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International Journal of Heat and Mass Transfer 47 (2004) 3583–3587
International Journal of HEAT and MASS TRANSFER
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Technical Note

Nucleation site interaction in pool nucleate boiling on a heated surface with triple artificial cavities

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Received 31 July 2003
Available online 19 March 2004

Abstract

The experiment of pool nucleate boiling of water was performed on a heated silicon surface with triple artificial cavities. The existence and the significance of three effect factors, the bubble coalescence factor 'C', the thermal interaction factor 'T' and the hydrodynamic interaction factor 'H', in the mechanism of nucleation site interaction is validated by comprehensive analysis and observation. It is revealed that the interaction is classified into three regions due to effects of the three factors.

1. Introduction

Many available researches of nucleate boiling focus on the physical process of nucleation site interaction [1–9]. Although the works were performed by the different approaches, all of them aimed to disclose the underlying mechanisms of nucleate site interaction. By employing an artificial surface with twin fabricated cavities, Zhang and Shoji [7] revealed the three significant effect factors on nucleation site interaction: factor 'C'—horizontal and declining bubble coalescence, factor 'T'—thermal interaction between nucleation sites, and factor 'H'—hydrodynamic interaction between bubbles. They identified that depending on the cavity spacing, the interaction can be classified into four regimes due to the competition and dominance of the three effect factors. In real boiling condition, however, there are more than two cavities on the heated surface. Therefore, the study on the heated surface with multiple cavities is required.

The present study makes one forward step on nucleation site interaction research. Namely, the heated surface with triple artificial cavities is employed in order to verify the existence and the significance of three effect factors on nucleation site interaction. The same concepts of experiment and analysis methods to those of Zhang and Shoji [7,8] are employed also in this work. Moreover, the thermal anemometry technique is also used to investigate the hydrodynamic interaction effect due to the fluid motion near the heated surface during the bubble generation. The results of this experiment clearly confirm that the three effect factors are influential and available in nucleate pool boiling.

2. Experimental apparatus

This experiment was conducted using the apparatus that was used in the research for twin artificial cavities by Zhang and Shoji [7] and Zhang [8]. In addition, the apparatuses were modified to install hot wire probes and anemometer unit. The heated surfaces with triple artificial cavities were fabricated by the same method of Zhang and Shoji [7]. The cavities were arranged on silicon surface into two patterns: "Inline" pattern and "Triangular" pattern. The spacing between cavities was varied as 1, 2, 3, 4, 5, 6, 7 and 8 mm, as demonstrated in Fig. 1. Nevertheless, for inline pattern, the cavity

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doi:10.1016/j.ijheatmasstransfer.2003.11.035

Nomenclature

f_d	mean bubble departure frequency per site (Hz)
$\bar{f}_c$	dimensionless bubble coalescence frequency
f_{HD}	horizontal and declining bubble coalescence frequency (Hz)
g	gravitational acceleration (m/s^2)
$\bar{h}$	dimensionless intensity of hydrodynamic interaction
L_c	the characteristic length scale from Fritz's equation (m)
R	temperature correlation coefficient
S	spacing between cavities (mm)

Greek symbols

σ	surface tension (N/m)
ρ	density (kg/m^3)
ψ_t	magnitude of thermal interaction between nucleation sites (m^{-1})

Subscripts

i	sampling number of data of a certain point around cavity
j	sampling number of data of a certain point around cavity
l	liquid
v	vapor

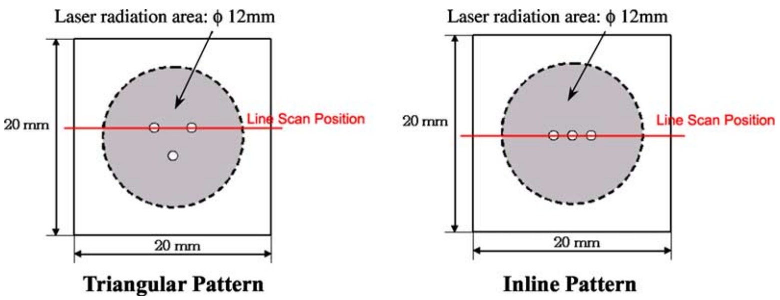

Fig. 1. Sketches of cavity arrangement and line-scan mode of temperature measurement.

spacing can be examined only for 1, 2, 3 and 4 mm because the effective laser diameter of the equipment was restricted in maximum 8 mm. All temperature data were recorded along the centerline of cavities in line-scan mode (see Fig. 1). Images of bubble behavior were captured by a high speed video camera with 1000 frames/s. Besides, the signals of hot wire probes were measured in voltage unit with time interval 0.001 s. In this experiment, video images, surface temperature and hot wire probe signals were simultaneously recorded in order to evaluate the relation among these three data.

