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Technical Note

On the growth behavior of bubbles during saturated nucleate pool boiling at sub-atmospheric pressure

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Abstract

Nucleate pool boiling analyses were performed using experimental results previously obtained at sub-atmospheric pressure and analytical results formerly proposed by the authors of this paper. The main objective was to reveal the differences between bubble growth behavior at atmospheric pressure and sub-atmospheric pressure. A secondary objective was to show the effect of the system pressure on bubble growth behavior. Experimental data were correlated using the non-dimensional characteristic radius and time scale parameters proposed in a previous study. The growth behavior at sub-atmospheric pressure was noticeably different from that at atmospheric pressure during saturated nucleate pool boiling.

Keywords: Bubble growth; Nucleate pool boiling; Atmospheric pressure; Sub-atmospheric pressure

1. Introduction

Many experiments and analyses have been performed to clarify the heat transfer mechanism of boiling. The overall characteristics of boiling are directly and indirectly influenced by the growth behavior of a single bubble on the heating surface. The heat transfer mechanism for single bubble growth is related to the characteristics of the thermal boundary layer on the heating surface. These characteristics can be controlled using the wall and pool temperatures, and the system pressure.

It has recently been discovered that the bubble growth rate at atmospheric pressure is proportional to the power of 1/5 of the time in the thermal growth region during saturated nucleate pool boiling of pure and binary mixtures [1,2]. The bubble growth rate is proportional to the power of 2/3 of the time in the initial (or inertia) growth region for the same conditions [3]. The bubble growth rate is also proportional to the power of 1/5 of the time in the thermal growth region during partial nucleate pool boiling ($Ja < 30$) experiments at various wall temperatures [4]. For subcooled and slightly superheated nucleate pool boiling, the bubble growth rate is proportional to the power of 2/3 and 1/5 of the time in the initial and thermal growth regions when using newly proposed characteristic temperature scales [5].

Several experiments have been performed for a high Jakob number, from 40 to 2100, using water, methanol, and *N*-pentane [6,7]. The experimental results, performed with a constant heat flux wall, have been compared with results obtained from previous analytical relationships. However, these studies did not quantitatively compare their data with each other and did not give the growth rate on the heating surface. Consequently, it is necessary to evaluate the differences in bubble growth behavior between low and high Ja numbers to further understand nucleate pool boiling.

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Nomenclature

b^*	van Stralen's bubble growth parameter
C_{pl}	specific heat of liquid (J/(kg K))
h_{fg}	latent heat (J/kg)
Ja	Jakob number ($=\rho_l C_{pl}\Delta T/(\rho_v h_{fg})$) (–)
Pr_l	Prandtl number (–)
P_{sys}	pool or system pressure (kPa)
P_v	vapor pressure (kPa)
$P_v(T_{wall})$	vapor pressure for T_{wall} (kPa)
ΔP^+	dimensionless pressure potential given by Eq. (1) (–)
R	bubble radius (m)
R^+	dimensionless bubble radius (–)
R_{ch}	characteristic bubble radius (m)
t	time (s)
t^+	dimensionless bubble time (–)
t_{ch}	characteristic time (s)
t_d	departure time of the bubble (s)
T_{sat}	saturation temperature (K)
T_{wall}	wall temperature (K)
ΔT	wall superheat ($=T_{wall} - T_{sat}$) (K)
α_l	thermal diffusivity of liquid (m^2/s)
ρ_l	density of liquid (kg/m^3)
ρ_v	density of vapor (kg/m^3)
υ_v	specific volume of vapor (m^3/kg)

2. Results and discussion

Bubble growth behavior obtained during saturated nucleate pool boiling at sub-atmospheric pressure is shown in Fig. 1. The bubble radius obtained at sub-atmospheric pressure was larger than that obtained at atmospheric pressure, as shown in Fig. 1a–d, and the bubble radius increased when system pressure decreased, regardless of the fluid. The bubble radius at departure at sub-atmospheric pressure was also larger than that at atmospheric pressure. This increase of bubble radius could have occurred due to the rise in pressure potential based on the wall temperature. We estimated the dimensionless pressure potential using Eq. (1), and the results are shown in Fig. 2. From Fig. 2, the dimensionless pressure potential and Jakob number at sub-atmospheric pressure were higher than those at atmospheric pressure, except for three conditions.

$$\Delta P^+ = \frac{P_v(T_{wall}) - P_{sys}}{P_{sys}} \tag{1}$$

The differences in the thermodynamic properties of water at atmospheric and sub-atmospheric pressure (6.7 kPa) are shown in Table 1. The specific volume at 6.7 kPa is 12 times greater than that at atmospheric pressure. Even if the mass of the liquid evaporated in the interface between the bubble and the surrounding liquid is the same, the volume change in the bubble will increase due to the high specific volume. Since the bubble growth rate is the ratio of the volume change of the bubble, or the volumetric evaporation rate of the bubble, to the change in time, this depends on the thermal boundary layer thickness around the bubble and the liquid-side temperature gradient at the bubble interface. At sub-atmospheric pressure, the growth rate could be higher than that at atmospheric pressure owing to the difference in the thermodynamic properties (high Jakob number) and the higher dimensionless pressure potential.

