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A model of the bubble waiting time in forced subcooled boiling

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1. Introduction

A bubble ebullition period is divided into the bubble waiting time and the bubble growing time. The bubble waiting time is defined as a time interval beginning at the moment of bubble departure and ending at the moment when a new bubble size grows beyond the wall cavity mouth. Continuously from this point to the time of the bubble departure is specified as the bubble growing time. From the two-time intervals, the bubble departure frequency (f) is determined as follows:

$$f = \frac{1}{t_w + t_g} \tag{1}$$

where: t_w and t_g are the bubble waiting time and the bubble growing time, respectively.

During nucleate boiling, the heat transfer mechanism between the heated surface and the liquid flow is significantly relevant to the bubble behaviors. Therefore, the bubble departure frequency became one of the governing parameters in the models of wall heat flux partitioning [1-3]. Gilman and Baglietto [2] suggested that it is necessary to develop a mechanistic bubble departure frequency by assembling separate mechanistic models for bubble waiting and growing times to better account for the effect of heat flux and flow conditions, which have not been appropriately captured in the existing correlated forms of bubble departure frequency.

For the forced convection subcooled boiling, there have been two models of bubble departure frequency that were based on the bubble waiting and growing times developed by Basu et al., [1] and Podowski et al., [4]. Basu et al., [1] developed the correlations of the bubble waiting and growing times by fitting them against their experimental data. Meanwhile, the model proposed by Podowski et al., [4] was a mechanistic model, in which the models of the bubble waiting and growing time were obtained by balancing transient heat transfer in the heated wall and from the wall to the liquid. However, the two models have not provided satisfactory predictions of the bubble departure frequency.

This study is the first step to develop a new mechanistic model of bubble departure frequency based on the bubble waiting and growing times. In this study, a new model of the bubble waiting time was theoretically developed based on an energy balance established for the system of the heated wall, new embryo, and subcooled liquid. Subsequently, the new model of the bubble waiting time was indirectly evaluated by combining it with the model of bubble growing time developed by Basu et al., [1] to predict the bubble departure frequency.

2. The theoretical model for the bubble waiting time

To obtain the model of the bubble waiting time, several assumptions were given as followings.

A new bubble embryo existed beneath the departure bubble as seen in Fig. 1. Because of bubble departure, the subcooled liquid occupied the vacant volume in the superheated liquid layer above the embryo (Fig. 1). The subcooled liquid contacted and prevented the growth of the embryo due to the condensation. However, the thermal diffusion from the heated wall to the embryo maintained the embryo size.

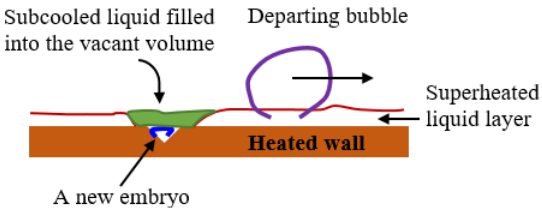

Fig.1. Demonstration of a new embryo, bubble departure, and subcooled liquid occupied the vacant volume

The embryo was initially assumed to be spherical with a radius of R_{eb}, and its volume completely occupied the volume of the wall cavity.

There was no change in the interface area between the embryo and the heated wall, and the heat flux diffused through the interface approximately equaled the wall heat flux.

There was a competence of condensation and evaporation at the interface between the embryo and the subcooled liquid volume. The heat transfer mechanism within the liquid volume was transient conduction, which was separated into two parts. A part would heat the liquid volume to the saturated condition, and the other transferred to the bulk liquid by convection.

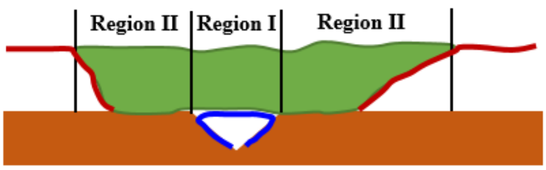

Fig. 2: An assumption of separating the subcooled liquid volume

The volume of subcooled liquid was separated into two regions (Fig. 2). Region I was right above the embryo and region II was contacted with the heated wall. It was assumed that the heat transfers in the two regions were independent of each other.