3. Results and discussions

For triple artificial cavities, the analysis of three nucleation site interaction effect factors was carried out based on two nucleation sites in order to compare with twin cavities and distinguish the effect of another remaining nucleation site—the third cavity. In case of inline pattern, left cavity and middle cavity (L+M) and middle cavity and right cavity (M+R) were considered. Otherwise, left cavity and right cavity (L+R) was examined for triangular pattern due to unavailability of temperature measurement.

The characteristic length scale from Fritz's equation was introduced to normalize the bubble departure diameter as defined in the following equation

$$L_c = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \quad (1)$$

Fig. 2 presents the relation between the mean bubble departure frequency per site and dimensionless distance (S/L_c) for triple cavities and twin cavities. Fig. 2 obviously shows that the triple cavities for triangular pattern can produce bubble more frequent than the twin cavities.

3.1. Bubble coalescence factor

By the experimental observation in twin cavities [7,8], it was found that there are three types of bubble coalescence near the heated surface, which are "horizontal", "vertical" and "declining" bubble coalescences. In the present experiment, these three types of bubble coales-

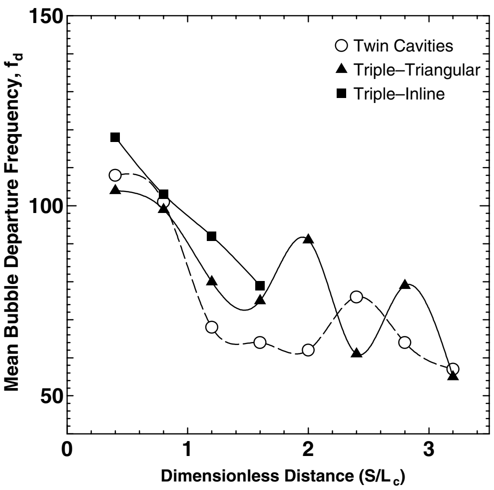

Fig. 2. The mean bubble departure frequency between triple cavities and twin cavities.

cence were observed also. However, only horizontal and declining bubble coalescences are important to the site interaction, the frequency of those bubble coalescences are considered as dimensionless H-D bubble coalescence frequency as

$$\bar{f}_c = \frac{f_{HD}}{2 \cdot f_d} \quad (2)$$

This dimensionless parameter indicates that how many percentage of the bubbles generated from neighboring two cavities will coalesce in horizontal and declining direction. Fig. 3 shows the comparison of the average value of dimensionless H-D bubble coalescence frequency ($\bar{f}_c$), evaluated from all the data of laser heat fluxes, between triple cavities and twin cavities for various dimensionless distances (S/L_c). It clearly indicates that the rate of H-D bubble coalescence frequency in triangular pattern is higher than that in inline pattern. However, the difference is not marked when compared with the case of twin cavities. It is identified in Fig. 3 that H-D bubble coalescence is greatly significant when $S/L_c < 1.5$ for both cases of twin and triple cavities.

3.2. Thermal interaction factor

The thermal interaction between nucleation sites was evaluated by the correlation coefficient between the temperature at the individual cavity and the temperature at a certain point around the cavity. The magnitude of the correlation coefficient was defined in the following expression

$$\psi_t = \frac{\sum_{i=x_{(1)}}^{x_2} R_{ci} + \sum_{j=x_2}^{x_3} R_{cj}}{X_3 - X_{(1)}} \quad (3)$$

where R_{ci} and R_{cj} are the temperature correlation coefficient between the cavity and other points i and j, respectively, and $X_{(1)}$, X_2 and X_3 are the position of first cavity, centerline of tested surface and second cavity, respectively (see Fig. 4).