Cole and Shulman [6] and van Stralen et al. [7] conducted experiments at sub-atmospheric pressure using various fluids. The results of the bubble radius obtained for almost the same system pressure using the same fluid (water) are compared in Fig. 3a–c for each system pressure. The growth behavior of the bubbles was almost identical, but the departure radius and time showed minor differences. There could be several reasons for this, such as the use of different heating surfaces.

Fig. 4 compares Cole and Shulman's experimental data [6] with results obtained previously from the analytical relations given by Eqs. (2)–(5) [9–12].

$$R = \sqrt{\frac{12}{\pi}} Ja \sqrt{\alpha_l t} \tag{2}$$

$$R = \frac{1}{\sqrt{\frac{3\rho_l T_{sat}}{2\rho_v h_{fg} \Delta T t^2}} + \frac{\sqrt{\pi} Pr_l}{4 Ja \sqrt{\alpha_l t}}} \tag{3}$$

$$R^+ = \frac{2}{3}\left[(t^+ + 1)^{3/2} - t^{+3/2} - 1\right] \tag{4}$$

$$R = \frac{1}{1/R_1(t) + 1/R_2(t)} \tag{5}$$

$$R_1(t) = 0.8165 \left[\frac{\rho_v h_{fg} \Delta T \mathrm{e}^{-\left(\frac{t}{t_d}\right)^{1/2}}}{\rho_l T_{sat}}\right]^{1/2} t \tag{6}$$

$$R_2(t) = 1.9544 \left[b^* \mathrm{e}^{-\left(\frac{t}{t_d}\right)^{1/2}}\right] Ja \sqrt{\alpha_l t} + 0.373 Pr_l^{-1/6} \left[\mathrm{e}^{-\left(\frac{t}{t_d}\right)}\right]^{1/2} Ja \sqrt{\alpha_l t} \tag{7}$$

There was a large deviation in the growth rate obtained from the experimental and analytical results.

The experimental data shown in Fig. 1 were correlated using the non-dimensional characteristic radius, the time scales of Eq. (8) proposed by Mikic et al. [11], and the relationships proposed by Kim et al. [4].