The embryo area contacting with the heated wall was assumed to equal 3/4 of its spherical area. Due to condensation, the flat area of the embryo was a circle with a radius of $a = \sqrt{3}/2\, R_{eb}$ (Fig. 3).

The thickness of the superheated liquid layer or the height of the subcooled liquid volume was scaled against the bubble waiting time, and given as $\sqrt{\pi\alpha_f t_w}$.

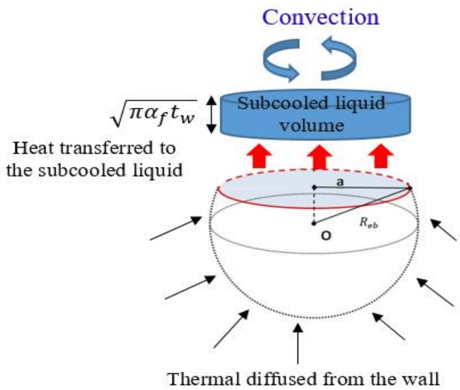

Fig. 3: The heat transfer mechanisms at the nucleation site within the waiting time

The heat transfer mechanism at the nucleation site during the waiting time is also demonstrated in Fig. 3. The heat diffused from the heated wall to the embryo played two roles. One was to heat the column of subcooled liquid right above the embryo to the superheated state, and the other transferred to the bulk flow by convection. The embryo could grow beyond the cavity mouth since its above-subcooled liquid was in the superheated state. Therefore, the energy conversation was expressed as follows:

$$\int_o^{t_w} 3\pi R_{eb}^2\, q_w dt = \frac{3}{4}\pi R_{eb}^2 \rho_f C_{pf}(dT_{sub} + dT_{sup}) \times \times \sqrt{\pi\alpha_f t_w} + \frac{3}{4}\int_0^{t_w} h_{fc} dT_{sub} \pi R_{eb}^2 dt \quad (1)$$

where: q_w is the wall heat flux, ρ_f is the liquid density, C_{pf} is the liquid heat capacity, dT_{sub} is the liquid subcooling, dT_{sup} is the wall superheating, α_f is the conductivity of liquid and h_{fc} is convective heat transfer coefficient.

Finally, the expression of the bubble waiting time was expressed as follows:

$$t_w^{1/2} = \frac{0.5\rho_f C_{pf} dT_{sub}\sqrt{\pi\alpha_f}}{3q_w - 0.75 h_{fc} dT_{sub}} \quad (2)$$

3. Evaluating the new model of bubble waiting time

Unfortunately, there are unavailable experimental data on the bubble waiting time. Therefore, the new model was indirectly evaluated in combination with the model of bubble growing time developed by Basu et al., [1] to predict the bubble departure frequency. The experimental data on bubble departure frequency were collected from Basu [5] and Brooks et al., [6]. The ranges of experimental data are given in Table I.

The present predictions were evaluated against experimental data and compared to the predictions of the models of Basu et al., [1]. The models of the bubble waiting and growing times of Basu et al., [1] and the present study are presented in Table II.

