid model, solved using a volume of fluid (VOF) method from the OpenFoam suite. The experimental data verifies the accuracy of the numerical model, which is then used to extrapolate further the empirical relationship and cover the full range of conditions expected in the volcanic system and not empirically explored.

Based on numerical and experimental results, we present empirical relationships for ascent velocity of bubbles in cylindrical pipes, scaled to the volcanic case. These relationships can be used to provide a better understanding of bubble ascent dynamics in the transitional regime between unconfined bubble ascent and slug flow.