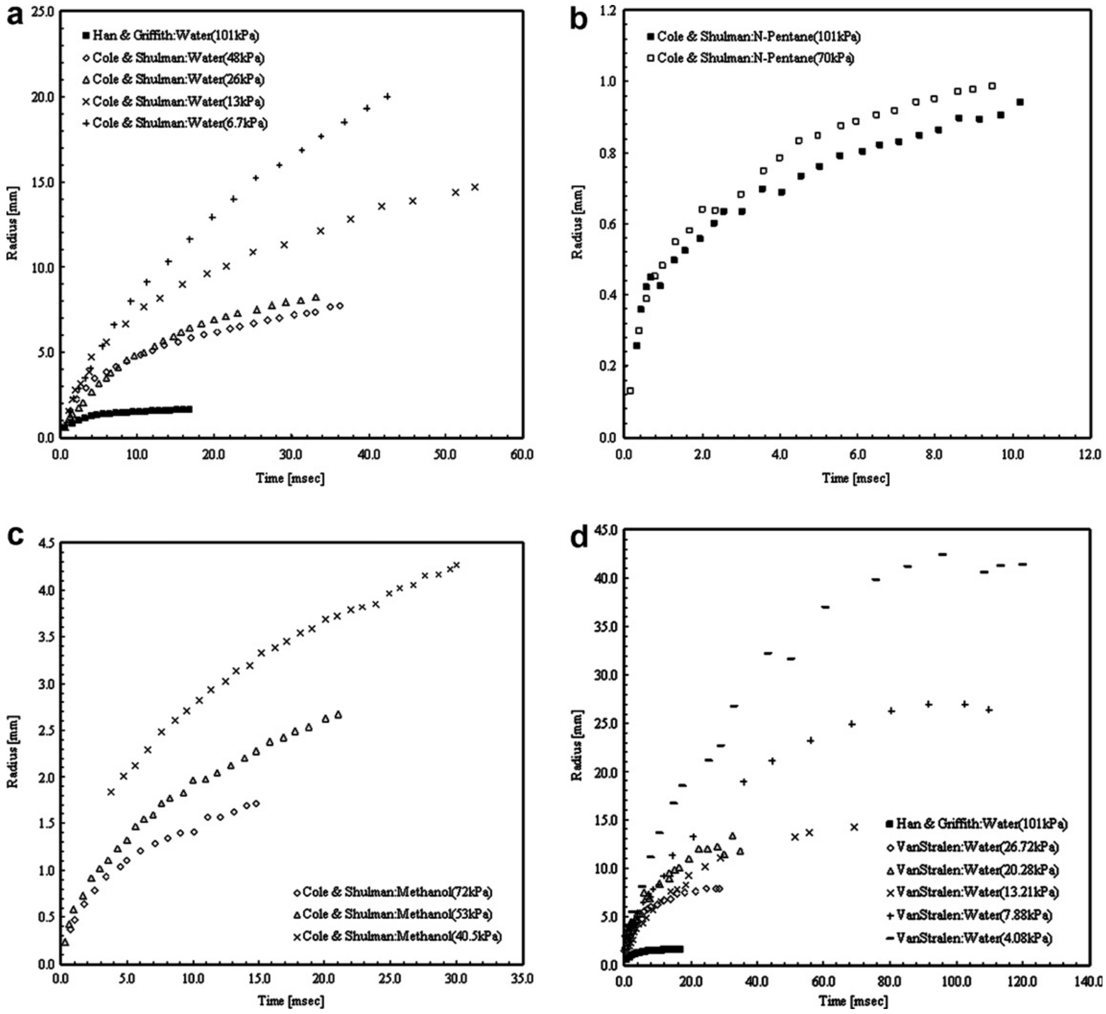

Fig. 1. Bubble radius to time at sub-atmospheric pressure. (a) Atm: Han and Griffith [8], Sub-atm: Cole and Shulman [6] using water. (b) Atm: Cole and Shulman [6], Sub-atm: Cole and Shulman [6] using *N*-pentane. (c) Sub-atm: Cole and Shulman [6] using methane. (d) Atm: Han and Griffith [8], Sub-atm: VanStralen [7] using water.

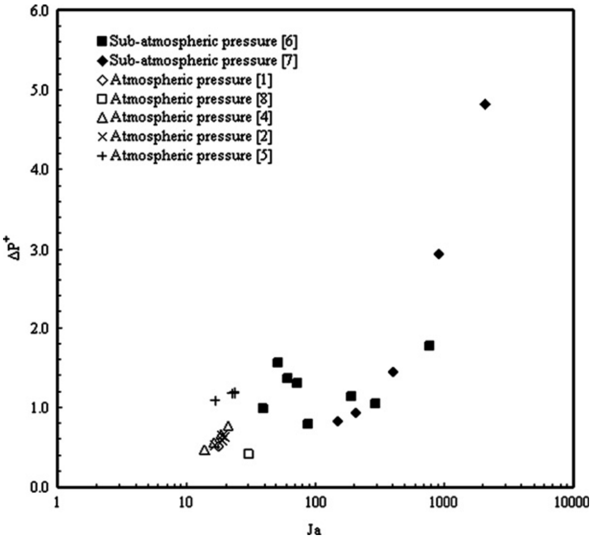

Fig. 2. Characteristics of the dimensionless pressure potential to the Jakob number.

Table 1
Comparison of thermodynamic properties at atmospheric and 6.7 kPa of water

Items	Unit	101.3 kPa	6.7 kPa	Ratio[a]
T_{sat}	(K)	373	311	83.3%
ρ_{l}	(kg/m^3)	959	993	103.6%
υ_{v}	(m^3/kg)	1.68	21.76	1295.0%
C_{pl}	(J/(kg K))	4216	4180	99.1%
h_{fg}	(J/kg)	2,256,500	2,411,500	106.9%
α_{l}	(m^2/s)	1.68E-07	1.512E-07	90.0%
σ_{l}	(N/m)	0.05894	0.06994	118.7%
μ_{l}	(N s/m^2)	0.00028	0.0006802	241.0%
k_{l}	(W/(m K))	0.68	0.63	92.4%

[a] Ratio were determined as the ratio of the properties at 6.7 kPa to those at 101.3 kPa.

