PERGAMON

International Journal of Heat and Mass Transfer 43 (2000) 3317–3330

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Investigation of randomness, overlap and the interaction of bubbles forming at adjacent nucleation sites in pool boiling

Robert Mallozzi[a,1], Ross Leonard Judd[a,*], Narayanaswamy Balakrishnan[b]

[a]*Department of Mechanical Engineering, McMaster University, 1280 Main Street West, Hamilton, Ont., Canada L8S 4L7*
[b]*Department of Mathematics and Statistics, McMaster University, 1280 Main Street West, Hamilton, Ont., Canada L8S 4K1*

Received 3 September 1998; received in revised form 23 November 1999

Abstract

A computer simulation of the experimental research carried out by Chopra (1992) using the same boiling conditions and boiling surface data is reported in this paper. The interaction of the bubbles forming at adjacent sites was governed by the site seeding principle as postulated by Judd. A Gamma distribution was used to analyse the time elapsed between the formation of bubbles at different pairs of dominant and passive sites. The relationship of the Gamma shape parameter with dimensionless separation distance as well as the conditions determining the promotion or inhibition of bubble interaction obtained through this simulation study closely resembles those observed experimentally by Chopra. The agreement between the results of this simulation study and the previously published experimental results provides support for Judd's site seeding interaction mechanism. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The ultimate goal of boiling research is to be able to predict boiling heat transfer rates without recourse to empiricism. Much effort has been devoted to this goal over the last 40 years, but a lot of it has been directed toward the determination of specific relationships between heat flux and surface superheat for various fluid/surface combinations. Concerted efforts to involve the physics underlying the phenomenon and to incorporate surface characteristics have been made only in the last 15 years. If the underlying mechanisms were better understood, it would be possible to predict boiling heat transfer rates and to design boiling heat transfer surfaces to specification. More importantly, the ability to predict boiling heat transfer rates reliably would permit the performance of boiling heat transfer surfaces to be optimized.

A probabilistic approach to relating boiling heat transfer rate to the surface characteristics is being pursued. If the number of nucleation sites per unit area were known and if the sites were known to be located randomly over the boiling surface, the active site density could be predicted provided that relationships were known for the probability of bubble nucleation at each of the sites. Once the active site density were known for a particular fluid/surface combination, the bubble flux density and boiling heat transfer rate could be predicted in the manner outlined in Shoukri and Judd [1]. The problem of relating boiling heat transfer rate to sur-

* Corresponding author. Tel.: +1-905-525-9140; fax: +1-905-572-7944.

E-mail address: juddr@mcmaster.ca (R.L. Judd).

[1] Present address: Atomic Energy of Canada Limited, 2251 Speakman Drive, Mississauga, Ont., Canada L5K 1B2

0017-9310/00/$ - see front matter
PII: S0017-9310(99)00377-4

Nomenclature

A	surface area
a	localized area
Na	number of active nucleation sites
N/A_T	active site density
$R(t)$	radius of a bubble at the dominant site
$\mathscr{R}(\tau)$	radius of a bubble at the passive site
S	separation distance
t	elapsed time for bubble growth at the dominant site
τ	elapsed time for bubble growth at the passive site
X	$\frac{\text{projected area of the overlapping bubbles}}{\text{projected area of the bubbles without overlap}}$

Greek symbols

α	$\frac{\text{projected area of the bubbles without overlap}}{\text{area of the boiling heat transfer surface}}$
α_l	thermal diffusivity of the liquid
λ	ν times the reciprocal of average time elapsed between two events
ν	shape parameter

Subscripts

l	liquid
v	vapour

face characteristics then becomes a matter of determining the probability relationships, which depend upon the interaction between bubbles emitted at adjacent nucleation sites.

Judd [2] postulated a bubble formation model based upon site activation (the process whereby a bubble forming at a nucleation site deposits a vapour nucleus in an adjacent nucleation cavity which subsequently grows into a bubble) and deactivation (the process whereby a bubble forming at a nucleation site absorbs/dislodges the vapour nucleus in an adjacent nucleation cavity and prevents it from growing into a bubble). A computer program running a simulation routine capable of generating statistics that can be compared with those of the experiment reported by Judd and Chopra [3] is the most effective way to test this postulate.

The idea of interaction between the bubbles forming at adjacent nucleation sites is not commonly accepted because the interaction phenomenon is not well understood. Though some research has been performed on the topic, no theory governing the interaction between the bubbles forming at adjacent nucleation sites has been developed. Models have been proposed separately by Judd and Lavdas [4] and Kenning and Yan [5], which attempt to describe the nature of interaction between the bubbles forming at adjacent nucleation sites. The appropriateness of these models is the focus of the present investigation.

Kenning's model postulates that the mechanism of bubble growth and interaction is energy dependent, which is to say that a nucleus will grow into a bubble only when the appropriate surface temperature has been reached such that there is sufficient energy to support bubble growth. Kenning's research has established that as a bubble grows at a nucleation site, there is a decrease in the energy contained in the surface in the vicinity of the nucleation site. If a neighbouring site exists within the area of influence, the temperature of the surface at the neighbouring site may have been diminished enough to delay nucleation. Kenning postulates that a site could constantly emit bubbles as long as there were sufficient energy. The implication is that there will always be a vapour nucleus available to grow into a bubble at a nucleation site.

Judd's model postulates that the mechanism of bubble growth and interaction is dependent upon the availability of a vapour nucleus trapped in the surface cavity. It is postulated that there is always sufficient energy to grow the bubbles and it is the availability of a vapour nucleus which determines whether or not a bubble will form. The implication is that when a bubble departs, it may deposit vapour in the neighbouring empty cavities or conversely, deplete the cavities of the vapour nucleus that they already have and render them inactive until vapour is re-deposited in them.

2. Previous research

Chekanov [6] researched the interaction between bubbles forming at neighbouring nucleation sites by investigating a model for bubble interaction in which the elapsed time between bubble departure at neighbouring nucleation sites is random and possesses a Gamma distribution. This distribution predicts the probability $g(\tau)$ of an event occurring within a time interval $(\tau,\ \tau + d\tau)$ according to

$$g(\tau) = \left[\frac{\lambda^{\nu}\tau^{\nu-1}}{\Gamma(\nu)}\right]e^{-\lambda\tau} \tag{1}$$

In this equation, λ is ν times the reciprocal of the average time that elapsed between events $\bar{\tau}$ and ν is the shape parameter of the Gamma distribution; in other words, ν/λ is the average elapsed time $\bar{\tau}$. The time difference between the formation of a bubble at one site and the formation of a bubble at another site was repeatedly measured for a variety of separation distances. Using the time difference measurements, histograms were constructed and the Gamma distribution was fitted to them. The shape parameter ν was indicative of the nature of the interaction.

Situations in which ν is greater than unity are evidence of bubble 'promotion' or positive interaction. In this case, bubbles form more frequently than would otherwise be expected as the separation distance between nucleation sites decreases. Situations in which ν is less than unity are evidence of bubble 'inhibition'. In this case, bubbles form less frequently than would otherwise be expected at the intermediate separation distances. When ν is identically equal to unity, the Gamma distribution becomes the Exponential distribution which implies that there is no interaction between the formation of bubbles at the adjacent nucleation sites, in which case bubble formation at the sites is independent of each other. Bubbles form independently of each other as the separation distance between nucleation sites becomes large.

