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On the mechanics of thermal collapse of a vapor bubble translating in an isothermal subcooled liquid

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ABSTRACT

In this work, we numerically simulate bubble radius and velocity in a thermal collapse of a vapor bubble translating in an isothermal subcooled liquid based on solving the equations of energy and motion simultaneously. The mechanics of the collapse in the thermal regime plays a significant role in the thermal convection from the vapor-liquid interface of a translating bubble. In our mathematical model, the equation of motion considers the added mass force due to phase change and shape change, while the equation of energy includes thermal conduction and convection. The simulations include both spherical and non-spherical bubbles, the effect of initial bubble diameter and degree of subcooling. The simulations have been performed in three modes of heat transfer (conduction, convection and combined conduction-convection) to observe their effect on the bubble dynamics. The numerical results have been compared with the two classes of thermal collapse experiments (Type A and B) and CFD analysis reported in literature. They agree well with the experiments and CFD-analysis. We have seen a remarkable effect of the initial shape of the bubble in terms of aspect ratio on the time scale and modes of the heat transfer and the collapse time. An interesting concern is that the mechanism of the collapse and the modes of heat transfer depends on how the collapse is initiated in the experiments. Type A and B thermal collapses are mainly classified based on the bubble motion and the modes of thermal transport from the interface.

1. Introduction

Collapse and motion of a vapor bubble are two essential features of bubble dynamics. Both growth and collapse of the vapor bubble in an unbounded liquid are caused by a temperature difference (thermal effect) and a pressure difference (liquid inertia effect) between the interface and the liquid. The inertia effect dominates at an early stage, when a vapor bubble is suddenly exposed to a subcooled liquid, and the thermal effect at a later stage (Paruya et al., 2022, Yang and Prosperetti, 2008, Paruya and Bhati, 2021, Florschuetz and Chao, 1965). Although the former retains for a fraction of a millisecond for a thermal bubble depending on the subcooling and initial bubble radius, it usually occurs for a longer time to a cavitation bubble. The relative effect of these two timescales suggests that the thermal model describes more accurately the experiments at a fairly high superheat and subcooling (Legendre et al., 1998; Prosperetti and Plesset, 1978; Prosperetti, 2017). The collapse of a vapor bubble in a subcooled liquid is relatively more complex than the growth – the radius of the bubble and the thickness of the thermal layer change in opposite directions; the ratio of the surface area to the volume of the bubble keeps increasing to a large value. Florschuetz and Chao (1965) examined experimentally and theoretically the relative importance of thermal effect over liquid-inertia effect in the collapse of a stationary and spherically-symmetric vapor bubble. They found that the assumption of a thin thermal layer (Plesset and Zwick, 1954) for the liquid-inertia was invalid in a slow collapse (Jakob number Ja is low). The assumption of a thin thermal layer is valid in a fast collapse (high Ja). Wittke and Chao (1967) studied experimentally and theoretically the effect of the translational motion of the bubble on the thermal collapse. The translational velocity increases the rate of heat transfer from the bubble surface in a slow collapse (low Ja). Their theory assumed a spherical bubble and a constant rise velocity. The bubble collapsed more rapidly with an increase in translational velocity. The effect is more pronounced in low Ja, at which the heat transfer regime dominates at the beginning of the collapse. The effect of noncondensable gases slows down the collapse. Gumerov (1996) obtained an asymptotic solution of the problem with a quasi-stationary thermal layer and showed that the thermal collapse of a spherical bubble occurred at Ja < 10. The effect of a non-stationary thermal layer for a translating bubble would be stronger. Chen and Mayinger (1992) experimentally observed

Abbreviations: CFD, Computational fluid dynamics; DFM4, Four-equation drift flux model; NCBL, Natural circulation boiling loop.

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