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Review of Bubble Lift-Off Behavior and Departure Diameter under Subcooled Flow Boiling Conditions

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1. Introduction

This review paper is based primarily on the experimental study of subcooled flow boiling conducted by Park et al. (2021) [1]. That study represents a significant contribution in which bubble departure behavior under subcooled flow boiling conditions on a vertical heated flat plate was precisely measured. By classifying departing bubbles into lifting-off and ejecting types, the authors clearly demonstrated the limitations of existing bubble departure models. The purpose of this review is to discuss the experimental findings, physical interpretations, and the proposed bubble departure diameter correlation presented in that work.

2. Challenges in Predicting Bubble Departure in Subcooled Flow Boiling

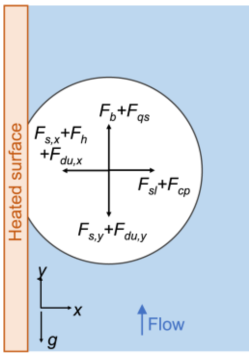

Fig. 1. Forces associated with bubble in upward vertical flow boiling.

2.1 Limitations of Force-Balance-Based Models

Traditionally, bubble departure from boiling surfaces has been explained based on a balance of various forces acting on the bubble, as shown in Fig. 1, such as buoyancy, drag, and surface tension. While this force-balance approach has the advantage of clearly identifying the physical mechanisms involved in bubble behavior, it exhibits several limitations under actual subcooled flow boiling conditions:

- Asymmetric force distribution depending on the flow direction
- Increased use of empirical coefficients and associated uncertainty due to model complexity

As a result, it has been consistently pointed out that simply refining force terms is insufficient to reliably predict bubble departure diameters.

2.2 Importance of Bubble Departure Diameter in Wall Boiling Models

Despite the abovementioned difficulties, several wall boiling models have been proposed to predict heat transfer mechanisms from a heated wall to a fluid. Kurul and Podowski proposed a heat flux partitioning model in which the wall heat flux is decomposed into three components [2]: latent heat transfer by evaporation (q_e''), single-phase convection in regions unaffected by vapor bubbles (q_c''), and quenching due to rewetting of the heated surface after bubble departure (q_q'').

In this model, the total wall heat flux is expressed as

$$q_w'' = q_e'' + q_c'' + q_q'' \tag{1}$$

Among these components, the evaporative heat flux can be written as

$$q_e'' = \frac{\pi}{6} D_{lo}^3 \varrho_v h_{fg} f_d N_a R_f \tag{2}$$

indicating that the evaporative heat flux is proportional to the cube of the bubble departure diameter. Consequently, even a small uncertainty in the bubble departure diameter may lead to significant deviations in overall heat transfer predictions. Therefore, accurately defining and predicting the bubble departure diameter is essential for improving the reliability of heat flux partitioning models.

3. Classification of Bubble Departure Behavior: Lifting-Off and Ejecting Bubbles

In recent experimental studies on subcooled flow boiling, bubble departure behavior has increasingly been treated not as a single mechanism but rather classified into distinct types according to their dynamic characteristics.