Chekanov saw evidence of all three of these types of interaction as indicated in Fig. 1. When dimensionless separation distance $S/\bar{D}_b$ was less than 3, the shape parameter ν was greater than unity, consistent with positive interaction. When dimensionless separation distance $S/\bar{D}_b$ was between 3 and 10, the shape parameter ν was less than unity which is consistent with negative interaction. When dimensionless separation distance $S/\bar{D}_b$ exceeded 10, the shape parameter ν approached unity which is consistent with independence.

Calka and Judd [7] boiled dichloromethane on a stannic oxide coated glass surface to investigate the interaction between bubbles forming at neighbouring nucleation sites, using laser light to identify them. A 2 mm diameter beam from a 50 mW helium–neon laser was directed through a diverging lens and a collimating lens to increase its diameter to approximately 20 mm. A mirror was then used to reflect the beam such that it illuminated the underside of the glass boiling surface. The light reflected by bubbles forming at the boiling surface was reflected off the surface of a rhomboidal prism to a locating apparatus which contained two photo-transistors and two eyepieces capable of focusing on the images of two different nucleation sites. When a bubble grew at the surface, the light intensity at the position at which the photo-transistor was located increased and its existence was acknowledged as a voltage spike which was distinguished from the background signal by means of Schmitt triggers. The Schmitt triggers generated clock counter interrupts within a DECLAB 11/03 laboratory computer each time the voltage spike exceeded a preset value which corresponded to the time of the occurrence. Elapsed time was measured between growth at neighbouring nucleation sites similar to Chekanov [6]. It was found that promotion existed between nucleation sites whose centres lay within one bubble departure diameter and that inhibition existed between nucleation sites whose centres were greater than one bubble departure diameter. A plot of dimensionless separation distance against shape parameter which presents the research performed by Calka is presented in Fig. 2.

The research performed by Calka and Judd was continued in 1984 by Knowles (Judd [2]). Knowles used the same apparatus as Calka and also boiled dichloromethane on a glass boiling surface. The boiling surface, however, was not the same one used by Calka since his boiling surface had been destroyed towards the end of his research. However, data acquisition was performed similar to Calka where Schmitt triggers were used to send elapsed time measurements to the DECLAB 11/03 laboratory computer. Calka's curve fit

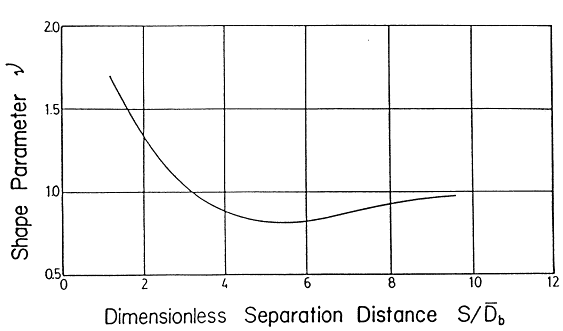

Fig. 1. Chekanov's results for the interaction of bubbles forming in water boiling on a thin Permalloy ribbon.

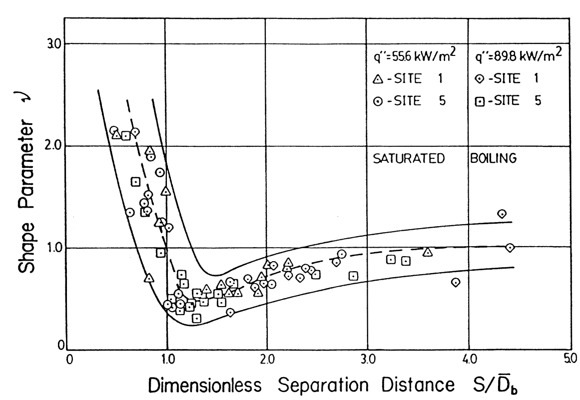

Fig. 2. Shape parameter vs. dimensionless separation distance for the research performed by Calka.

program (GAMFIT) was modified to include an optimization routine and used to fit the data acquired by Knowles with the Gamma density function. While Calka's version required the parameters of the distribution to be input manually until the fit of the distribution to the data was within tolerable limits, Knowles' version of the program searched for a minimum value of the chi-square statistic based on the difference between successive distributions.

Knowles' results differed from both Calka's and Chekanov's as seen in Fig. 3. In the research conducted earlier by Chekanov [6] and Calka and Judd [7], the shape parameter ν was greater than one for those situations in which $S/\bar{D}_b$ was between 0.5 and 1.0 and Knowles' research agreed with this. In the previous research, however, ν took on values less than one when $S/\bar{D}_b$ was between 1.0 and 4.0 while Knowles' research did not show this effect. Instead, the shape parameter remained approximately equal to unity for values of $S/\bar{D}_b$ greater than 1.0.

The difference was interpreted by Judd [2] as the result of differences in the surfaces used. Calka's boiling surface had been used for hundreds of hours and was, therefore, 'well aged' whereas Knowles' boiling surface had been in use for a much shorter period of time. Because of the nature of the stannic oxide coating on the surface, the surfaces have to be "broken-in" for a period of time to develop the pits and scratches which can hold vapour and form the nucleation sites. It is reported that Knowles had a very difficult time "breaking-in" the surface on which he was conducting his experiments. His surface had approximately half as many potentially active sites as Calka's and his separation distances were, therefore, greater than Calka's.

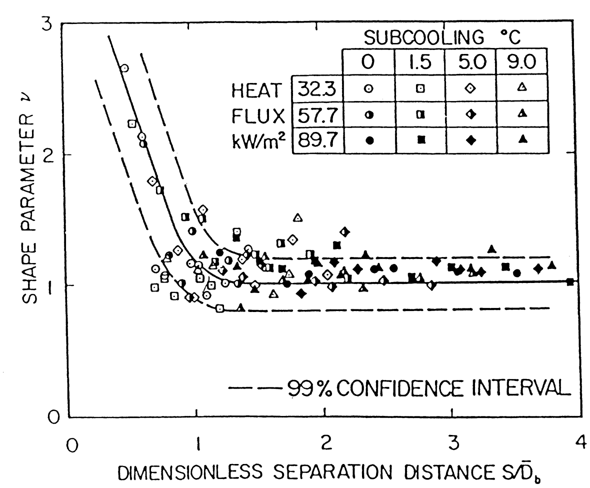

Fig. 3. Results of Knowles' investigation of boiling dichloromethane on a glass surface.

3. Research investigation

Chopra [8] investigated the relationship between the shape parameter ν and the dimensionless separation distance $S/\bar{D}_b$ in order to determine the difference between Calka's and Knowles' results. The apparatus that he used, which is depicted in Judd and Chopra [3], was the same as that used by both Calka and Knowles. It was capable of locating nucleation sites as well as measuring the time elapsed between bubble formation at one site and the formation of a bubble at another site. Chopra varied bubble departure size and nucleation site density independently in the course of the investigation by manipulating the vessel pressure and heat flux, respectively.