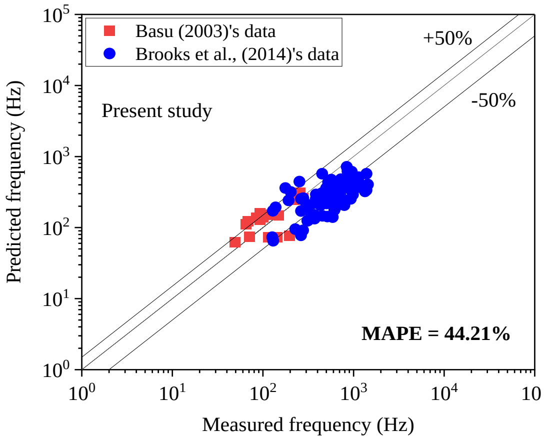

Fig. 4: A comparison between the predictions of the present study and experimental data

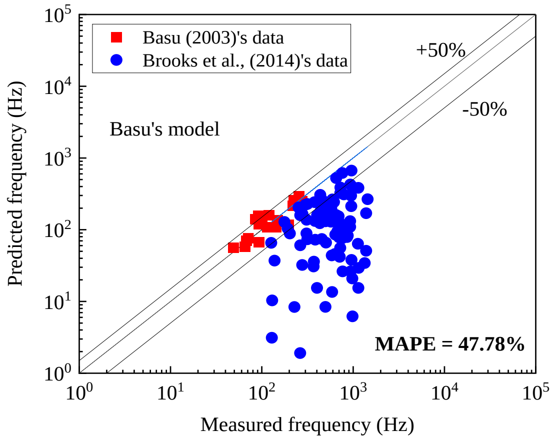

Fig.5: Comparing the predictions of Basu's model with experimental data

The Mean Absolute Percentage Error (MAPE) was used to evaluate the accuracies of the predictions. A comparison between the predicted frequency of the present study and experimental data is presented in Fig.4. It shows the present predictions are reasonable with a MAPE value of 44.21%. Fig.5 presenting the re-produced predictions of the model of Basu et al., [1] shows its predictions for Brooks' data are more scattered than that of the present study. Since Basu et al., [1] fitted their models of the bubble waiting and growing times based on their data [5], hence their predictions for their data are better than the present predictions. The prediction accuracies of the model of Basu et al., [1] and the present study are given in Table III.

Table I: Available experimental data of bubble departure frequency

Properties / Experimental data	Pressure (kPa)	Mass flux (kg/m^{2}s)	Heat flux (kW/m^2)	Superheated (K)	Subcooling (K)
Basu [5]	Atmosphere	340-348	200-417	10-17.5	7.7-46.5
Brooks et al., [6]	151-450	232-999	100-492	3.9-17.6	5.4-39.8

Table II: Models of the bubble waiting and growing times

Models / Authors	Bubble waiting time	Bubble growing time
Basu et al., [1]	$t_w = 139.1(dT_w)^{-4.1}$	$t_g = \frac{D_d^2}{45\alpha_f Ja_{sup} exp(-0.02 Ja_{sub})}$
Present study	$t_w^{1/2} = \frac{0.5\rho_f C_{pf} dT_{sub}\sqrt{\pi\alpha_f}}{3q_w - 0.75h_{fc}dT_{sub}}$	

where: D_d is bubble departure diameter, $Ja_{sup} = \rho_f C_{pf} dT_{sup}/\rho_g h_{fg}$ is the superheated Jacob number, $Ja_{sub} = \rho_f C_{pf} dT_{sub}/\rho_g h_{fg}$ is the subcooled Jacob number, dT_{sup} is the wall superheating, ρ_g is the vapor density, and h_{fg} is the latent heat.

Table III: The prediction accuracies of the calculations

Models	MAPE (%)	
	Basu (2003)'s data	Brooks et al., (2014)'s data
Basu et al., [1]	22.27	73.29
Present study	36.72	51.7

4. Conclusion

This study presented a theoretical approach to developing a model of the bubble waiting time. Due to a lack of experimental data on the bubble waiting time, the new model was indirectly evaluated in combination with the model of bubble growing time developed by Basu et al., [1] to predict the bubble departure frequency. The results showed the present study's predictions were reasonable in comparison with experimental data. It also indicated that the present approach was reasonable to develop the new mechanistic model of the bubble waiting time. The results also motivated the process of developing a mechanistic model of the bubble departure frequency.

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