ID PhD Project Details

Title: Study of Droplet Dynamics Using Experimental, Computational, and Machine Learning Methods

Principal Investigators:
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Broad Area: Fluid Mechanics

1. Abstract:

The project aims to study droplet dynamics using an integrated approach combining experiments, computational fluid dynamics (CFD), and machine learning methods. Controlled experiments will be carried out to examine droplet motion, deformation, breakup, and interactions under varying flow and environmental conditions, using high-speed imaging techniques already established within the group. CFD simulations will complement the experiments and provide detailed insight into the underlying fluid dynamic mechanisms. Machine learning techniques will then be employed to analyse the generated data obtained from the experiments and numerical simulations. This combined approach will lead to a clearer understanding of droplet dynamics and offer a robust framework for modeling complex droplet-driven processes relevant to both natural phenomena and engineering applications, including microfluidic devices.

Objectives:

- To experimentally investigate droplet motion, deformation, breakup, and interactions under varying flow and environmental conditions.
- To employ CFD simulations to understand the underlying physics of droplet dynamics.
- To apply machine learning techniques to analyse the data obtained from the experiments and numerical simulations.
- To establish an integrated experimental–computational framework for modeling droplet-driven processes in natural and engineering systems.
- The exeprimental facility, basic CFD solver and the machine learining approaches are well-established in our group; however, some modification to these exisiting technieques may be necessary. Please see https://www.youtube.com/watch?v=x6k-emUTnmA.

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2. Experimental methodology:

A state-of-the-art experimental facility at IIT Hyderabad has been developed to simulate a wide range of atmospheric conditions and relative humidities. A photograph of the facility is shown in Figure 1. This unique experimental setup features a Z-type vertical wind tunnel integrated with primary and secondary air-conditioning units, a vacuum pump, and several auxiliary components. The uniqueness of this facility lies in its capability to maintain droplets (ranging from 1 mm to approximately 1 cm) in a stationary state within the experimental test section. This is achieved by regulating the upward wind speed using a sonic nozzle valve and a vacuum pump. We will utilize shadowgraphy to visualize the overall morphology of droplet fragmentation, while deep-learning-enhanced digital in-line holography will be employed to accurately characterize the resulting child droplets. The digital in-line holography (DIH) system includes a continuous-wave laser, a spatial filtering unit, collimating optics, and a high-speed camera. After passing through the spatial filter, the laser beam is expanded and collimated before illuminating the droplet field, where it forms holograms on the camera sensor. Figure 2 presents a schematic of the convolutional neural network (CNN)-based holographic system employed for post-processing.

3. Computational approach:

In line with the project objectives, numerical simulations will be employed to investigate interfacial flows involving key microphysical processes such as fragmentation, collision–coalescence, and phase change under varying

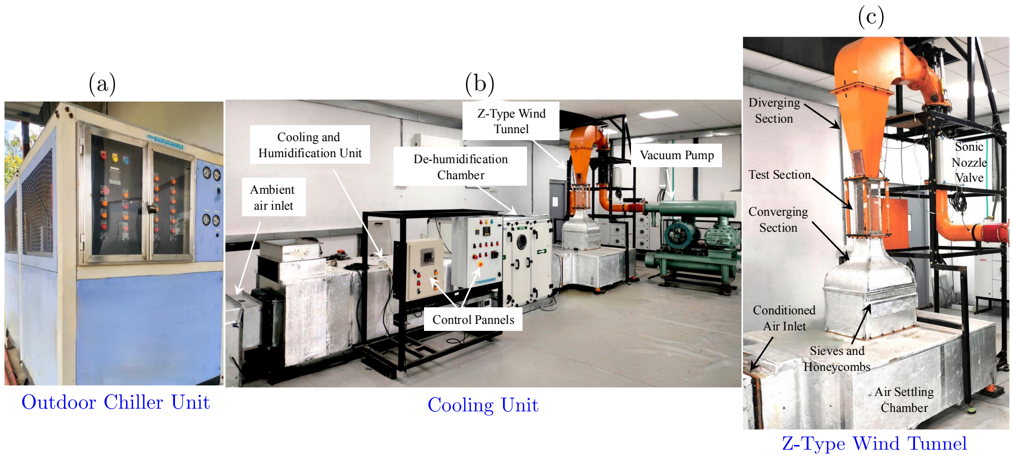

FIG. 1: A unique experimental facility at IIT Hyderabad to study the microphysics of raindrops in dynamic weather conditions. (a) Outdoor chiller unit, (b) Cooling unit and humidification and (c) Z-type wind tunnel.

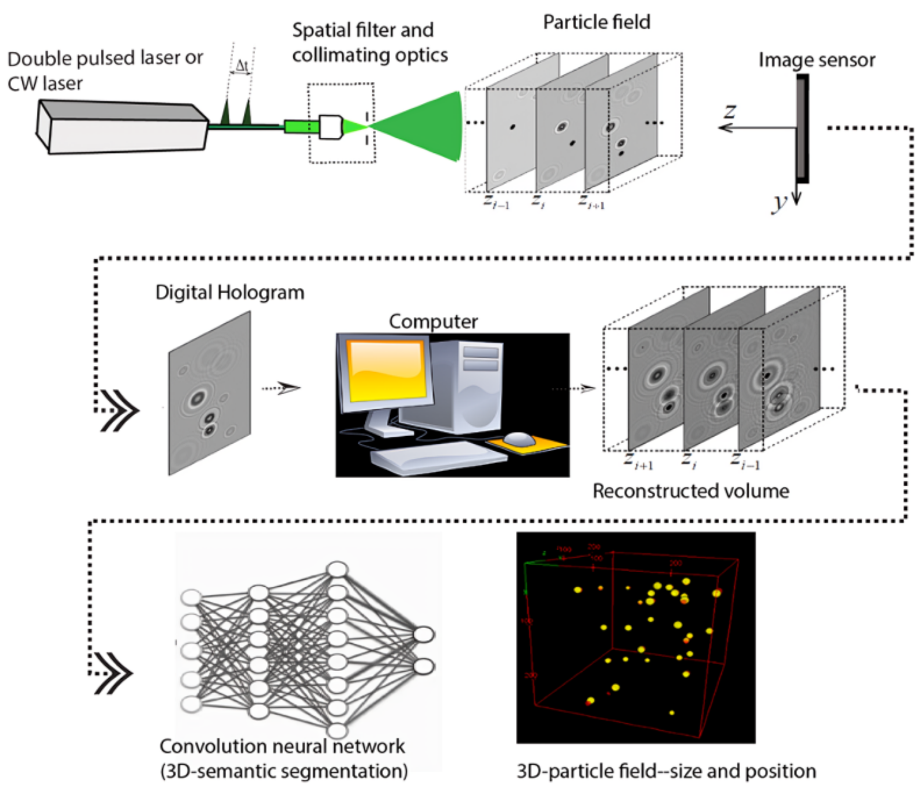

FIG. 2: Digital holography for raindrop size and velocity measurements.

temperature and humidity conditions. A dedicated multiphase flow solver, developed within the OpenFOAM and Basilisk frameworks, will be further refined to address the specific problems considered in this project. Resolving droplet breakup and interfacial dynamics requires large computational domains and fine mesh resolution, making the simulations computationally demanding. To ensure computational efficiency and scalability, parallel computing with domain decomposition will be adopted. High-fidelity simulations will be performed using the Param Seva High-Performance Computing (HPC) facility with allocated computational resources, enabling accurate and robust modeling of droplet microphysics under diverse environmental conditions.