As depicted in Fig. 4, Chopra's field of view captured 22 active nucleation sites in an area 9.8 mm × 5.8 mm. This is an arbitrary small section of the boiling surface which was thought to be representative of the entire surface. To substantiate the assumption that Chopra performed his investigation on a boiling surface without any distinguishing features, a randomness test was performed. Chopra's boiling surface was subdivided into local cells and the number of sites found to exist in each cell was noted as seen in Fig. 4. The Poisson distribution was used for evaluation purposes since it could be used to predict the probability of finding a specific number of active sites (Na) within a specified local area (a) of the total boiling surface area (A) assuming the sites to be randomly distributed. Many natural processes follow a Poisson distribution which is represented mathematically as follows:

$$P(Na) = \frac{e^{-\overline{Na}}\,\overline{Na}^{Na}}{Na!} \tag{2}$$

where

$P(Na)$ probability of finding 'Na' active sites in area 'a'

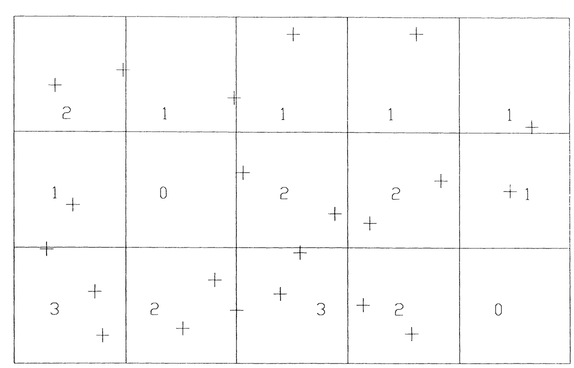

Fig. 4. Depiction of cells used to divide Chopra's boiling surface. Numbers indicate the number of active sites found to exist in each cell.

Na actual number of active sites in area 'a'
$\overline{Na}$ expected number of active sites in area 'a'
a local surface area

The results of the comparison are presented graphically in Fig. 5. It is seen that the agreement between the Poisson distribution and Chopra's active site distribution is reasonable in as much as the value of χ^2 based upon the differences is of the order of 3 which can arise by chance alone 55 times out of 100. The implication is that the distribution of active nucleation sites on Chopra's boiling surface may in fact be considered to be adequately represented by a Poisson distribution which supports the hypothesis that the active sites are randomly distributed. Better agreement would have been attained if the active nucleation sites had been more numerous.

Kenning and Del Valle have performed analyses of the overlap of bubbles forming at nucleation sites on a boiling surface [9,10]. By comparing the actual boiling area covered by bubbles with the nominal area covered by boiling, the distribution of nucleation sites on the boiling surface can be distinguished and compared to regular patterns or random distributions. The nominal area covered by bubbles is a mathematical concept which is equal to the total projected area of all the bubbles on the boiling surface at departure. The actual

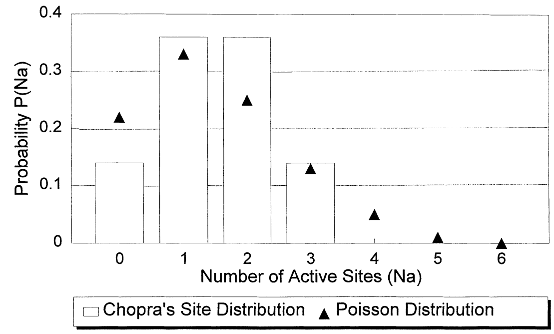

Fig. 5. Chart depicting active site distribution on Chopra's boiling surface.

boiling surface area covered by bubbles takes overlap into account. Physically, the actual area is calculated by transcribing and calculating the area of the bubbles at departure from each nucleation site, including the overlap. Fig. 6 presents the images of the bubbles at departure on Chopra's boiling surface with 2.5 mm diameter bubbles centred at each site location. The surface area covered by these bubbles was traced and calculated. The results of the present investigation are presented in Fig. 7 where the results are compared with those for a theoretically random distribution of sites and that of a regular array of sites. Chopra's

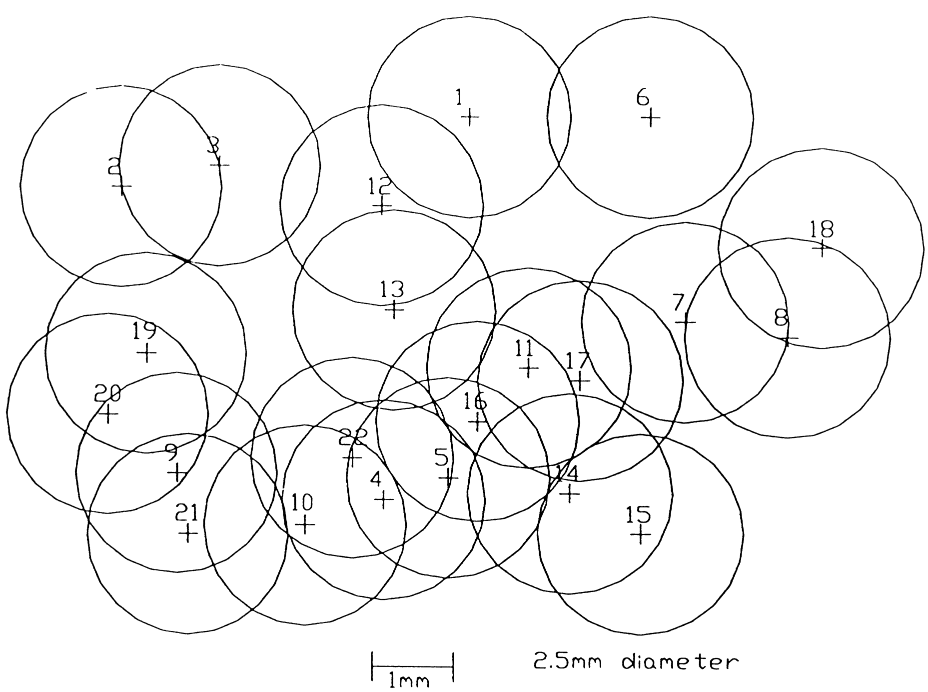

Fig. 6. Chopra's experimental boiling site map with 2.5 mm diameter bubble overlap.