Fig. 5 illustrates the relation between the average values of the magnitude of thermal interaction with the different cavity spacing. As can be seen in Fig. 5, the thermal interaction between nucleation sites is

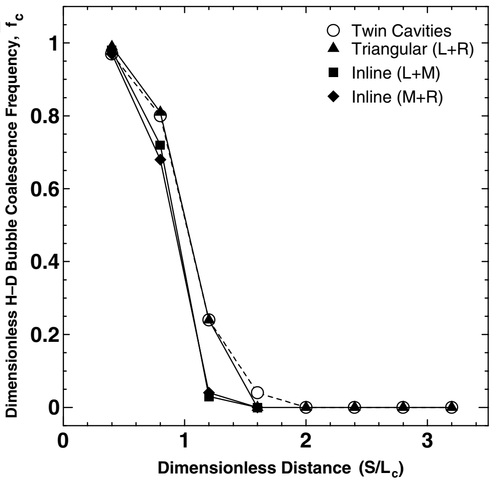

Fig. 3. The average dimensionless H-D bubble coalescence frequency for triple cavities and twin cavities.

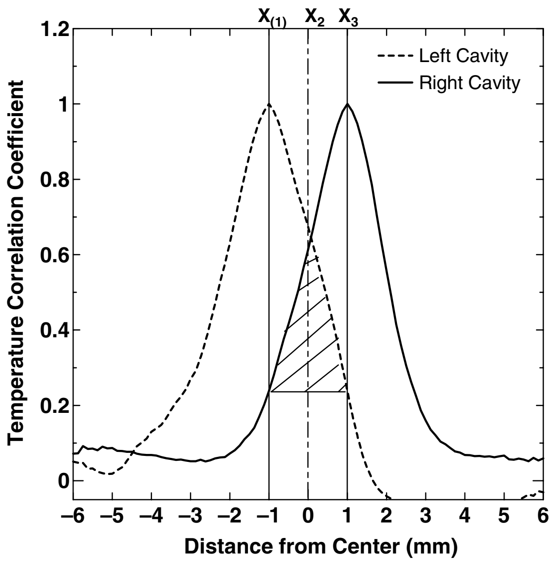

Fig. 4. Evaluation method for thermal interaction length for triple cavities: triangular pattern.

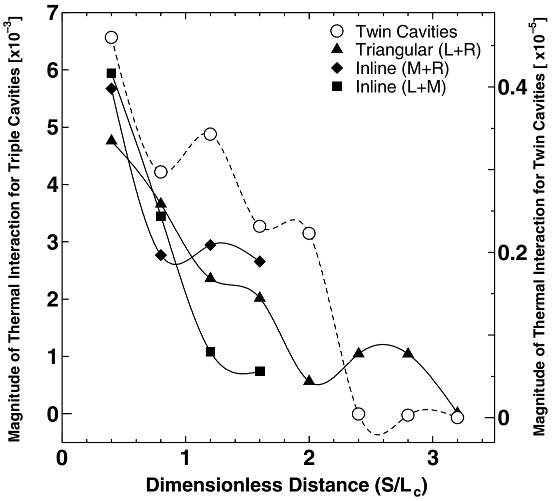

Fig. 5. The average magnitude of thermal interaction between triple cavities and twin cavities.

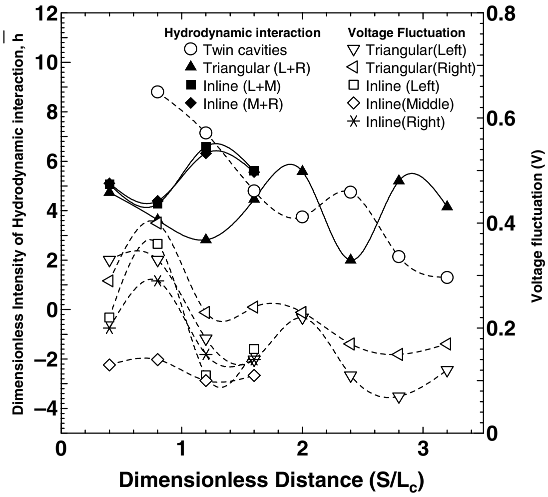

Fig. 6. Comparison between two approaches for evaluation of the hydrodynamic interaction factor in triple cavities.

significant when the distance between cavities is small. For $S/L_c < 0.8$, it seems that inline pattern has the effect of factor 'T' stronger than in case of triangular pattern, whereas it is reversed when $0.8 < S/L_c < 1.5$. By overall, the tendencies of both triple cavities patterns tend to the same direction to that of twin cavities.

