ME – PhD Thesis Colloquium

Bubble Coalescence in Electrolyte Solutions

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ABSTRACT

Bubble coalescence in electrolyte solutions is governed by the formation and drainage of thin liquid films that arise when gas bubbles approach solid or liquid interfaces in aqueous media containing dissolved ions. The stability and thinning dynamics of these films determine whether adjacent bubbles merge or remain separated, thereby controlling bubble size distributions, mass transfer rates, and phase separation in electrolytic multiphase systems. These processes are central to applications such as flotation, desalination, boiling heat transfer, electrolysis, pulmonary airway reopening, and gas exchange in natural waters. Despite their importance, the coupled roles of hydrodynamics, ion-specific interfacial phenomena, and intermolecular forces in controlling bubble coalescence remain incompletely understood.

This thesis addresses these gaps through a combined experimental and theoretical investigation of electrolyte-mediated bubble–wall interactions and the associated thin-film dynamics. High-speed colour interferometry is used to resolve the spatiotemporal evolution of thin films formed between a rising bubble and a glass substrate. Increasing ionic strength significantly retards film drainage through two coupled mechanisms. Ion-specific exclusion from the air–water interface generates concentration gradients that produce Marangoni stresses opposing the drainage flow, while compression of the electrical double layer enables extreme thinning at the film rim, creating a hydraulic choke that restricts fluid outflow. Divalent ions amplify both effects, with Na_2SO_4 producing slower drainage and thinner equilibrium films than monovalent salts. The drainage dynamics reveal two universal regimes: an early visco-capillary regime with effectively immobile interfaces, where the minimum film thickness scales as $h \sim t^{-1/4}$, followed by a geometric relaxation regime with a mobile interface characterized by $h \sim t^{-1}$. Appropriate normalization collapses the drainage dynamics across electrolyte types and concentrations onto a single master curve.

To interpret these observations mechanistically, a thin-film model incorporating Marangoni stresses and electrolyte-dependent surface tension variations through Graham's equation is developed. The model captures drainage times spanning several orders of magnitude, from $O(10)$ seconds for dilute NaCl solutions to $O(1000)$ seconds for more concentrated electrolytes, and reproduces the experimentally observed decrease in equilibrium film thickness with increasing ionic strength. It also distinguishes electrolytes that strongly retard drainage (NaCl, NaI, and Na_2SO_4) from acids such as HCl and HNO_3, which behave similarly to pure water due to weaker interfacial exclusion. Simulations further show that rapidly evolving films generate smaller dimples early in drainage, whereas slower-draining systems produce larger dimples that evolve more gradually.

Finally, a coupled boundary-integral–lubrication framework is developed to resolve global Stokes flow together with local thin-film hydrodynamics. In this formulation, the interfacial velocity emerges naturally from the interfacial stress balance, enabling the model to capture the transition of the entrapped film from initially immobilized to mobile interfacial conditions. Simulations show excellent agreement with interferometric measurements for DI water and for NaCl and Na_2SO_4 solutions at concentrations of 1–100 mM without case-specific tuning. Together, these results provide a unified, experimentally validated multiscale description of electrolyte-mediated thin-film dynamics governing bubble interactions, offering predictive capability for engineering bubble behaviour in flotation, foam control, saline multiphase flows, enhanced oil recovery, wastewater treatment, and biological thin-film systems.

ABOUT THE SPEAKER

Afsal C P is a PhD student in the Department of Mechanical Engineering working with Prof. Gaurav Tomar and Prof. Susmita Dash, joined in January 2019. He holds a B.Tech degree in Mechanical Engineering from Government Engineering College, Thrissur (Kerala) and M.Tech degree in Thermal Science from National Institute of Technology, Calicut. His research focuses on Interfacial fluid dynamics.