Measurements of micro-mushroom patterns in a magnetic micromixer

F. Gökhan ERGİN [1,*]

* Corresponding author: Tel.: +45 4457 8173; Fax: +45 4457 8001; Email: gokhan.ergin@dantecdynamics.com
1 Product Manager, Dantec Dynamics, Skovlunde, DK

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Fingers and mushroom patterns are common features at the interface of surface instabilities. These can be observed in different scales: large-scale examples are the remnants of supernova explosions, (Fig. 1a), nuclear detonations (Fig. 1b), hot gas and ash produced by volcanic eruptions (Fig. 1c). Smaller scale examples can be produced at home using 2 liquids with different densities (Fig. 1d). These patterns are often described by the Rayleigh-Taylor Instability (RTI), where a heavy fluid is above a lighter fluid in the presence of a gravitational field. Similar patterns can be produced with other mechanisms, as long as one fluid is forced to penetrate into another across a flat interface. For example if magneto-hydrodynamic forces are used the instability is called Magnetic Rayleigh-Taylor Instability (MaRTI).

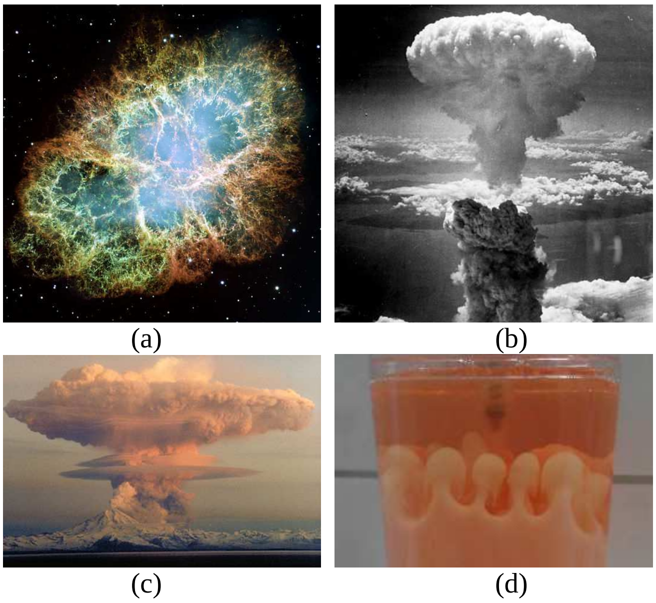

Figure 1 Examples of finger and mushroom formations observed in nature. (a) Crab nebula (b) Nuclear explosion (c) 1990 Redoubt volcano (d) Two liquids with different densities in a glass container. Image credits: Wikipedia commons

Recently, MaRTI has been the subject of several experimental studies in micro scale, where a magnetic fluid and water was forced to penetrate into each other using an electromagnet [1-5]. The first quantitative velocity field was measured using MicroPIV in combination with image pre-processing functions, such as contrast normalization and Gaussian difference filters [1]. A successful model was developed for the magnetic microconvection problem [2] based on the experimental results. In order to understand the reasons behind the formation of these finger and mushroom patterns the flow field information and the interface front is required simultaneously [3]. Time-resolved information on velocity and interface location revealed the well-known finger and mushroom patterns typical to this instability in Ref. 4 where an uncertainty analysis of the measurement was also reported [4]. Modal analysis of the MaRTI instability was performed using Proper Orthogonal Decomposition (POD) and Oscillating Pattern Decomposition (OPD) [5]. In this study we revisit the data acquired in Ref. 4 and focus on an individual finger turning into a mushroom.

MicroPIV technique has great potential in providing multi-parameter information in microfluidics research on mixing and the details of the experimental setup can be found in Ref. 4. Briefly, the Hele-Shaw cell was constructed using two cover glasses separated with a 127-µm-thick Parafilm. A magnetic fluid and deionised water was brought into contact in the cell with a relatively flat interface. Then the Hele-Shaw cell was placed in the center of the electro-magnet and the magnetic field was applied before pure solvent was mixed in the magnetic fluid. The magnetic forces were produced using an electromagnet, which produced a magnetic field strength of 1.8 mT in the central part of the coil. Both phases were seeded with 1µm Nile-red fluorescent particles with the same seeding density. Experiments are performed using a MicroPIV system consisting of an inverted fluorescence microscope, a high quantum efficiency PIV camera, a pulsed LED illumination device, a synchronization box and a system controller. Image recording, image pre-processing, MicroPIV analysis, vector processing and graphical display of results were performed using the DynamicStudio software.