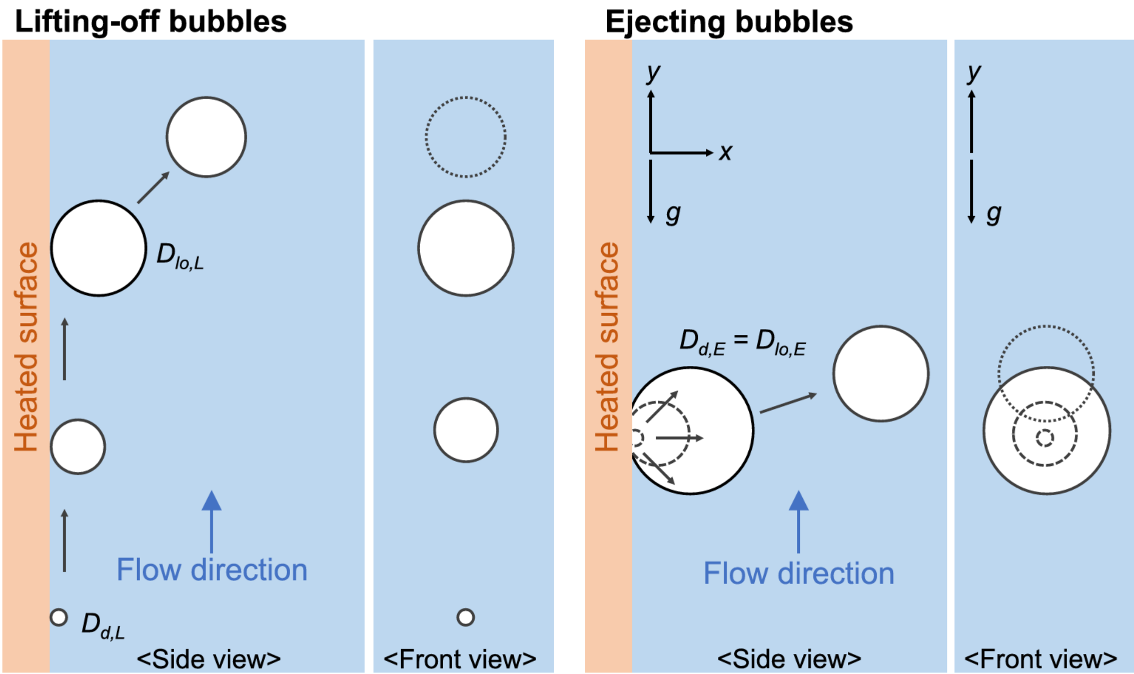

Fig. 2. Different types of bubble detachment.

3.1 Lifting-Off Bubbles

Lifting-off bubbles are generated on the wall surface and do not depart immediately, as shown in Fig. 2. and Fig. 3. Instead, they slide along the heated surface over a certain distance before completely detaching from the wall. During this process, the bubbles continue to grow while receiving energy from the heated wall and the superheated liquid layer adjacent to the surface, eventually departing from the wall.

3.2 Ejecting Bubbles

Ejecting bubbles depart almost instantaneously from their nucleation sites, with little to no sliding motion, and are expelled in a direction nearly normal to the wall surface, as shown in Fig. 2. and Fig. 3. In this case, the initial departure diameter is nearly identical to the final departure diameter, and the departure process is completed within a relatively short time. Experimental observations have reported that ejecting bubbles predominantly occur under high heat flux conditions.

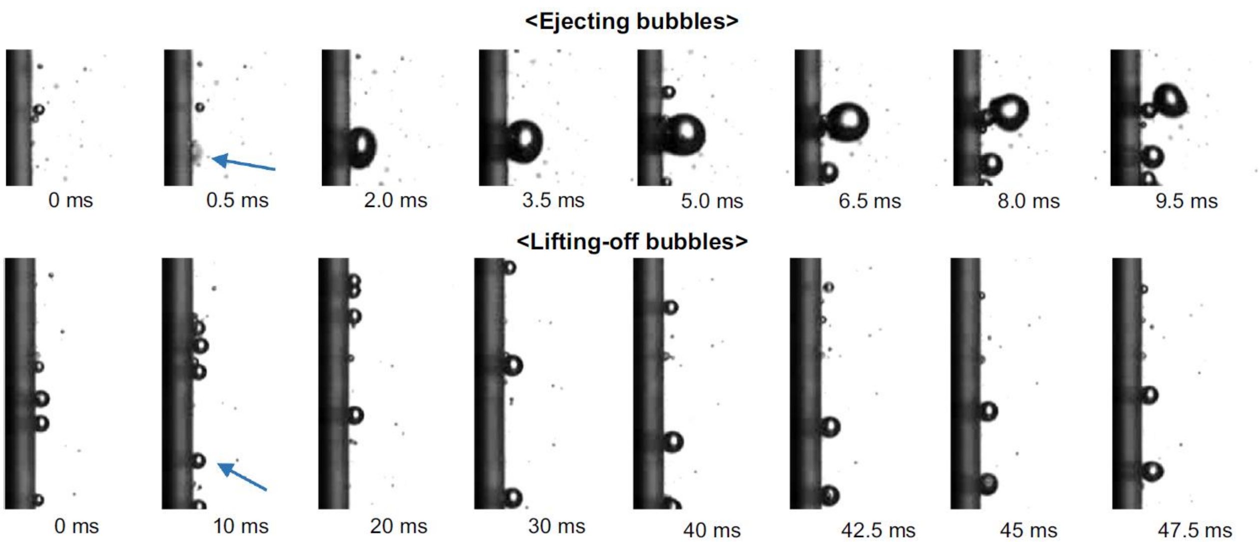

Fig. 3. High-speed images of ejecting and lifting-off bubbles from side view (conditions for lifting-off bubbles were G: 75 kg/m^2s ,T_{sub}: 4.5 K and q'' :200 kW/m^{2}K; conditions for ejecting bubbles were G: 200 kg/m^2s, T_{sub}:: 4.5K and q'' :225 kW/m^{2}K).