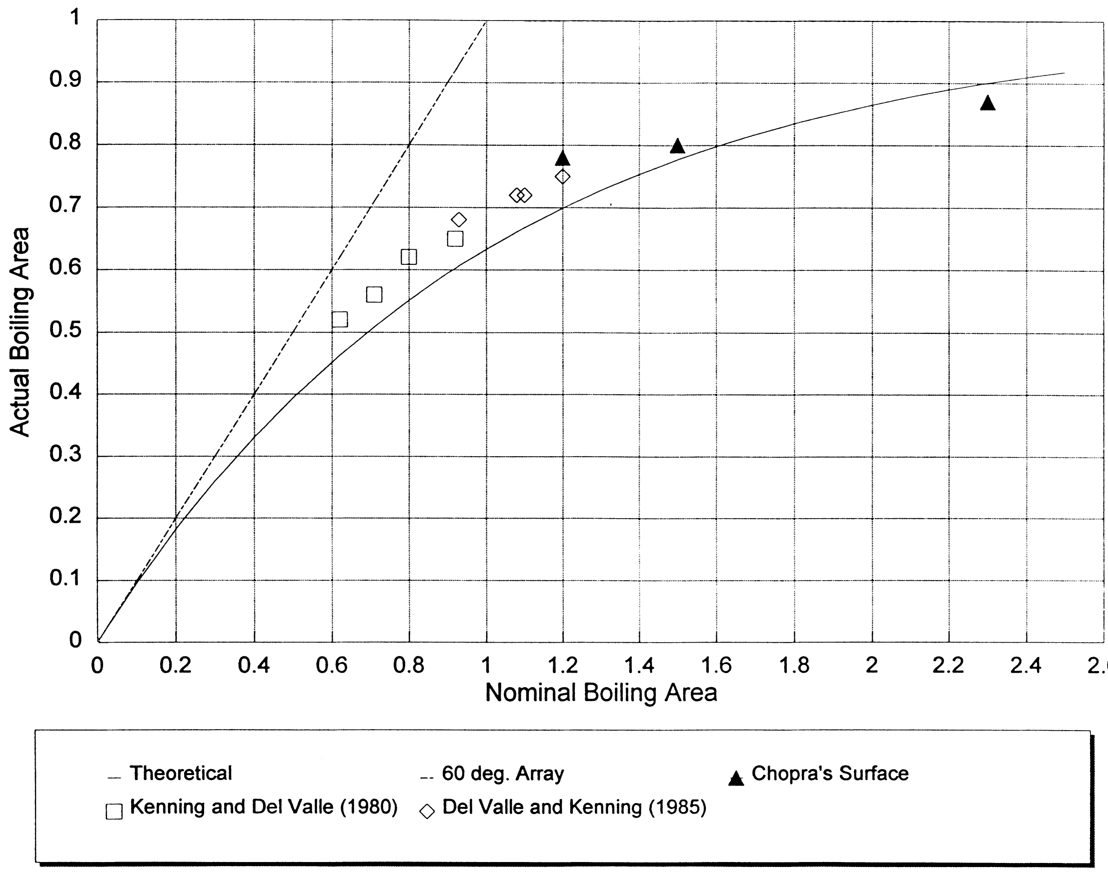

Fig. 7. Correlation of Chopra's surface data with random and 60° array of boiling sites.

nucleation site distribution results agree well with the random curve predicted by the relationship developed by Del Valle and Kenning [10].

$$X\alpha = 1 - e^{-\alpha} \tag{3}$$

where

$$X = \frac{\text{projected area of the overlapping bubbles}}{\text{projected area of the bubbles without overlap}}$$

and

$$\alpha = \frac{\text{projected area of the bubbles without overlap}}{\text{area of the boiling heat transfer surface}}$$

The above analyses of randomness and overlap were performed to demonstrate that the distribution of nucleation sites on Chopra's boiling surface contains no special or unusual characteristics. Since the results obtained with Chopra's boiling surface are the basis of comparison for the results of the simulation to be described subsequently, it is essential that this is determined to ensure that the results of the simulation are representative of those that could be obtained on ordinary surfaces with random nucleation site distributions.

As noted above, Chopra boiled dichloromethane on a glass surface coated with a thin stannic oxide layer. By conducting a current through the stannic oxide coating, a uniform heat flux was generated. In the course of his experiment, Chopra was able to vary the average bubble departure diameter by varying system pressure in addition to being able to vary the site density by varying the heat flux. Chopra noticed that there was one particularly active nucleation site in his field of view. This site (site #1 in the current investigation) was deemed to be the dominant site in his investigation. All other sites were deemed to be passive sites. The elapsed time between bubble departure at the active site and bubble departure at all other sites within his field of view was measured. Time histograms were obtained and a Gamma distribution was fitted to these histograms in order to determine the nature of the interaction as evidenced by the shape parameter.

The shape parameter ν obtained from the best fit Gamma distribution and the dimensionless separation distance between the two boiling sites under study $S/\bar{D}_b$ were then plotted as depicted in Fig. 8. Chopra's results followed patterns similar to those identified in the previous investigations. The curve begins with a shape parameter ν greater than unity when the separation distance $S/\bar{D}_b$ is less than unity. This would imply that there is a positive correlation between the two events, meaning that bubbles forming at the dominant site were responsible to some extent for the formation of bubbles at the passive site under investigation. The curve relating the two parameters intersects the axes at unity. Beyond this, as dimensionless separation $S/\bar{D}_b$ increases, two different behaviours arise. The shape parameter ν either remains constant at unity, or drops below unity until $S/\bar{D}_b$ attains a value of approximately 2.5, after which the shape parameter returns to unity once again. While it is easy to comprehend that no interaction would exist at greater separation distances where the shape parameter is equal to unity, negative interaction is less obvious. This is the condition where shape parameter is less than unity. The authors postulate that the interaction that causes the shape parameter to drop below unity is that whereby an intermediate passive nucleation site which is seeded by the dominant site is responsible for the formation of bubbles at the passive site. In this manner, the dominant site is not directly responsible for the formation of bubbles at the passive site.

4. Boiling simulation (BOILSIM)

The basis of the simulation routine known as BOILSIM is the concept of site-seeding. This concept is believed by Judd [2] to be responsible for the interaction between bubbles forming at adjacent nucleation sites. The simulation routine requires categorization of the nucleation sites as either dominant or passive. Dominant sites are those which emit bubbles continually. The site-seeding postulate explains this continual emission to be a product of the ability of the dominant site to retain a vapour nucleus in the surface cavity. Passive sites are sites which are seen to emit bubbles in an irregular manner. This is explained by the site-seeding postulate as the inability of a passive site to maintain vapour nuclei for a prolonged period. The fundamental principle of site seeding is that a dominant site 'donates' vapour to passive sites. When a bubble growing at a dominant site covers a neighbouring passive site and departs, it leaves vapour behind in the cavity of the passive site. There are also circumstances where a bubble developing at a neighbouring passive site will donate vapour to a neighbouring cavity. It is also envisaged that there are circumstances where a bubble developing at a dominant or passive

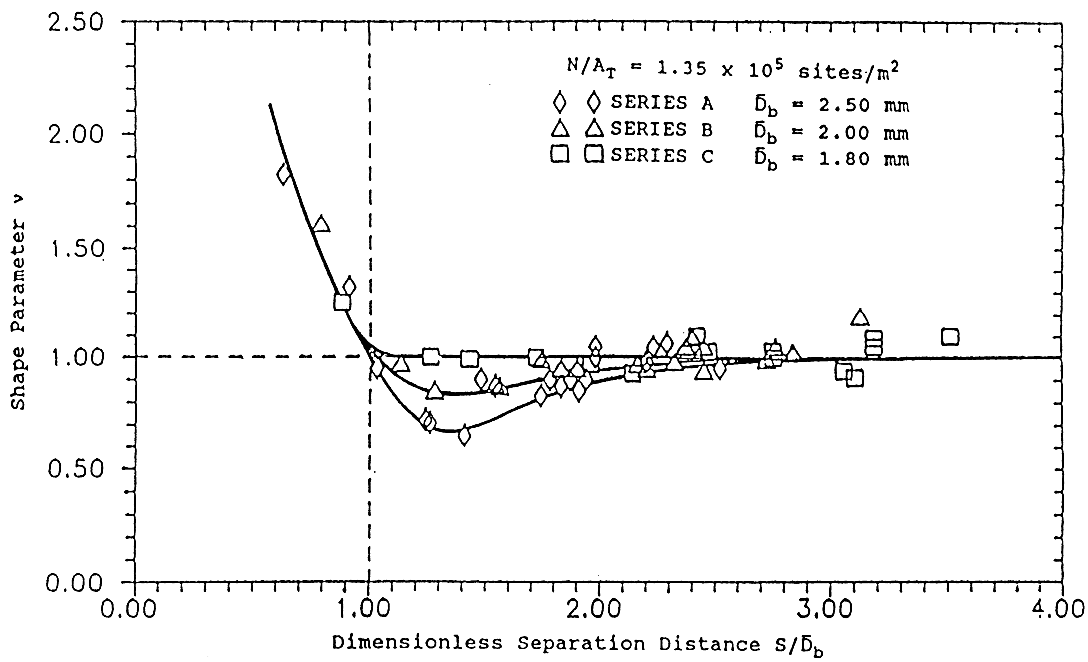

Fig. 8. Chopra's results.

site will cover a neighbouring cavity and dislodge/absorb the nucleus in it, thereby preventing bubble formation.

