Bubble Departure Behaviors and Prediction of Critical Heat Flux in Subcooled Flow Boiling on Inclined Heating Surface

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論 文 名　：Bubble Departure Behaviors and Prediction of Critical Heat Flux in Subcooled Flow Boiling on Inclined Heating Surface
（傾斜加熱面における強制流動サブクール沸騰の気泡離脱挙動と限界熱流束の予測）

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論 文 内 容 の 要 旨

During severe reactor accidents in a light water reactor (LWR), a molten core may accumulate at the lower plenum of the reactor pressure vessel (RPV), generating a considerable amount of decay heat that may result in the thermal failure of RPV integrity. In-vessel retention (IVR) is a viable concept to maintain the integrity of RPVs and is accomplished in the LWR by the natural circulation of cooling water along the cooling path on the outer surface of the RPV, whose orientation angle varies gradually from downward-facing horizontal to vertical. The water removes the decay heat through the subcooled flow boiling process, whose cooling ability is limited by critical heat flux (CHF). The subcooled flow boiling CHF is typically associated with bubble development characteristics over a heating surface and is significantly influenced by the void fraction, which develops starting from the net vapor generation (NVG) point. The NVG used to be defined as the point of bubble departure; however, it is more accurately represented now as the point of bubble lift-off from the heating surface. Thus, studying the bubble departure and lift-off diameters and prediction of CHF in subcooled flow boiling on an inclined heating surface is significant to ensure the success of the implementation of IVR concept as specified in CHF.

In this study, a series of experiments are conducted to investigate the bubble departure and lift-off diameters in subcooled flow boiling for different heating surface inclinations ranging from downward-facing horizontal to vertical. An improved mechanistic model is proposed to predict the bubble departure and lift-off diameters on an inclined heating surface. The liquid sublayer dryout model, which is a model for the CHF prediction, is modified to take into account the effects of channel inclination on the behavior of a vapor clot hovering over the heating surface. The proposed CHF model, coupling with the new model for the bubble lift-off on an inclined heating surface, makes it possible to predict CHF under IVR conditions.

The whole thesis is organized into five chapters.

Chapter 1 introduces the research background and summarizes prior experimental works on bubble departure and lift-off diameter in subcooled flow boiling. The concept of IVR, the fundamentals of nucleate boiling, void fraction, and CHF are briefly introduced. The existing models and correlations for bubble departure and lift-off diameters are thoroughly reviewed. Finally, this chapter clarifies the motivation and objectives of the thesis.

Chapter 2 describes the subcooled flow boiling experimental setup. The design, fabrication, and installation are thoroughly discussed. One of the essential features of the test section is its mounting angle, which can be changed from downward-facing horizontal to vertical in 5° increments, allowing for the acquisition of experimental data under IVR conditions. This chapter also covers the experimental studies of the bubble departure and lift-off diameter at the NVG point on a heating surface whose inclination changes from downward-facing horizontal to vertical. A novel database of bubble lift-off diameter is developed for the inclined heating surface. The effect of channel inclination angle on bubble lift-off diameter is found to be

significant. Results indicated that the lift-off diameter increases as the channel inclined towards the downward-facing horizontal condition. A decreasing trend of bubble lift-off diameter is observed by increasing the inlet subcooling and mass flux and decreasing heat flux. The subcooling at the NVG point is found to reduce with increasing mass flux and decreasing heat flux for a given inlet subcooling. Additionally, this chapter discusses calibration and uncertainty analysis.

Chapter 3 describes the modeling of bubble departure and lift-off diameters. The model is developed based on the force balance approach on a growing bubble considering the channel inclination effect. Bubble departure and lift-off are assumed to occur when the force balances are disrupted in either the x (parallel to the heating surface) or y (vertical to the heating surface) direction. Usually, a bubble lift-off occurs following a short distance sliding over the heating surface, and the bubble relative velocity is a key parameter in accurately predicting the lift-off diameter. The bubble relative velocity is calculated as a dynamic variable in the proposed lift-off model using a simplified force balance parallel to the heating surface. The model is validated with obtained experimental data and other existing data from the literature. Copmpared to existing models that predict lift-off diameter with a relative error of 77.0%, the new model shows an improved accuracy with a mean relative error of 9.9%. Additionally, a supplementary model, the bubble growth model, that calculates the bubble growth with time and is essential for the proposed lift-off model, is also validated with the experimental data.

Chapter 4 discusses the prediction capabilities of the liquid sublayer dryout model under IVR conditions. A modified liquid sublayer dryout model that includes the effect of channel inclination is proposed for the force balance analysis of a hovering vapor clot formed by the coalescence of departed bubbles. The proposed CHF model, coupled with the new lift-off model for the vapor clot diameter, is found to be capable of predicting the experimental data with a mean relative error of 26.4% under IVR conditions.

Chapter 5 concludes with key findings that demonstrate the study's uniqueness and contribution. The current research was conducted in order to better understand the bubble departure behaviors at NVG on an downward facing inclined heating surface in order to facilitate the implementation of IVR concepts following the CHF. The novel experimental database of bubble lift-off diameters for various channel inclinations was developed not only to validate the existing models, but also to developed new ones. The proposed CHF model, combining with the developed bubble lift-off model enables the prediction of the CHF under IVR conditions. As a result, the existing research shows a potential solicitation opportunity to substantiate the IVR safety approach. Although more experimental research with high heat flux circumstances would be required to analyze bubble departure behaviors near CHF, the present study is likely to contribute to a better understanding of the fundamentals of bubble departure behaviors and NVG with CHF in IVR.