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Mesoscopic Numerical Study of Cryogenic Bubble Generation and Liquid-Vapor Interface Movement in Microgravity

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Liquid oxygen, a potential spacecraft fuel, exhibits distinct behaviors under varying gravitational conditions, particularly at the liquid-vapor interface. While this interface remains static under standard gravity, it shifts significantly in microgravity environments. Accurately predicting this movement is essential for designing spacecraft fuel tanks to ensure uninterrupted fuel supply, a challenge compounded in saturated liquid boiling scenarios due to experimental constraints in simulating gravity variations. This study addresses the gap through a mesoscopic numerical approach, focusing on cryogenic bubble generation and liquid-vapor interface dynamics in microgravity conditions.

The Lattice Boltzmann Method (LBM) has emerged as a powerful computational tool for simulating boiling phenomena, offering a unique mesoscopic approach that bridges the gap between the microscopic interactions and macroscopic fluid behavior. Distinguished by its simplicity, parallelizability, and versatility in handling complex boundaries and interfaces, LBM excels in modeling the intricate dynamics of vapor-liquid phase transitions inherent in boiling processes. By employing various models, such as the pseudo-potential, free-energy, and phase-field models, LBM provides insights into multiphase flow dynamics, making it indispensable for optimizing industrial applications and advancing theoretical understanding of boiling phenomena.

This research utilizes the pseudopotential LBM, integrated with the Peng-Robinson equation of state to accurately model oxygen properties. Temperature variations within the computational domain are determined using a finite difference scheme, and a slip boundary condition is applied to mimic the movement of the liquid-vapor interface against surfaces.

In the first stage of simulation, pool boiling occurs under the normal earth gravity. After bubble generation and departure during certain time step, gravity is changed to the microgravity. In terms of energy balance, internal energy change is reflected during this step as a result of gravity change. For the comparison of interface movement, saturated liquid case where boiling phenomena occurs and subcooled liquid case in which bubble is not generated are simulated.

This study's findings offer critical insights into the behavior of cryogenic fluids in space, facilitating the design of more reliable and efficient spacecraft fuel systems.

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