PRF# 57789-ND9

Structured-Illumination Microscopy (SIM) to Visualize Bubble Deformation and Breakup in Minichannel T-Junctions

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

Introduction

Unconventional natural gas recovery involves the multiphase transport of water-gas mixtures through fractured and porous media. 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 gas bubbles confined in minichannel T-junctions as a basic model of multiphase transport through pore and fracture networks. A minichannel is a channel with a hydraulic diameter D_h less than the capillary (Laplace) length scale, typically about 2 mm for air-water interfaces. Gas-liquid transport at these spatial scales is fundamentally different from that at the macroscale because surface (interfacial) tension effects play a major role.

Experimentally quantifying the dynamics of the gas-liquid interface in minichannels requires visualizing and tracking the water-gas interface at spatial resolutions of 10 μm or less. Yet there are very few flow visualization methods with such fine spatial resolution. Nearly all methods use laser light sheet illumination to obtain 2D "slices" of the flow at a resolution determined by the thickness of the light sheet, which typically exceeds 0.5 mm. So most, if not all, of the channel is illuminated when visualizing mini- and microchannel (where $D_h < 500$ μm for a "microchannel") flows, including those in T-junctions. Although only the features within the focal plane, whose thickness is characterized by the depth of field δz, are in focus in an image of such a flow, features beyond the focal plane (again, because most of the flow is illuminated) are also visible the image. Such features, even if unfocused, "contaminate" the slice, contributing to the background and reducing the signal-to-noise ratio (SNR) of the images.

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
- Determine the characteristics of the images and the structured illumination to obtain optimal results for SIM
- Use SIM to visualize air-water flows through a T-junction with $D_h < 2$ mm, focusing on confined bubble breakup.

Personnel

A new Ph.D. student in Mechanical Engineering (ME), Mr. Michael Spadaro, started this project in September 2017. Mr. Spadaro, whose doctoral dissertation will be on developing SIM for quantitative flow visualization, has taken courses on optics and image processing methods, and has learned about microscopy and microfluidics during his first year.

Current Status

After some discussion, we have decided to focus on a single two-image SIM approach, double-exposure SIM, which combines two "raw" images which are both illuminated by light with a sinusoidally varying intensity at the same frequency where there is a phase shift in the illumination for the second image.[1] The actual slice can then be isolated using a Hilbert transform of the difference between these two raw images.

To date, Mr. Spadaro has designed and set up a basic optical system for generating interference fringes from a (split) laser beam to obtain structured illumination with a sinusoidally varying intensity profile, and imaged a pollen sample using this system. He has become familiar with the intensified CCD camera (Princeton Instrument PI-MAX4) that will be used for the visualizations, LabVIEW to control the timing of the SIM visualizations, and MATLAB for processing raw images and reconstructing double-exposure SIM images.

Given the temporal resolution required for SIM-based flow visualization, the structured illumination and the phase shift required for double-exposure SIM will be generated using a digital micromirror device (DMD). After discussions with colleagues in ME who work in the area of 3D printing, we have ordered a DMD system to generate the sinusoidally varying intensity profile, and shift the phase of the intensity profile within 110 μs. The proposed double-exposure SIM setup based on illumination by a light-emitting diode (LED) is shown in Figure 1.

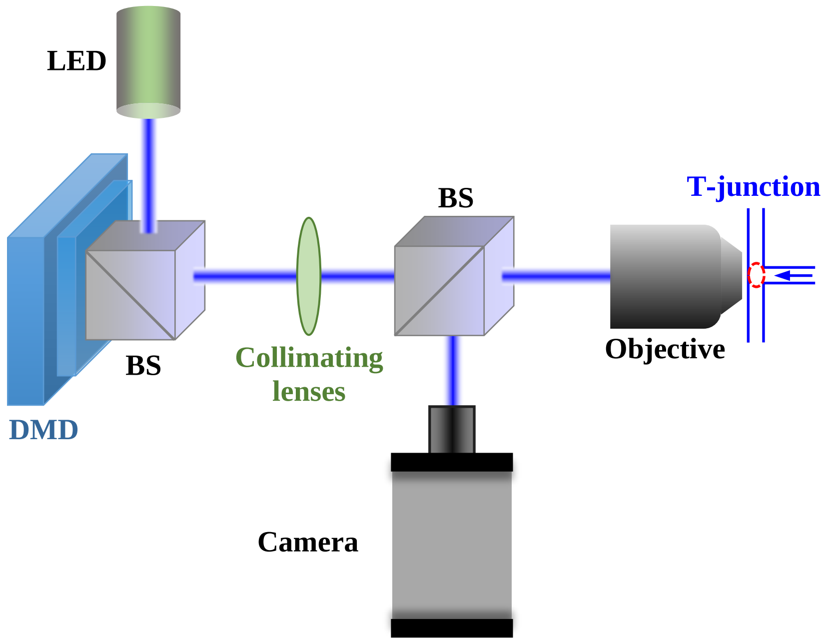

Figure 1 Sketch of double-exposure SIM setup (*cf.* Fig. 2 in Ref. [1]) for visualizing air-water flows in a T-junction. The region illuminated by the structured illumination in the flow is indicated by the red oval. The cubes labeled "BS" are beamsplitter cubes.

Mr. Spadaro is currently focused on studying for his doctoral qualifying exams at the end of October 2018. He will be giving a conference presentation on proof-of-concept SIM visualizations (of fluorescent microparticles) in November 2018 at the 71st Annual Meeting of the American Physical Society Division of Fluid Dynamics (APS/DFD) here in Atlanta.

Once double-exposure SIM is implemented, we plan to first image a bubble embedded in a clear polymer (*e.g.* Carbopol), to determine the characteristics of the raw images required to optimize the quality of the reconstructed SIM images. The air-water minichannel T-junction flow setup required to obtain SIM visualizations of the breakup or "pinch-off" of bubbles with a diameter comparable to D_h at (or near) the junction will be designed and built based on these results. Finally, the PI will meet with potential collaborators at the Delft University of Technology (the Netherlands) during the APS/DFD meeting in Atlanta to discuss comparing our experimental results, once obtained, with their numerical simulations of this flow.[2]

---

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

[2] D.A. Hoang, *et al.* (2013) Dynamics of droplet breakup in a T-junction. *Journal of Fluid Mechanics* **717,** R4.