$$R^+ = \frac{R}{R_{\mathrm{ch}}(=B^2/A)}, \quad t^+ = \frac{t}{t_{\mathrm{ch}}(=B^2/A^2)} \tag{8}$$

$$A = \left[\frac{\pi}{7}\frac{\rho_v h_{fg}\Delta T}{\rho_l T_{\mathrm{sat}}}\right]^{1/2}, \quad B = \left[\frac{12}{\pi}Ja^2\alpha_l\right]^{1/2} \tag{9}$$

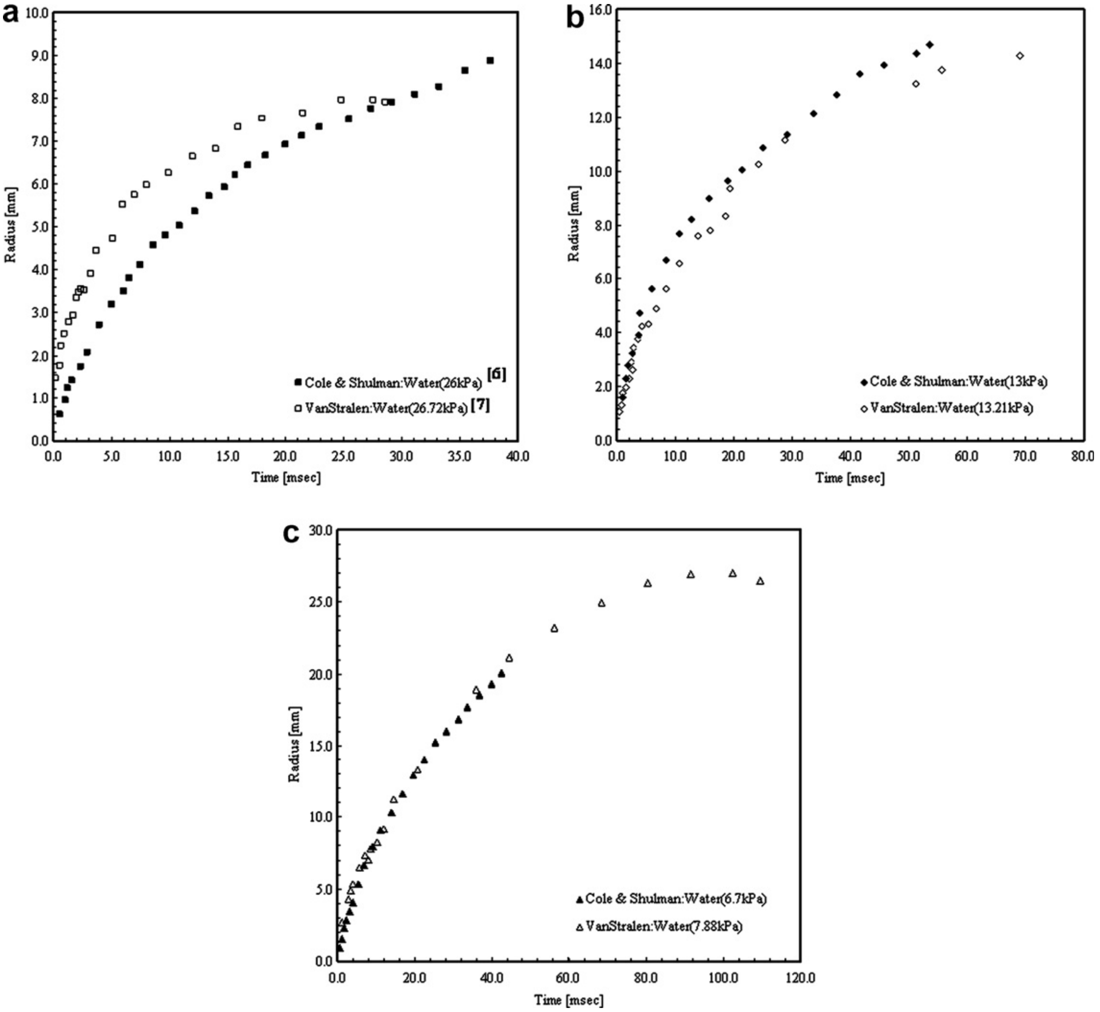

Fig. 3. Bubble growth behavior for the same system pressure and fluid. (a) Behavior at 26 kPa. (b) Behavior at 13 kPa. (c) Behavior at 7–8 kPa.