In the simulation, dominant and passive sites identified in the research investigation performed by Chopra [8] were modelled and the procedures followed in the simulation were those governed by the site-seeding postulate. As noted above, dominant sites are boiling sites which continually emit bubbles. These sites are assumed to always have a vapour nucleus which cannot be dislodged or quenched. A schematic representation of bubble formation at the dominant site is presented in Fig. 9.

Passive sites can produce bubbles only when they hold a vapour nucleus. A passive site can only obtain a vapour nucleus by the donation of vapour from a bubble developing at a neighbouring passive or dominant site. The only possibility that vapour would be deposited in a neighbouring passive site (seeding) is that the site might be covered by a bubble during its growth and departure cycle. A 50% probability was assigned to the event that a passive site might become seeded each time that a bubble from either the dominant or passive site departed and covered the passive site under investigation. This process is illustrated in Fig. 10. The 50% seed probability was chosen so as not to bias the results. The choice of 50% probability makes the event of the passive site becoming seeded or not becoming seeded equally likely. Although a nucleus could be donated by the bubble developing at any neighbouring site, only the time elapsed between the growth of a bubble at the dominant site identified in Chopra's research investigation and the subsequent growth of a bubble at a particular passive site was studied in as much as Chopra only investigated the interaction between pairs of sites.

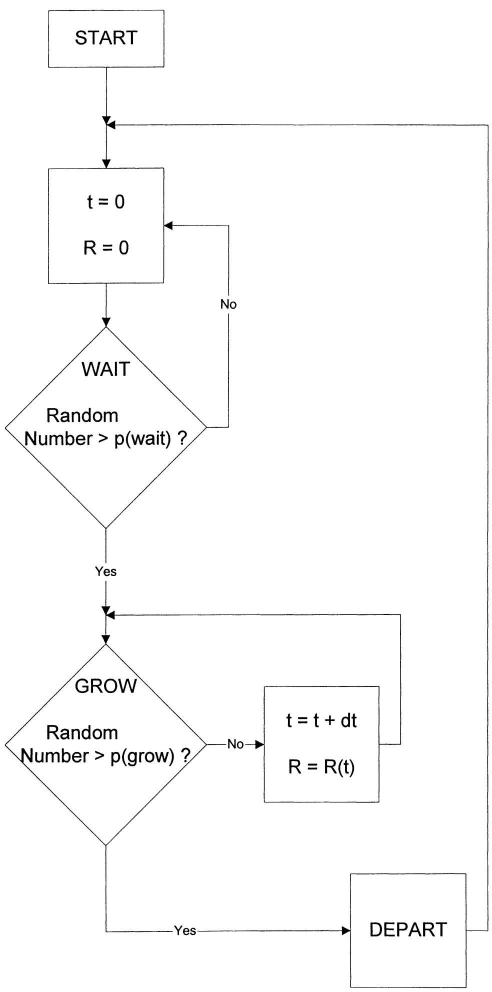

Fig. 9. Schematic representation of bubble formation at the dominant site.

A computer routine evaluated the separation distance among all of the sites that were to be simulated based upon the location of the sites on the boiling surface used in Chopra's research investigation. These separation distances S were used in determining whether or not a site was covered by a bubble forming at a neighbouring site and to determine whether or not two bubbles had clashed or overlapped. Due to the significant increase in processing time required with the simulation of large numbers of nucleation sites, the simulation was performed with up to a maximum of 10 active nucleation sites. The selection of these sites was based on their proximity to the two sites for which data was being collected. It is important to note that it is possible for the neighbouring passive sites to interact with the passive site under investigation.

Due to the nature of the simulation, it was essential that average growth and waiting times be assigned probabilities. Average waiting and growing times from the experiments published in Chopra's research were used. These parameters depend on system conditions such as wall superheat and system pressure. The simulation determines the probability of a bubble being able to continue growing or waiting during each iteration or time step. This method of calculating growth time keeps the model consistent for all time step intervals and also allows for a random distribution of bubble departure diameters about the average bubble diameter. The probability of a site growing during the period of one iteration p(grow) is a function of the time-step and the growth time, given as

$$p(\text{grow}) = \frac{\text{time-step}}{\text{growth time}} \tag{4}$$

The probability that a site will continue waiting to initiate bubble growth p(wait) during an iteration of the

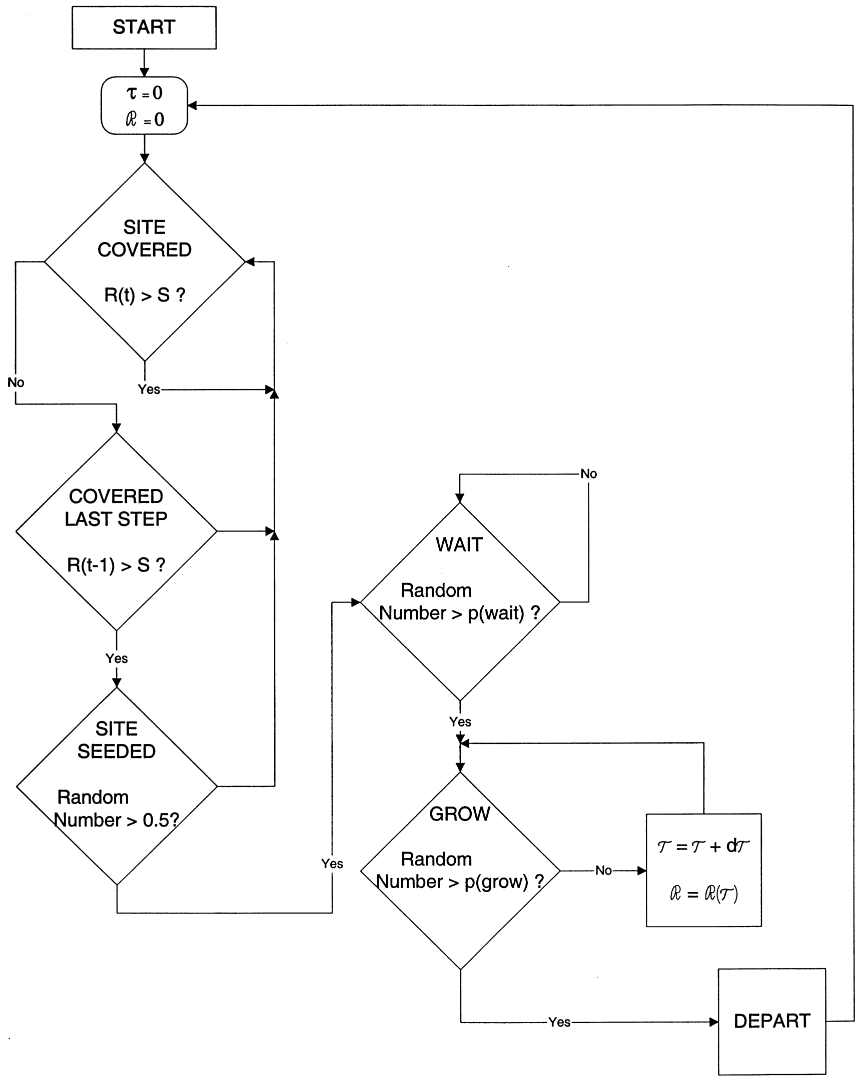

Fig. 10. Schematic representation of bubble formation at a passive site.

