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Boiling Across the Pressure Spectrum: Linking Fundamental Nucleation Theory with Engineering Applications

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Abstract

The onset of boiling under rapid depressurization remains one of the most intriguing and practically relevant phenomena in thermal sciences. Recent advances in nucleation theory demonstrate that the same physical framework can capture liquid rupture across both positive and negative pressure regimes, bridging classical cavitation with the less explored domain of tensioned liquids. This plenary lecture will review new predictive approaches capable of describing nucleation onset across the entire pressure spectrum, supported by both experimental evidence and theoretical modeling. Particular emphasis will be given to the formulation of critical nucleation conditions, their sensitivity to thermodynamic pathways, and their implications for engineering-scale processes. Applications are broad, spanning spray cooling of high-power electronics, flash boiling atomization in propulsion and energy systems, and the thermal management of space platforms, where extreme operating conditions challenge conventional models. By linking mesoscale nucleation physics with continuum-level simulations, these models not only enhance predictive accuracy but also open new possibilities for robust design and optimization of advanced cooling and atomization technologies. The lecture will highlight ongoing efforts to integrate fundamental nucleation theory with computational and experimental tools, demonstrating how insights at the molecular level can translate into practical solutions for engineering innovation.