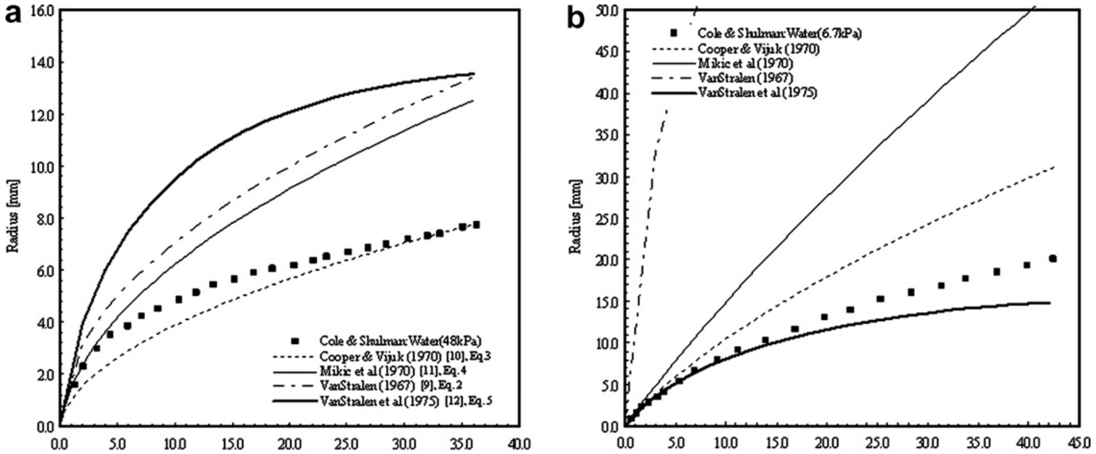

Fig. 4. Comparison of the measured and calculated bubble radius (a) $P_{sys} = 48$ kPa and water (Cole and Shulman [6]). (b) $P_{sys} = 6.7$ kPa and water (Cole and Shulman [6]).

This allowed a comparison of the experimental results and illustrated the growth rate characteristics at sub-atmospheric pressure using the same reference scales for length and time. The results are presented in Fig. 5. The growth rate at sub-atmospheric pressure was very different from that at atmospheric pressure. When the dimensionless time

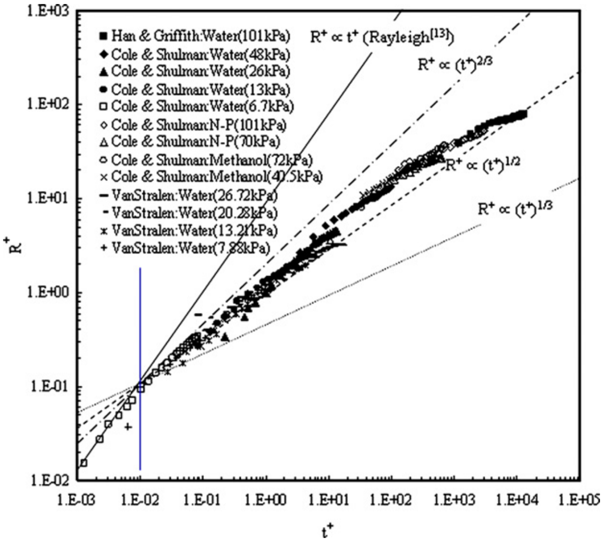

Fig. 5. Dimensionless bubble growth behavior.

(t^+) was less than 0.01, the dimensionless radius (R^+) was linearly proportional to t^+ and almost coincided with the growth rate proposed by Rayleigh [13], with R^+ proportional to the power of 2/3–1/2 of t^+. Some of the results showed a lower growth rate closer to the departure time.

There appeared to be no discernible difference between the working fluids. The bubble growth behavior at sub-atmospheric pressure was definitely higher than that at atmospheric pressure during saturated nucleate pool boiling because the relatively high pressure potential created more momentum based on the Rayleigh–Plesset equation owing to the high specific volume.

Revealing the growth rate during the time from inception to departure is important because the heat flow rate supplied to the bubble corresponds to that required for the total bubble volume change. This is based on the assumption that the volume change is induced by latent heat transfer. These phenomena at sub-atmospheric pressure need to be analyzed, and the results from this study can supply good analytical results as a first approach to non-dimensional comparisons of bubble growth behavior at sub-atmospheric pressure.

3. Conclusions

Non-dimensional comparisons of the single bubble growth rate during saturated nucleate pool boiling were conducted for atmospheric and sub-atmospheric pressure conditions presented in previous studies. The bubble growth rate at sub-atmospheric pressure was fundamentally different from that at atmospheric pressure during saturated nucleate pool boiling and showed a higher growth rate throughout. When the growth rates were plotted in the non-dimensional form, general trends became apparent irrespective of the system pressure.

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