program is calculated in a similar manner, as

$$p(\text{wait}) = \frac{\text{time-step}}{\text{wait time}} \tag{5}$$

It can be seen that as the program's time step decreases, the probability of a site beginning to grow or wait will decrease at each iteration. Conversely, when the time step is increased, the probability that a site will begin waiting or growing during an iteration of the program also increases.

If a bubble is growing at a site and continues to grow during an iteration of the program, the radius of the bubble $R(t)$ or $\mathscr{R}(\tau)$ is incremented according to

$$R(t) = \sqrt{\frac{3}{\pi}} Ja \sqrt{(\alpha_l t)} \tag{6a}$$

$$\mathscr{R}(\tau) = \sqrt{\frac{3}{\pi}} Ja \sqrt{(\alpha_l \tau)} \tag{6b}$$

where Jakob number $Ja = \rho_l C_l \theta_{sup} / \rho_v h_{fg}$.

A direct comparison can be drawn between Chopra's experiments and the results of the BOILSIM simulations. The experimental results of the interaction between dominant nucleation site 1 and passive nucleation sites 3 and 12 as determined by Chopra are shown in Figs. 11 and 12, respectively. A Gamma distribution

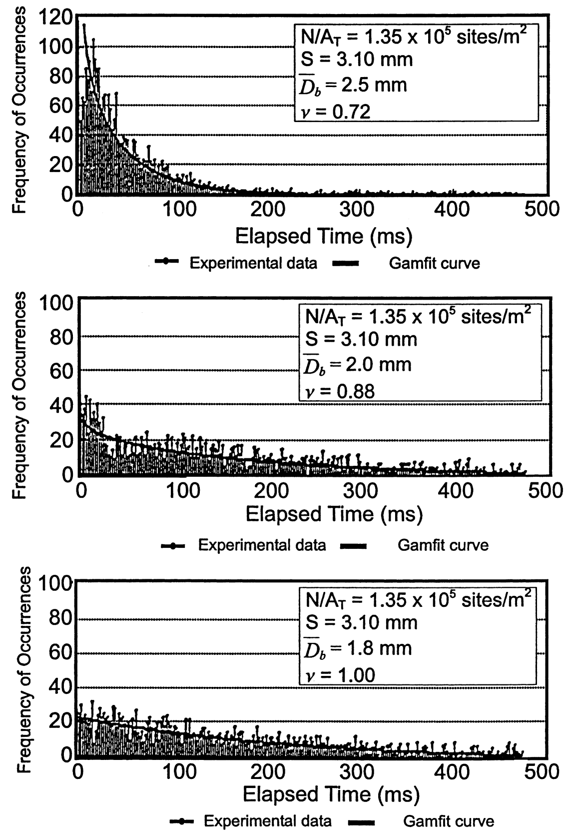

Fig. 11. Chopra's results. Histograms for the interaction between sites 1 and 3.

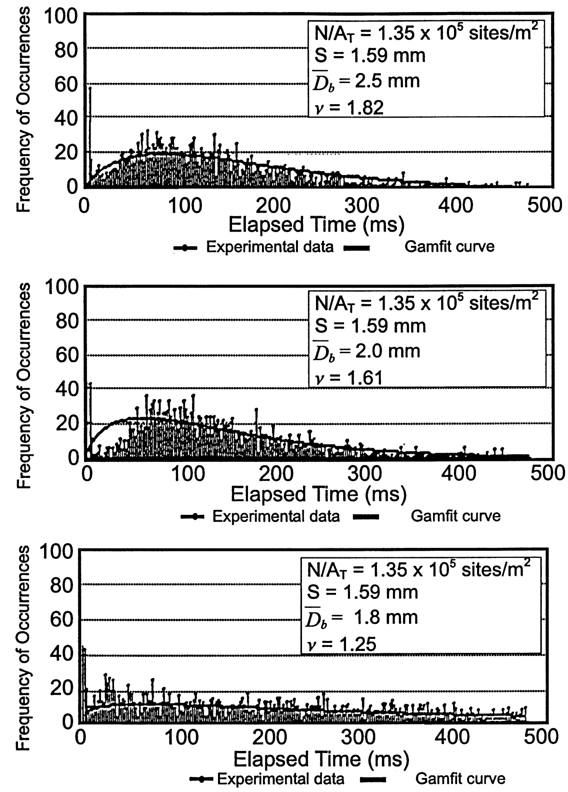

Fig. 12. Chopra's results. Histograms for interaction between sites 1 and 12.

has been fitted to the histograms of the elapsed times yielding the shape parameter for each set of trials as indicated. These two cases were investigated by Chopra because they represented two distinctly different situations with respect to dimensionless separation distance. Nucleation site 3 is farther away from site 1 than site 12. The separation between sites 1 and 3 is approximately 3.1 mm whereas the separation between sites 1 and 12 is 1.59 mm.

As average bubble departure diameter decreases and dimensionless separation distance increases, the shape parameter for site 3 approaches unity from an initial value of 0.72 as seen in Fig. 11. This situation represents the occurrence of a shape parameter less than unity in the dimensionless separation distance region $S/\bar{D}_b$ between 1.0 and 2.5. The dimensionless separation distance $S/\bar{D}_b$ between sites 1 and 12 is between 0 and 1.0 so that the shape parameter decreases with increasing bubble departure diameter as seen in Fig. 12. These results represent the effects of small separation distances where a shape parameter greater than one indicates that the formation of a bubble depends on the formation of a bubble at a neighbouring site.

Fig. 13 presents the results of the BOILSIM simulations of the interaction between dominant site 1 and passive site 3. The results for the interaction between sites 1 and 12 is presented in Fig. 14. The results of the BOILSIM simulations are quite similar to those obtained experimentally by Chopra. The shape parameter for site 3 follows the same increasing trend with increasing dimensionless separation distance as in Chopra's experiments. Similarly, the shape parameter results for site 12 lie above unity and decrease with increasing dimensionless separation distance. Slight discrepancies exist with respect to the exact value of the shape parameter. The agreement between the shape parameter values obtained from Chopra's experiments and those from the computer simulation routine BOILSIM is quite close although the shape parameter never achieved a value quite as low as was reported in Chopra's experiments.

