Probing Interfacial Induced Flows and Instabilities Induced by Plasma Action at the Gas-liquid Interface

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Motivation: Plasma-liquid interactions

- Radicals and RONS produced by plasma is transported into the bulk liquid
- The transport has important implications in applications such as plasma medicine and plasma-based water purification
- Nature of radical transport via liquid-gas interface is thus important in understanding plasma-driven reactivity.
- Swirl patterns observed in previous studies can be crucial in the transport process
- Instabilities at the gas-liquid interface can be the source of the swirl currents observed

Streamers reaching liquid-gas boundary, oxidizing yellow methyl orange into an orange color, showing species transport into the bulk liquid.

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Experimental set-up
- 2D Hele-shaw-like cell enclosed a bubble in liquid between two quartz plates
- ns-pulser is used to initiate plasma breakdown
- Bubble’s gas-liquid interface is available for active interrogation such as imaging and spectroscopy measurements

DOE Plasma Science Center
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Previous work

• Using chemical probes (methyl orange), the oxidation fronts were imaged (right)
• Swirl flow patterns were observed in the streamer mode
• Speculated that swirl patterns might be caused by body forces where streamers interact at the bubble boundary
• Circulation facilitates active species transport in bulk liquid

Time-lapsed image of swirl patter observed in methyl orange solution. Streamers caused two distinct lobes of swirl currents.

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**Previous work**
- Precipitate particles were tracked in video data taken.
- Particulates flow velocity considerably sped up at the interface (suggesting circumferentially acting force present).
- Evidence of swirls transporting active species through the bulk liquid.
- Further question: what is the cause of the swirl currents?

![Graph showing particulate speed during streamer mode](image)

Particle speed and its corresponding distance from center of electrode at various time.

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Experimental set-up: Schlieren photography
- Photron Mini UX100 was used to capture the data

Light source → Concave mirror → 2D cell → Convex lens → Iris → Projection screen → Fast camera

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Results: Schlieren photography

Density gradient observed

Center electrode/ Gas inlet

Air bubble

Air bubble

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Results: Schlieren
- Gradient front is active and exhibit instability-like structure
- Area near bubble is lighter thus indicates positive density gradient region
- Dark line indicates negative density gradient region
- Gradient front remains similar distances from bubble in time
- Density gradient suggests the possibility of presence of Rayleigh-Taylor instability

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Results: Rayleigh-Taylor instability

- Instability of an interface between fluids of different densities, where the lighter fluid pushes onto the heavier fluid.
- Growth rate is usually calculated as $\gamma = (Agk)^{1/2}$, where $A = (\rho_h - \rho_l) / (\rho_h + \rho_l)$ is the Atwood number, $k$ is the wave number and $g$ is acceleration imparted on the heavy fluid [1].
- While $k$ is readily measured between visible nodes (right), the density of fluid needs to be experimentally obtained using calibrated concentration of fluorescent probes, or calibrated absorption of methylene blue; and acceleration can be estimated using PIV data if split imaging can be used to overlay PIV data on top of Schlieren imagery.

Experimental set up: Time-resolved Particle Image Velocimetry (PIV)

- PIV system from LaVision Inc. was used to measure fluid flow field (collaboration with Prof. Manera and Dr. Petrov)
- A pulsed sheet laser is used in conjunction with a timing unit to shine light on microbeads mixed in with tap water used in the test cell
- Microbeads are particles of the same density of water that reflects laser light
- Images of reflected laser light allows for the tracking of movement of said microbeads by analyzing the images taken at a time fixed interval by a fast camera

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Results: PIV
• Sharp velocity shear occurs between bubble boundary and high speed region in bulk liquid
• This extreme shear is indicative of presence of Kelvin-Helmholtz instability
• In bulk liquid, particles are pulled into the interface, accelerated along the interface and ejected back into the bulk liquid
• This fluid movement derives active species transport into bulk liquid
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Results: PIV

- Coherent vortex-like structures are evident near the interface
- Such vortices are often present in Kelvin-Helmholtz instability
- Flow field appear to be presence in area far away from interface
- Range of velocity here was between 0.5 to 3 mm/s, though it is important to note that the white area has speeds exceed that of 3mm/s

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Results: Kelvin-Helmholtz Instability

- Instability of an interface experiencing velocity shear
- Growth rate is again calculated as $\gamma = (Agk)^{1/2}$, where $A = (\rho_h - \rho_l) / (\rho_h + \rho_l)$ is the Atwood number, $k$ is the wave number and $g$ is acceleration derived from velocity shear [1]
- While $k$ is readily measured between visible nodes (right bottom), the density of fluid needs to be experimentally obtained using calibrated concentration of fluorescent probes, or calibrated absorption of methylene blue; and acceleration can be estimated using PIV obtained

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Future work

- Schlieren photography
  - Improves the resolution of images by directing images into camera
  - Improves the sharpness of images by employing a dual lens system
  - Improves the contrast of images by replacing iris with knife’s edge
  - Images initial phase of plasma formation to understand Rayleigh-Taylor instability growth rate

- PIV
  - Employs fluorescent microbeads to look at fluid flow
  - Improves the light transmission efficiency by replacing the plexiglass setup with quartz parts
  - Removes shadow of bubble by replacing the sheet laser with a collimated bottom lit laser
  - Images initial phase of plasma formation to understand Kelvin-Helmholtz instability growth rate