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STRUCTURED-ILLUMINATION MICROSCOPY (SIM) TO VISUALIZE BUBBLE DEFORMATION AND BREAKUP IN MINICHANNEL T-JUNCTIONS

Minami Yoda (minami@gatech.edu)
School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405

Introduction

The multiphase transport of liquid-gas mixtures through fractured and porous media is important in unconventional natural gas recovery. The goal of this research is to develop a new flow visualization method based on structured-illumination microscopy (SIM) to study the deformation and breakup of confined gas bubbles in minichannel T-junctions as a basic model of multiphase transport through pore and fracture networks. At small spatial scales, gas-liquid transport is fundamentally different from that at larger scales because surface (interfacial) tension effects are more significant, while buoyancy effects are less significant.

In many cases, studying the dynamics of the gas-liquid interface in minichannels (with hydraulic diameter $D_h <$ 2 mm) and microchannels ($D_h <$ 500 μm) requires visualizing the water-gas interface at spatial resolutions of O(1–10 μm). Although nonintrusive optical methods are usually used to minimize disturbances in these small flows, there are few, if any, visualization methods with such fine spatial resolution. In most cases, planes of the flow are obtained by "slicing" the flow with a light sheet. Since the thickness of the sheet usually exceeds 0.5 mm, however, most, if not all, of the flow is illuminated. Although only the features within the focal plane (with thickness as small as 0.5 μm) are in focus in such a flow image, the unfocused signal from features beyond the focal plane "contaminates," and in most cases greatly reduces the signal-to-noise ratio (SNR) of, the image.

The specific research objectives of this project are therefore to:

- Implement and evaluate SIM techniques that only require two images to reconstruct and *isolate* (*i.e.*, "optically section") a single "slice" of the flow with a thickness comparable to δz
- Optimize the structured illumination and image characteristics for SIM
- Use SIM to visualize air-water flows through a minichannel T-junction, focusing on confined bubble breakup.

This year, double-exposure SIM[1] was implemented and used to improve the spatial resolution of particle tracking velocimetry (PTV) in minichannel flows because of funding deadlines for a grant from the Army Research Office. Visualization of air-water flows and bubble breakup through a T-junction will therefore be the focus of 2019–20 efforts (a one-year no-cost extension was granted by PRF for this grant).

Personnel

A Ph.D. student in Mechanical Engineering (ME), Mr. Michael Spadaro, started this project in September 2017, and has spent the last year working on double-exposure SIM. Mr. Spadaro passed his doctoral qualifying examinations in November 2018.

Current Status

The two-image SIM approach called double-exposure SIM combines two "raw" images, which are both illuminated by light with a sinusoidally varying intensity at the same frequency with a phase shift in the illumination between the images. The actual slice is then reconstructed using a Hilbert transform of the difference between these two images.

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[1] X. Zhou, *et al*. (2015) Double-exposure optical sectioning structured illumination microscopy based on Hilbert transform reconstruction. *PLOS One* **10**(3):e0120892

The current double-exposure SIM system (Fig. 1) uses the illumination from a 7 W plasma lamp passing through a spike filter (transmission band wavelengths $\lambda = 480 \pm 10$ nm) and a digital micromirror device (DMD) to create a sinusoidally varying intensity profile (spatial frequency = 0.0185 μm^{-1}) (*cf.* Fig. 2 [*left*]) whose phase was shifted by π between the first and second images. Images were acquired of 4.8 μm diameter fluorescent polystyrene (PS) particles embedded in a block of a transparent gel (Carbopol) sandwiched between glass microscope slides which was sheared by displacing one of the slides by ~50 μm. Images of the embedded particles before and after shearing the block were recorded by an intensified CCD camera. The particle displacements obtained from the images reconstructed with double-exposure SIM $\Delta x = 5.7 \pm 0.89$ μm (from 11 particles with displacements of 4.6–7.2 μm); $\Delta x = 5.5 \pm 2.3$ μm (from 41 particles with displacements of 0.48–9.4 μm) for the images obtained from illuminating the entire block. Assuming that shearing the block leads to particle displacements that vary (nearly) linearly with the distance between the slides from 0 to 50 μm, these initial results indicate that double-exposure SIM can successfully image (*i.e.*, isolate) particles within a thin slice of the block.

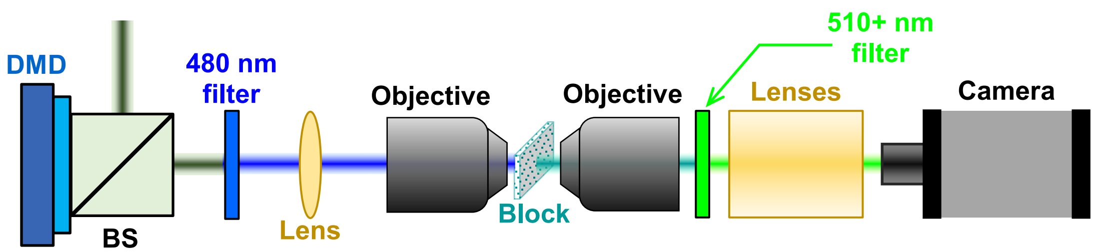

Figure 1 The double-exposure SIM setup (BS = beamsplitter cube).

Figure 2 A "raw" image of 4.8 μm PS particles embedded in the Carbopol block illuminated by a sinusoidally varying intensity profile [*left*], a reconstructed image of the same particles using double-exposure SIM [*center*], and a "raw" image of the same region obtained by illuminating the entire block [*right*]. The center and right images have been processed so that all pixels with grayscales below a threshold value are considered "background" and reset to a grayscale value of zero (black). All three images have a physical field of view of 245 μm square.

Mr. Spadaro is currently studying laminar fully-developed Poiseuille flow through a 0.5 mm square glass minichannel, and will be presenting his results this November at the 72nd Annual Meeting of the American Physical Society Division of Fluid Dynamics (APS/DFD). We plan to compare our experimental results, once obtained, with those from the group at the Delft University of Technology (the Netherlands).[2, 3]

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[2] C. Haringa, *et al.* (2019) Breakup of elongated droplets in microfluidic T-junctions. *Physical Review Fluids* **4**(2):024203
[3] D.A. Hoang, *et al.* (2013) Dynamics of droplet breakup in a T-junction. *Journal of Fluid Mechanics* **717**:R4