3.3. Hydrodynamic interaction factor

The hydrodynamic interaction between bubbles was determined by the dimensionless intensity of hydrodynamic interaction ($\bar{h}$). It is defined as the ratio of the convective heat transfer coefficient from two sites of triple cavities case to that in the single cavity condition. The tendencies of the intensity are demonstrated in Fig. 6 as a function of dimensionless distance. When only triple cavities case was considered, it can be seen from Fig. 6 that the tendencies of this dimensionless parameter between inline pattern and triangular pattern are apparently opposite for $0.8 \leqslant S/L_c \leqslant 1.5$. Furthermore, when focused between twin cavities and triangular pattern, it is evident that both tendencies are contrary in range of $1.2 \leqslant S/L_c \leqslant 2.8$. From this comparison, the variation of the dimensionless intensity of hydrodynamic interaction in triple cavities is less than that in twin cavities. This appearance is possibly caused by the effect of the remaining nucleation site. It was suggested in twin cavities study [7,8] that the occurrence of the hydrodynamic interaction may influence the liquid flow velocity, especially liquid wake effect around bubbles which impact on bubble behaviors. Therefore, excluding the dimensionless intensity of hydrodynamic interaction was computed in triple cavities, the fluid motion near the heated surface during bubble generation is also detected by hot wire anemometer. The average voltage fluctuation from hot wire probe signals is considered at the different dimensionless distance as shown in Fig. 6. The results of voltage fluctuation simply indicate that the smaller cavity spacing, the stronger flow field around bubbles becomes. Although the tendencies between the dimensionless intensity of hydrodynamic interaction and the voltage fluctuation from hot wire probes are not exactly compatible, it may suppose that these two approaches can be applied to evaluate the influence of hydrodynamic interaction in nucleate pool boiling.

3.4. Mechanism of nucleation site interaction

The nucleation site interaction regions on heated surface with triple cavities can be classified into three regions due to the results of intensity, competition and dominance of three effect factor: factor 'C', factor 'T' and factor 'H' as summarized in Table 1. When compared with the results for twin cavities, it is said that the effect of thermal interaction is stronger and the region 'H' cannot clearly identify. This may be the result of effective radial thermal interference from the third cavity.

3.5. Experimental uncertainty

In this study, the quantitative analysis was performed on the temperature data, video images and hot wire probe signals. Therefore, the amount of data is important and it also takes effect on the experimental results. Moreover, the uncertainties in experimental set up may also cause the experimental error.

Table 1
Influence intensity of three effect factors of nucleation site interaction at the different S/L_c for triple cavities

Main effect factors	Triangular pattern		
	Inline pattern		
	S/L_c		
	$S/L_c \leqslant 1.5$	$1.5 < S/L_c \leqslant 3$	$S/L_c > 3$
Hydrodynamic interaction between bubbles (factor 'H')	O	O	X
Thermal interaction between nucleation sites (factor 'T')	O	O	X
Horizontal and Declining bubble coalescences (factor 'C')	O	X	X

X: negligible; O: considerable.

4. Conclusion

The investigation in this study verified the existence and significance of three nucleation site interaction effect factors: factor 'C'—horizontal and declining bubble coalescence, factor 'T'—thermal interaction between nucleation sites and factor 'H'—hydrodynamic interaction between bubbles. It was found that the nucleation site interaction regions can be classified into three regions depending on the significance of the three effect factors. The fundamental mechanism of nucleation site interaction is the same to the case of twin cavities but there seems to be minute difference between cases of triple cavities and twin cavities. This result implies that the complexity of nucleation site interaction is a function of the number of nucleation site.

Acknowledgements

The authors would like to thank Mr. Jiunnjye Tsaur of the national institute of advanced industrial science and technology (AIST) for his contribution in artificial surface fabrication. They would like to extend their thanks also to Dr. Lei Zhang for her valuable suggestions in carrying out the present research.

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