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Electrohydrodynamic Flows: From Numerical to Experimentation

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1. Introduction: The Allure of Multi-Physics Complexity

Electrohydrodynamics (EHD) sits at the fascinating intersection of fluid mechanics and electrodynamics, where the interplay between electric fields and fluid flow gives rise to a rich spectrum of complex phenomena. These include droplet deformation and manipulation, jet instabilities, enhanced mixing and heat transfer, and the control of large-scale interfacial instabilities. The ability to actively control fluid behavior using electric fields has profound implications for a diverse range of industrial and energy applications, from microfluidic lab-on-a-chip devices and efficient oil-water separation to advanced printing technologies and smart material processing.

However, the multi-physics nature of EHD—coupling fluid dynamics, interface tracking, and electrostatics—presents formidable challenges for both numerical simulation and experimental analysis. Accurately capturing the transient deformation of interfaces, the distribution of electric stresses, and the resulting flow fields requires robust, high-fidelity computational models. Similarly, designing experiments to probe these often fast and small-scale dynamics demands sophisticated diagnostic techniques. This lecture will chart a journey through our group's integrated strategy, bridging advanced numerical modeling with cutting-edge experimentation to unravel the complexities of EHD flows.

2. A Computational Odyssey: Developing High-Fidelity Tools

Our work in EHD has been significantly advanced by the development and application of sophisticated mesh-free and mesh-based numerical methods, chosen for their inherent advantages in handling large interface deformations and complex multi-physics coupling.

- **The Smoothed Particle Hydrodynamics (SPH) Framework:** We have pioneered the development of a fully explicit, incompressible SPH method tailored for multi-phase EHD problems. This Lagrangian approach naturally handles interfacial dynamics without the need for complex interface reconstruction. Our contributions include the formulation of electrohydrodynamic forces within the SPH formalism, the development of stable time-integration schemes, and the extension to include thermo-capillary effects. This has enabled the simulation of complex scenarios such as the EHD deformation of droplets in neutrally buoyant fluids, the coalescence and break-up of leaky dielectric droplets under electric fields, and the coupled electro-thermo-capillary instabilities in multi-phase systems [1-3].
- **The Lattice Boltzmann Method (LBM) for Reactive EHD Porous Media:** For problems involving complex geometries and surface reactions, such as soot deposition and regeneration in particulate filters, we have leveraged the LBM. Our group has developed "CooLBM," a GPU-accelerated, open-source LBM code capable of simulating reactive multi-phase flows within porous structures. This approach has been instrumental in modeling the regeneration process in soot filters, where surface combustion reactions are strongly coupled with the fluid flow and electric fields used for active regeneration [4-6].
- **Machine Learning (ML) Augmentation:** Recognizing the computational cost of high-fidelity simulations, we have integrated ML as a powerful adjunct. We employ Physics-Informed Neural Networks (PINNs) and hybrid deep learning-CFD approaches to accelerate the prediction of flow fields, optimize control parameters, and model long-term processes like nanoparticle sedimentation in EHD-influenced environments [7-9].

3. Bridging the Gap: From Simulation to Experimental Validation

A core philosophy of our research is that numerical models must be rigorously validated and informed by quantitative experiments. We have established a parallel, synergistic track of experimental work to close the loop between simulation and reality.

- **Advanced Laser Diagnostics:** To probe the internal flow dynamics within droplets and jets under electric fields, we employ sophisticated laser velocimetry techniques. Our experimental setup allows for non-intrusive measurement of velocity fields inside neutrally buoyant leaky dielectric drops subjected to high-voltage AC and DC fields. This provides an unprecedented view of the toroidal and more complex flow structures that develop, serving as a direct and quantitative benchmark for our SPH and other computational models [10].

- **Controlling Interfacial Instabilities:** Beyond droplet dynamics, we explore the control of macroscopic interfacial instabilities using electric fields. Our recent work involves applying oblique electric fields to suppress or manipulate the Rayleigh-Taylor instability (RTI). This research, combining direct numerical simulation with scaled experiments, demonstrates the potential of EHD as a powerful tool for passive and active flow control in energy and environmental systems, offering a new paradigm for managing mixing and instability in multi-fluid layers.

4. An Integrated Vision: Future Directions and Synergistic Applications

The continuous dialogue between our numerical and experimental efforts creates a virtuous cycle: experiments validate and reveal shortcomings in models, while simulations provide full-field data and predictive capability that guide new experimental campaigns. This integrated approach is the cornerstone of our ongoing projects, which aim to:

- **Optimize Carbon Capture:** Using pore-scale LBM simulations to design and optimize multi-component adsorption columns for enhanced CO_2 capture, where EHD principles can potentially improve separation efficiency.
- **Revolutionize Thermal Management:** Developing novel EHD-based cooling systems for electric vehicle batteries, leveraging electro-convective effects to enhance heat transfer.
- **Master Drop Dynamics:** Fully characterizing the dynamic response and interface topology of electrohydrodynamically controlled drops for applications in advanced manufacturing and chemistry.

5. Conclusion

This lecture will present a coherent narrative of how a multi-methodological approach, weaving together state-of-the-art computational fluid dynamics (SPH, LBM), high-performance computing, machine learning, and advanced laser-based experimentation, can be harnessed to tackle the multi-scale and multi-physics challenges inherent in electrohydrodynamics. By demonstrating this journey "from numerical to experimentation," we will highlight not only the fundamental insights gained into EHD phenomena but also the pathway to translating these insights into transformative technologies for energy, environment, and industrial processes. The future of EHD research lies in this tight integration, fostering a deeper understanding and greater innovative potential.

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