In Ref. 4 both the velocity and the interface information are extracted from a sequence of time-resolved particle images. Planar velocity measurements are obtained using an adaptive cross-correlation algorithm, where particle image contrast was enhanced using image pre-processing. The use of image pre-processing functions proved to be essential: First, local contrast normalization and difference of Gaussian filters are used to enhance the particle image contrast [1]. Second, interface location is estimated using Prewitt edge detection filter together with a combination of standard image processing functions [3].

It was found that only some of the fingers turn into mushroom patterns in the presence of counter-rotating vortex system [4]. The fingers oriented in the horizontal plane (against the flow) tend to produce some mushroom patterns. On the other hand, the fingers located at the top and bottom of the FoV oriented vertically (perpendicular to the flow direction) are simply convected towards left under the influence of the main flow of the water phase. In particular, one horizontal finger close to the middle of the FoV in Fig. 8k to 8o in Ref. 4 gradually changes into a mushroom shape (Fig. 2). The thickness of the finger in Fig. 2a is approx 120µm, and this gradually turns into a mushroom shape with a size of approx 195µm (Fig 2c). The size of the transforming finger at each time step is shown next to each subfigure and the velocity vectors are placed every 20µm in Fig. 2. To the authors knowledge this is the smallest mushroom pattern measured as a result of a RTI, where quantitative flow field and interface information is available simultaneously. Motion of raw particle images, time resolved velocity field, POD-filtered flow field and the interface are available in Ref. 6. When the average flow velocity is subtracted, a counter-rotating vortex system is observed with the center of the vortex system coinciding with the centerline of the growing finger. In fact, the observed counter-rotating vortex system in the plane is the cross-sectional view of a toroidal vortex in three dimensions.

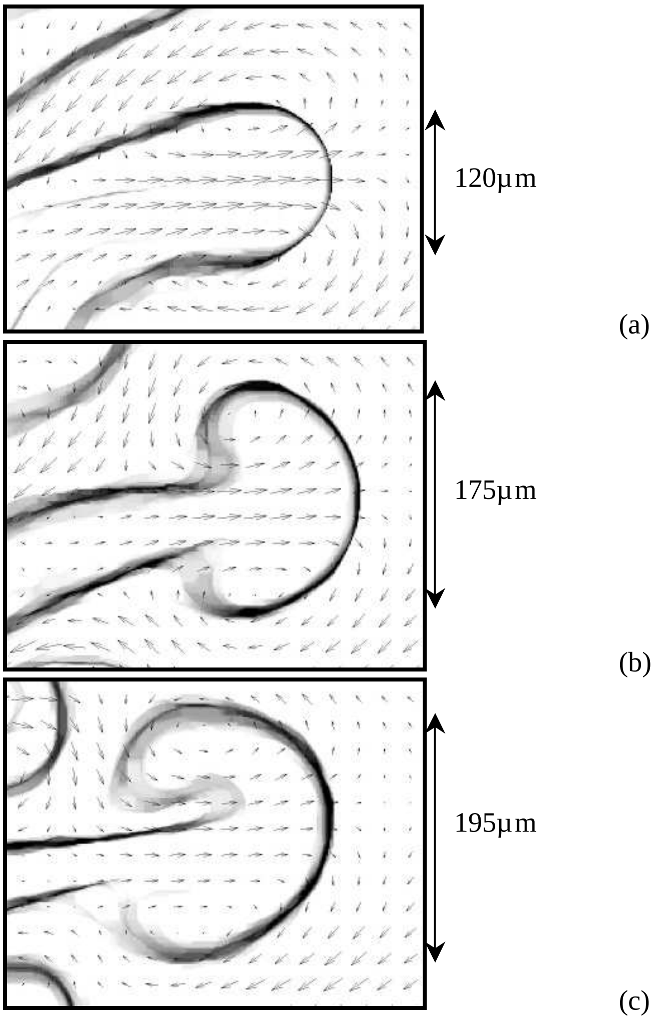

Figure 2 Flow field around an individual finger turning into a mushroom. (a) t=12.5 s (b) t=15 s (c) t=17.5 s

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