More important than the exact values themselves are the trends observed for these two important cases. It is important to note that shape parameter values dropped below unity for dimensionless separation distances in the range between 1.0 and 3.0 which can be interpreted as bubble inhibition. Also of importance is

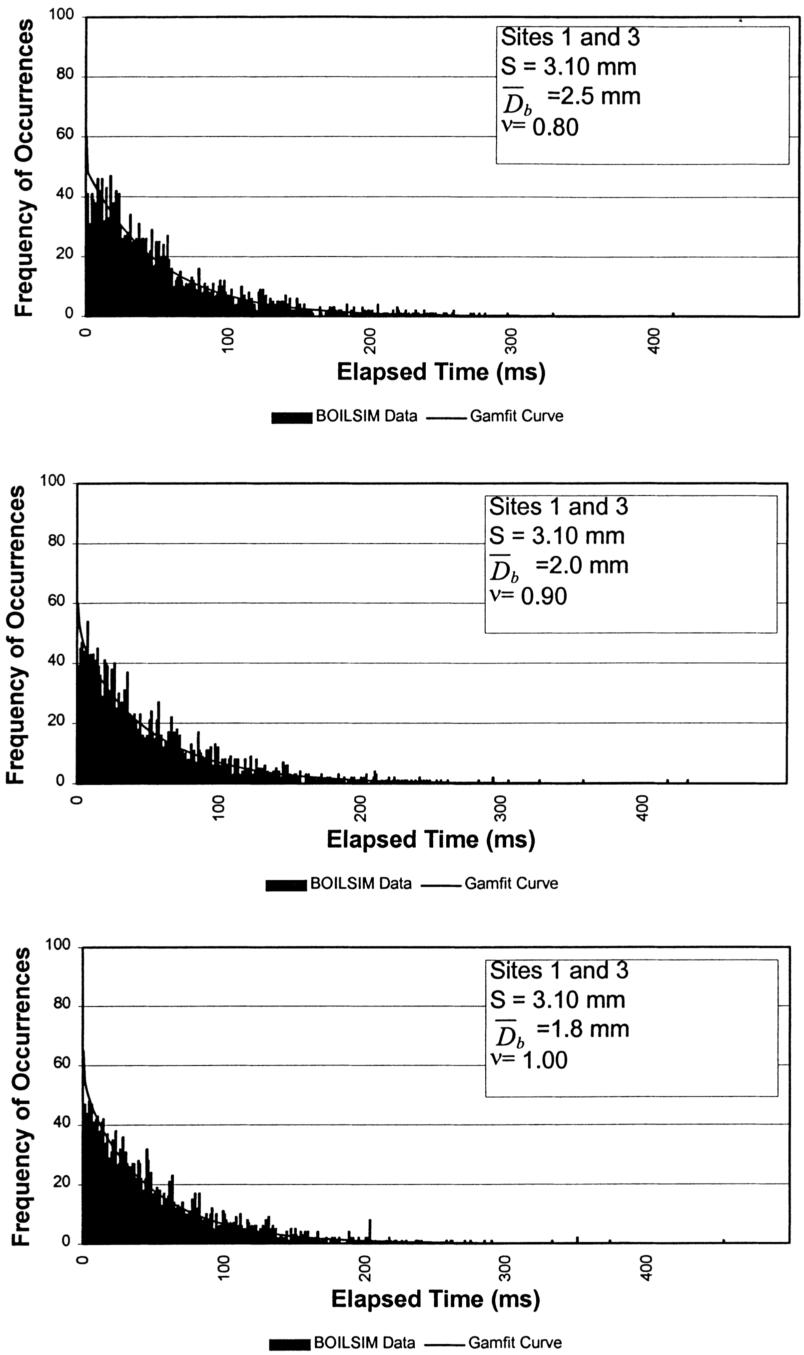

Fig. 13. BOILSIM results. Histograms for interaction between sites 1 and 3.

the shape parameter values above unity for small dimensionless separation distances which can be interpreted as bubble promotion where the frequency of bubble formation is dependent on neighbouring nucleation sites.

The BOILSIM simulations yielded results that follow a trend similar to that of the previous research that it is attempting to simulate. Fig. 15 presents the results of the simulations superimposed upon Chopra's experimental results. The curve fitting to the data is

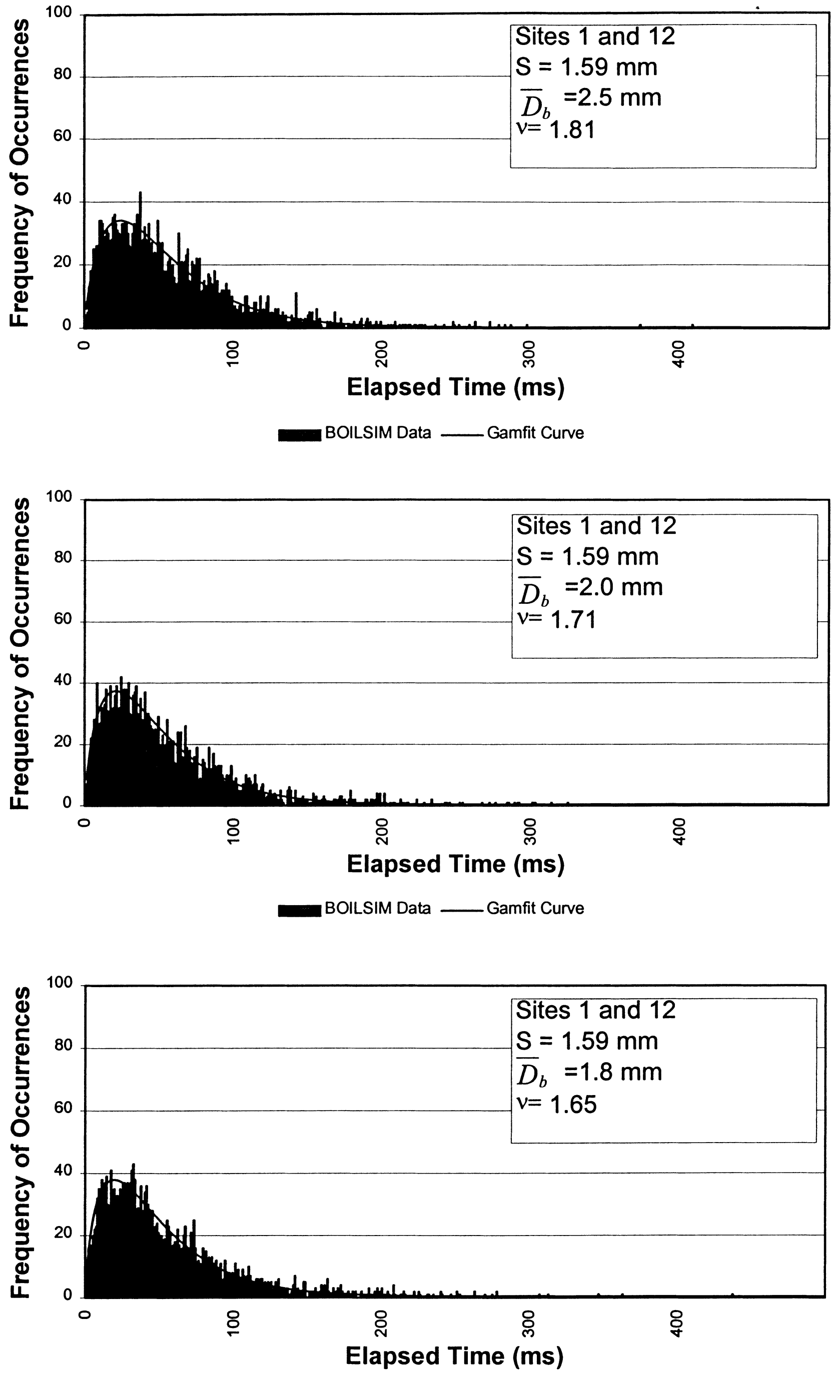

Fig. 14. BOILSIM results. Histograms for interaction between sites 1 and 12.

