ME – PhD Thesis Colloquium

Shear-Dominated Flows across Spatiotemporal Scales: Fundamental Dynamics, Multiphase Interactions, and Applications

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ABSTRACT

Velocity gradients exist everywhere: at walls, between adjacent streams, across interfaces, and within the core of a vortex, and wherever they exist, shear follows, dictating how energy is dissipated, scalars are transported, and how any entrained body deforms. This thesis explores fluid shear from two distinct perspectives: as a ‘tool’ and as a ‘stressor’. In the first part, organized shear embodied in coherent vortical structures, particularly vortex rings, is harnessed for targeted transport and cleaning. In the second part, shear at the microscale is examined as a mechanical stressor acting on individual bacteria within confined microenvironments.

Fluid shear as a ‘tool’

In the first part, a vortex ring is made to impinge on perforated plates over a range of thicknesses, open-area ratios, alignments and included angles. Because the ring induces motion ahead of itself, fluid crosses the perforation before the ring does, and the shear resistance of the holes produces mushroom-like fronts near the wall downstream. These fronts carry 20–30% of the total downstream kinetic energy and, with the Kelvin - Helmholtz instability of the emerging jets, determine whether and where the ring reforms. Over included angles from 60° to 180°, the angle emerges as the dominant geometric parameter: a single ring splits into two at small angles, and reformation far downstream can be selectively suppressed. The circulation growth downstream is shown to follow a cumulative slug-flow model. The utility of this controlled energy delivery is demonstrated through vortical cleaning, where an impinging ring expunges oil trapped within a bead-based porous surface.

Next, the interaction and transport of underwater oil droplets by horizontally translating vortex rings is investigated, with relevance to submerged oil-spill mitigation. Vortex rings of varying circulation interact with oil droplets of different sizes, enabling analysis of deformation, breakup, trapping, and transport. Atomization criteria based on competing inertial and interfacial forces are identified, and the effects of droplet size and vortex strength on transport efficiency are quantified. The findings demonstrate the potential of vortex rings as hydrodynamic dispersive mechanisms for oil atomization and transport.

Fluid shear as a ‘stressor’

Now, vortex generation as a by-product of droplet pinch-off is examined in a flow-focusing microfluidic generator. Bi-directional acceleration during pinch-off generates vortex structures within the droplet and retracting ligament. Core vorticity decays inversely with time, while a slug-flow model predicts peak circulation during necking. The retracting vortex subsequently re-intensifies, sustaining shear beyond pinch-off, with smaller droplets experiencing a larger fraction of intense shear.

The biological consequence of stress is quantified for *Klebsiella pneumoniae* in capillary-like microchannels under four stress conditions set by flow rate, channel geometry and stressing time. Morphological changes and a decline in viability are observed, counter-intuitively, the stressed populations proliferate far more inside murine macrophages than unstressed controls, indicating that mechanical history enhances virulence. Repeating the experiments in nutrient-rich, nutrient-deficient and nutrient-free media isolates the mechanical cue from the biochemical one, with proliferation rising by 20–50% and shear rate, not nutrient availability, emerging as the dominant variable.

Collectively, these studies establish shear as a designable quantity: one that can be steered to clean a surface or transport a payload, and one that must be budgeted wherever living cells are handled in flow.

ABOUT THE SPEAKER

Siddhant Jain is a PhD scholar at the Department of Mechanical Engineering, Indian Institute of Science, Bengaluru, working under the supervision of Prof. Saptarshi Basu. He received his Bachelor’s degree in Mechanical Engineering from Assam Science and Technology University and his Master's degree from IIT Guwahati in Energy. His current research focuses on multiphase interactions, vortex dynamics, droplet microfluidics and bio-microfluidics.