ME – PhD Thesis Defense

Evaporation and Atomization Dynamics of Multi-component Droplets

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ABSTRACT

The atomization, evaporation, and breakup of liquid droplets are central to many engineering and societal applications, including combustion, spray cooling, aerosol generation, and filtration. In advanced combustion and public-health–related aerosol transport, understanding the coupled thermo-fluid dynamics of multicomponent droplets is particularly important. This thesis presents an experimental investigation of the evaporation, deformation, and atomization of microemulsion droplets under controlled thermal and hydrodynamic conditions and extends droplet-impact physics to fabric-based mask substrates relevant to respiratory aerosol mitigation.

The first part of the thesis examines the evaporation of stable water-in-oil microemulsion droplets under non-contact infrared laser heating. Three stages are identified: an initial preheating phase, a steady D^2-law–governed regime, and a final unsteady stage unique to microemulsions. This unsteady behavior arises from surfactant accumulation and phase redistribution, forming a solid, surfactant-rich shell that halts evaporation. The dynamics depend strongly on the dispersed-phase volume fraction and base-oil properties. Xylene-based microemulsions form larger shells due to their higher vapor pressure.

Building on these results, the thesis investigates bubble-induced breakup of microemulsion droplets. Vapor bubble nucleation, growth, and collapse lead to diverse fragmentation behaviors, classified into three primary modes and several sub-regimes. A breakup impact parameter, β, is introduced to describe bubble growth and associated interfacial instabilities. Two dominant rupture mechanisms are identified: Faraday-wave–driven rupture for $\beta \geq 1$, and combined Rayleigh–Taylor–Kelvin–Helmholtz destabilization for $\beta < 1$. Bubble collapse produces ligaments that undergo secondary breakup, resulting in symmetric or asymmetric fragmentation. At high heating rates, xylene microemulsions exhibit sheet fragmentation due to the rupture of small, high-pressure bubbles.

The thesis further examines shock-induced atomization of microemulsion droplets subjected to laser heating and blast-wave–driven flows. The interaction occurs in two stages: a brief initial deformation caused by the decaying blast wave, followed by a longer interaction with a compressible vortex ring that governs atomization. Breakup strongly depends on the droplet's evaporation stage. Early-stage droplets undergo shear-driven sheet formation and bag breakup, whereas fully evaporated droplets form viscous shells that rupture from the periphery, releasing and atomizing the confined liquid core. Differences between decane- and xylene-based microemulsions significantly affect deformation of timescales and atomization modes.

Finally, the thesis extends droplet-scale physics to droplet impact on fabric-based face masks, motivated by the need to understand penetration and aerosolization during respiratory events. Penetration depends on both surface tension and viscous dissipation, with multilayer fabrics significantly reducing penetration and secondary aerosol generation.

ABOUT THE SPEAKER

Bal Krishan is a PhD student in the Department of Mechanical Engineering at the Indian Institute of Science. He completed his B.Tech. in Mechanical Engineering from Pantnagar University and went on to pursue an M.Tech. in Aerospace Engineering at the Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram, where he worked on numerical simulations of a supersonic nozzle. His current research focuses on the atomization and breakup of multi-component droplets. Beyond academics, he enjoys swimming and following sports such as cricket, and football.