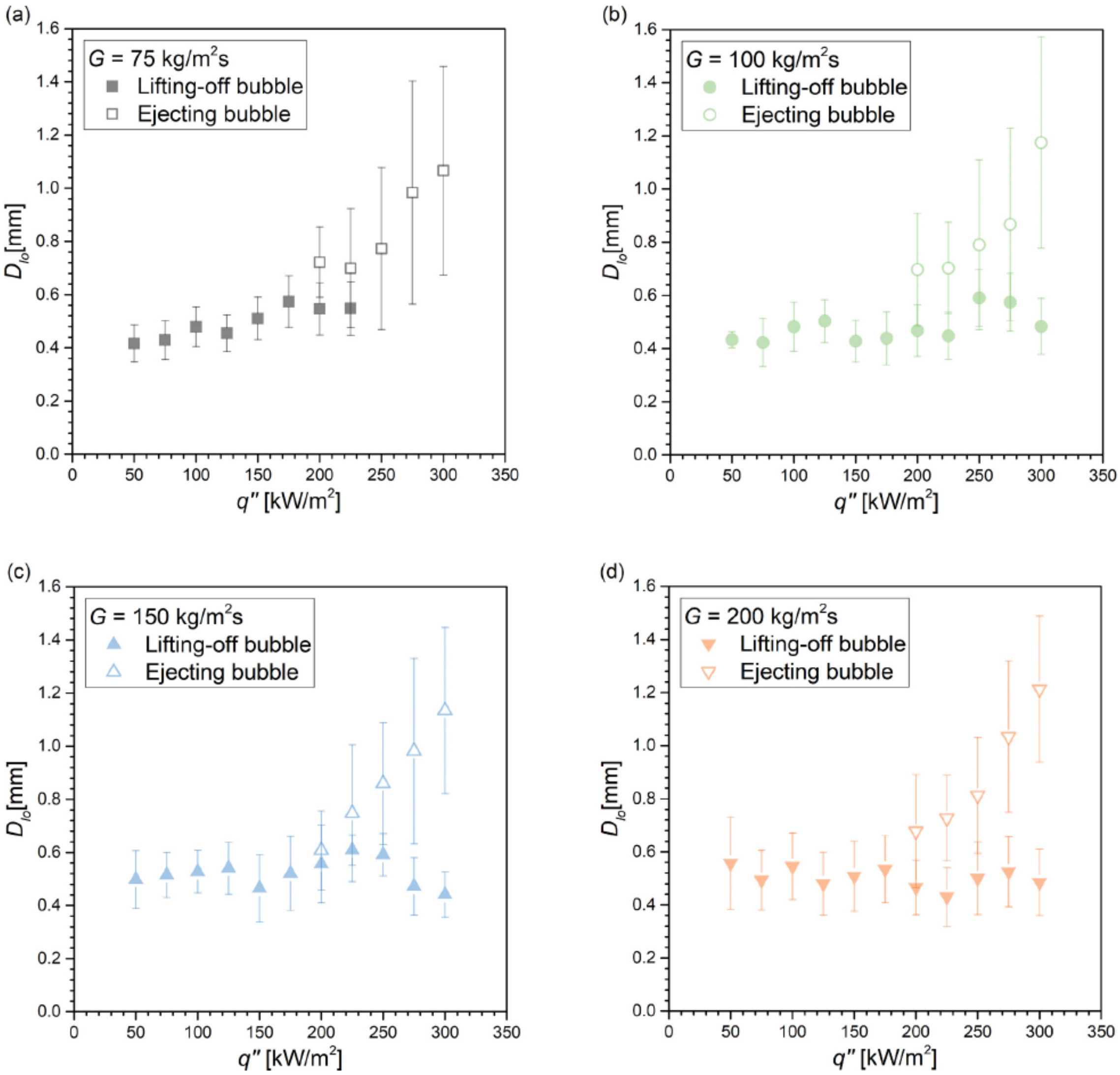

Fig. 4. Bubble lift-off diameter of lifting-off and ejecting bubbles.

3.3 Experimental Studies on Subcooled Flow Boiling

In a recently conducted experimental study, subcooled flow boiling experiments were performed on a flat heated surface in a vertical rectangular channel under atmospheric pressure conditions [1]. Deionized water was used as the working fluid, and the experiments were carried out under mass fluxes of 75–200 kg/m²·s, heat fluxes of 25–300 kW/m², and an inlet subcooling of 4.5 K. Using high-speed camera imaging, more than 1,600 individual bubbles were analyzed, and the bubble departure diameter and post-departure velocity were quantitatively measured at the moment of departure. As a result, distinct differences between lifting-off bubbles and ejecting bubbles were clearly observed, as shown in Fig. 4. The departure diameter of lifting-off bubbles was in the range of approximately 0.4–0.6 mm and was observed over a wide range of heat flux conditions. In contrast, the departure diameter of ejecting bubbles increased with increasing heat flux, reaching up to approximately 1.2 mm, and was predominantly observed under relatively high heat flux conditions.

4. Classification of Bubble Departure Behavior: Lifting-Off and Ejecting Bubbles

Based on experimental observations, the present study classified bubbles into lifting-off and ejecting types and proposed a new bubble departure diameter correlation that reflects the collective behavior characteristics of bubble populations. The proposed correlation simplifies conventional force-balance-based approaches and empirically incorporates the effects of dominant thermodynamic and hydrodynamic parameters under subcooled flow boiling conditions.