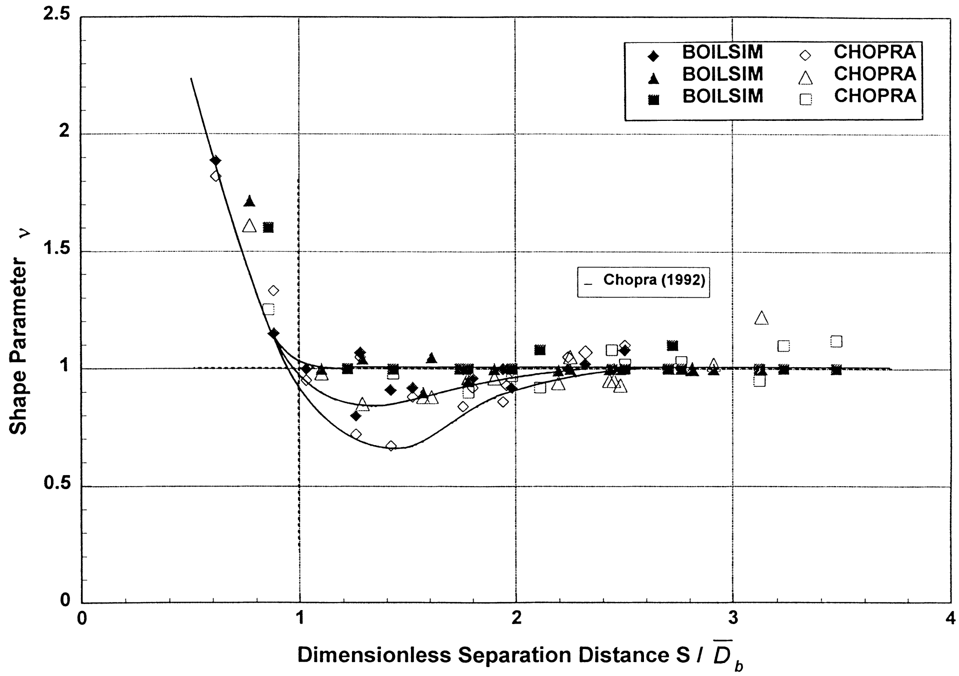

Fig. 15. Comparison of the BOILSIM simulations and Chopra's experimental results showing the shape parameter as a function of dimensionless separation distance.

that presented in Chopra's investigation. As dimensionless separation distances increase from 0 to 1.0, the shape parameter decreases from an initial value of approximately 2 to unity. As dimensionless separation distance increases further, two trends are observed with respect to the shape parameter.

The first trend to be noted is similar to that noted in the experiments performed by Knowles (Judd [2]) where the shape parameter remains constant at unity as dimensionless separation distance increases. The second trend is similar to the one observed in Calka's research. The shape parameter decreases to values as low as 0.8 until dimensionless separation distance attained a value of approximately 2.5 or greater. Beyond values of approximately 2.5, the shape parameter remained fairly constant at a value of approximately 1.0.

5. Concluding remarks

The research presented here is a continuation of the ongoing study of the interaction between bubbles forming at adjacent nucleation sites. The basis of this study is the experimental research performed by Chopra [8], which were reproduced closely in this investigation using a computer simulation routine BOILSIM. In order to establish confidence in the results, randomness and overlap analyses were performed to confirm that the distribution of the nucleation sites on Chopra's surface was typical of that found on real boiling surfaces.

The computer simulation routine performed in this investigation was based on the boiling conditions and boiling surface data investigated in Chopra's research. The simulation produced values of the time elapsed between bubble formation at a particular passive site and the most recent occurrence of bubble formation at a particular dominant site. The outcome was plots of the shape parameter values against the dimensionless separation distance values which were very similar to the ones obtained by Chopra through his experimental research investigation. In keeping with previous research, the plots suggest that bubble growth was promoted when dimensionless separation distances were less than unity. When dimensionless separation distances were greater than unity, the shape parameter either maintained a value of unity or dropped below unity for a range of dimensionless separation distance. A shape parameter equal to unity suggests no promotion or inhibition of bubble growth at a nucleation site by a neighbour. The trends resulting from the simulation are similar to those observed in previous research.

Interaction between bubbles forming at these sites was modelled according to Judd's [2] postulate that interaction is based on the principle of site-seeding, whereby a departing bubble may or may not deposit vapour into a neighbouring nucleation site. This vapour deposit may or may not lead to the formation of a bubble at the nucleation site. It was also postulated that a neighbouring bubble could remove the vapour from a cavity if the bubble covered the neighbouring site at departure. Assigning a 50/50 likelihood to these events ensures that departing bubbles may leave or deplete vapour at nucleation sites with equal probability. In doing so, results were obtained that were in good agreement with previously observed results.

The fact that the simulation produced results similar to those obtained earlier by experimental research is supportive of the site-seeding bubble interaction mechanism. Though this simulation does not disprove Kenning's postulate of the mechanism of bubble growth and interaction, it is a small step in the verification of the site-seeding postulate

References

[1] M. Shoukri, R.L. Judd, On the influence of surface conditions in nucleate pool boiling — the concept of bubble flux density, ASME Journal of Heat Transfer 100 (4) (1978) 618–623.

[2] R.L. Judd, On nucleation site interaction, ASME Journal of Heat Transfer 110 (1988) 475–478.

[3] R.L. Judd, A. Chopra, Interaction of nucleation processes occurring at adjacent nucleation sites, ASME Journal of Heat Transfer 115 (1993) 955–962.

[4] R.L. Judd, C.H. Lavdas, The nature of nucleation site interaction, ASME Journal of Heat Transfer 102 (3) (1980) 461–464.

[5] D.B.R. Kenning, Youyou Yan, Pool boiling heat transfer on a thin plate: features revealed by liquid crystal thermography, International Journal of Heat and Mass Transfer 39 (1996) 3117–3137.

[6] V.V. Chekanov, Interaction of centres in nucleate boiling, Teplofizika Vysokikh Temperatur 15 (1) (1997) 101–106.

[7] A. Calka, R.L. Judd, Some aspects of the interaction among nucleation sites during saturated nucleate boiling, International Journal of Heat and Mass Transfer 28 (12) (1985) 2331–2342.

[8] A. Chopra, Interaction of bubbles forming at adjacent nucleation sites, M. Eng. Thesis, McMaster University, Canada, 1992.

[9] D.B.R. Kenning, V.H. Del Valle, Fully developed nucleate boiling: overlap and areas of influence and interference between bubble sites, OUEL Report, 1324/80, 1981.

[10] V.H. Del Valle, D.B.R. Kenning, Subcooled flow boiling at high heat flux, International Journal of Heat and Mass Transfer 28 (10) (1985) 1907–1920.