# An Improved Mechanistic Model for Prediction of Bubble Lift-off Diameter in Subcooled Flow Boiling for Inclined Heating Surface

* M. A. Rafiq Akand, Kei Kitahara, Tatsuya Matsumoto, Wei Liu, and Koji Morita
Kyushu Univ.

**Abstract:** The accurate prediction capabilities of bubble lift-off diameter for the inclined heating surface is essential to evaluate the critical heat flux (CHF) in In-vessel retention (IVR) conditions. An improved force-balanced model is proposed to predict the lift-off diameter in IVR conditions by considering the bubble sliding velocity as a dynamic basis.
**Keywords:** Mechanistic model, sliding velocity. lift-off diameter, inclination angle, in-vessel retention.

## 1. Introduction

IVR is an effective method for protecting the reactor pressure vessel integrity in a severe nuclear reactor accident [1]. The study of bubble lift-off diameter for inclined heating surface is still lacking, which is essential to CHF prediction in IVR conditions. An experimental facility has been designed with a high-speed video camera system to investigate the bubble lift-off process. Bubble lift-off data for different inclination angles of heating surface from downward-facing horizontal to vertical condition was acquired. The existing lift-off models and correlations unveiled that the lift-off size is greatly associated with bubble sliding velocity. However, the models were developed either ignoring [2] or using a constant bubble sliding velocity [3], which is basically greater than that of local liquid. The present research aims to develop a mechanistic model to predict the bubble lift-off diameter for inclined heating surface in IVR conditions.

## 2. Mechanistic model

The forces acting on a vapor bubble in both parallel and perpendicular to the heating surface are [4],

$$\sum F_x = F_{s,x} + F_{qs} + F_{b,x} + F_{du,x} \geq 0 \quad (1); \qquad \sum F_y = F_{s,y} + F_{sl} + F_{b,y} + F_{du,y} + F_{cp} + F_h \geq 0 \quad (2)$$

where, $F_s$, $F_{qs}$, $F_b$, $F_{du}$, $F_{sl}$, $F_{cp}$, and $F_h$ are surface tension force, quasi-steady drag force, buoyancy force, bubble growth force, shear lift force, contact pressure force, and hydrodynamic pressure force, respectively. Subscripts x and y represent the components of parallel and perpendicular directions of the heating surface, respectively. To model the bubble lift-off behavior, we only consider the force balance in the y-direction. Because of the necking effect [2], the bubble contact diameter becomes zero at the moment of lift-off. These three forces ($F_s$, $F_{cp}$ and $F_h$) relies on the bubble contact diameter and are omitted in the new model. Then, the model is simplified to:

$$\sum F_y = F_{sl} + F_{b,y} + F_{du,y} \geq 0 \quad (3)$$

$F_{sl}$ is the only dominant force for bubble lift-off, which significantly relies on the bubble relative velocity. We proposed a new method to calculate the bubble relative velocity by considering force balance in the x-direction. For all the inclination conditions except downward-facing horizontal, the force balance in the x-direction, Eq. (1), can be simplified to Eq. (4) because $F_{s,x}$ and $F_{du,x}$ can be neglected due to the necking effect and small bubble inclination angles, respectively.

$$\sum F_x = F_{b,x} + F_{qs} \geq 0 \quad (4)$$

For the case of the downward-facing horizontal condition, $F_b$ acts in the normal direction, no $F_{b,x}$, to the heating surface that keeps to stick the bubble to the surface and the bubbles slide with an effective contact diameter. Therefore, $F_{s,x}$ is considered as an active force in downward-facing horizontal condition, and the force balance can be expressed as:

$$\sum F_x = F_{s,x} + F_{qs} \geq 0 \quad (5)$$

Equations 3,4 and 5 were solved numerically by iteration to calculate the bubble relative velocity and the lift-off diameter.

## 3. Model validation with experimental data

The predictive potential of the proposed model against the experimental data is shown in Fig 1. The experimental and model-predicted bubble lift-off diameter as a function of channel inclination angle is shown in Fig 2.

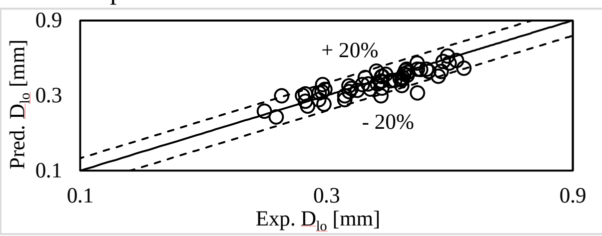


Fig. 1: Experimental vs predicted lift-off diameter.

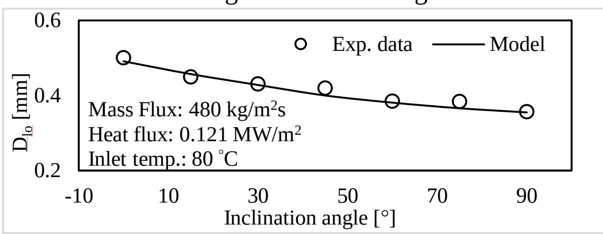


Fig. 2: Lift off diameters as a function of inclination angle.

## 4. Conclusions

An improved mechanistic model is developed including the inclination effect of heating surface to simulate the bubble lift-off characteristics in IVR conditions by considering the bubble sliding velocity as a dynamic basis. The proposed model shows good agreement with experimental data with a mean relative error of 8.25 %.

**References**

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