Table 1.
Correlations for bubble lift-off diameter in vertical forced convective flow boiling.

Author	Correlation
Prodanovic et al. (2002)	$D_{lo} = 440.98\rho_f \alpha_f^2 \sigma^{-1} \left(\frac{\rho_f c_{p,f}(T_w - T_{sat})}{\rho_g h_{fg}}\right)^{-0.708} \left(\frac{T_w - T_b}{T_w - T_{sat}}\right)^{-1.112} \left(\frac{\rho_f}{\rho_g}\right)^{1.747} \left(\frac{q''}{G h_{fg}}\right)^{0.124}$
Chu et al. (2011)	$D_{lo} = 12788.5\rho_f \alpha_f^2 \sigma^{-1} \left(\frac{\rho_f c_{p,f}(T_w - T_{sat})}{\rho_g h_{fg}}\right)^{-0.28} \left(\frac{T_w - T_b}{T_w - T_{sat}}\right)^{-1.07} \left(\frac{\rho_f}{\rho_g}\right)^{1.36} \left(\frac{q''}{G h_{fg}}\right)^{0.35}$

4.1 Proposed Bubble Departure Diameter Correlation

The correlation proposed in this study for the departure diameter of lifting-off bubbles is expressed as follow

$$D_{lo} = 13 \times 10^5 \rho_f \alpha_f^2 \sigma^{-1} \left(\frac{\rho_f c_{p,f}(T_w - T_{sat})}{\rho_g h_{fg}}\right)^{-1.75} \times \left(\frac{T_w - T_b}{T_w - T_{sat}}\right)^{-0.12} \left(\frac{\rho_f}{\rho_g}\right)^{1.36} \left(\frac{q''}{h_{fg}}\right)^{2.25} \quad (3)$$

The proposed model is effective for the following ranges:

$50 < q'' < 300$ kW/m^2

$75 < \mathrm{G} < 200$ kg/m$^2 s$

4.2 Improvements over Existing Models

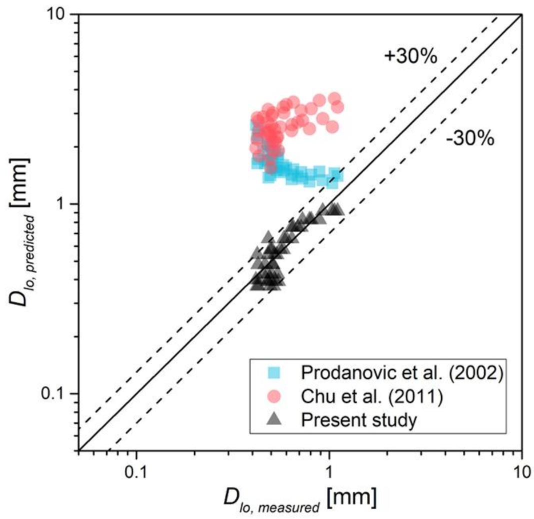

Fig. 5. Prediction of lift-off diameter.

The proposed correlation does not explicitly include a mass flux term, reflecting experimental observations that the influence of mass flux was limited within the range of experimental conditions considered in this study. Instead, heat flux and wall superheat were employed as the primary variables, enabling effective reproduction of the observed trends in bubble departure diameter under subcooled flow boiling conditions.

Comparisons with representative existing bubble departure diameter models, summarized in Table 1, demonstrated that the proposed correlation achieved a prediction performance with a mean absolute error (MAE) of approximately 13%, representing a significant improvement over previous models, as shown in Fig. 5. In particular, the correlation successfully captured both qualitatively and quantitatively the increase in bubble departure diameter associated with bubble behavior transition in the high heat flux regime.

5. Conclusion

This review summarized recent research trends on bubble departure behavior and diameter under subcooled flow boiling conditions. Experimental studies classifying bubbles into lifting-off and ejecting types suggest that the departure diameter is not a static value but a dynamic quantity contingent upon bubble behavior and heat flux.

Notably, the literature lacks a definitive threshold—such as a specific Critical Heat Flux (CHF) or subcooling level—that demarcates these two behaviors. For instance, the subcooling level of 4.5 K used in previous studies was a pragmatic choice to minimize condensation, rather than a physical transition criterion. Furthermore, at low mass fluxes (75–200 kg/m²·s), heat flux emerges as the dominant driver of bubble dynamics, with ejecting bubbles becoming more prevalent above approximately 200 kW/m². Consequently, the transition between lifting-off and ejecting modes should be viewed as a gradual process driven primarily by heat flux, rather than a discrete shift at a specific CHF.

Future research should expand into broader subcooling ranges and higher mass flux conditions to further elucidate the dependence of bubble population distributions on diverse flow parameters.

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