AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

**MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.**

1 of 1

Conf-941142--1

725

LA-UR-94-

TSA-6-94-R106

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

**TITLE: NONLINEAR ASPECTS OF HIGH HEAT FLUX
NUCLEATE BOILING HEAT TRANSFER
Part II: Results**

AUTHOR(S): Pratap Sadasivan
Cetin Unal
Ralph Nelson

SUBMITTED TO: 1994 ASME Winter Meeting
November 13-18, 1994
Chicago, IL

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

APR 08 1994
OS 11

By acceptance of this article, the publisher recognizes that the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, to allow others to do so, for U. S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U. S. Department of Energy.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NONLINEAR ASPECTS OF HIGH HEAT FLUX NUCLEATE BOILING HEAT TRANSFER

—Part II: Results

Pratap Sadasivan, Cetin Unal, and Ralph Nelson

*Los Alamos National Laboratory
Technology and Safety Assessment Division
Safety Assessment Group
Los Alamos, NM 87545*

This paper describes the results of a study aimed at understanding nonlinear aspects of the macrolayer-controlled heat transfer process associated with high heat flux nucleate boiling and the critical heat flux. Simulations of realistic heater surfaces have been carried out by detailed microscopic modeling of the surfaces. Individual nucleation sites are allowed to activate or deactivate depending on the thermal conditions that prevail at the site. The results indicate that significant spatial and temporal temperature variations can occur on the surface, and that thermal interactions among sites can result in some sites operating extremely intermittently. Surface-averaged temperatures show highly nonlinear behavior. This suggests the possibility of the system exhibiting chaotic behavior under appropriate experimental conditions. It is proposed that such nonlinear behavior is one of the reasons why mechanistic predictive capabilities for the boiling process have remained elusive.

INTRODUCTION

The details of the formulation of a model used to study nonlinearities associated with macrolayer-controlled boiling were presented in Part I of this paper. MACRO3D is the computer code developed for the numerical implementation of the model. Preliminary results of simulations carried out using MACRO3D are detailed in this paper.

The objective of the study is to undertake detailed microscopic simulations of the heater surface by focusing on the behavior of individual nucleation sites on the

surface. Nucleation sites are distributed on the heater surface in a prespecified manner—random or according to specified spatial distributions. A site is allowed to activate at any time when the temperature exceeds its activation temperature. The choice of the expression used to determine the activation temperature was discussed in Part I. In the absence of predictive expressions for deactivation temperature, the present study assumes that the deactivation temperature is 5°C less than the corresponding activation value. As detailed in Part I, the heat dissipation from the heater is modeled as the sum of transient transport into the macrolayer and the heat loss owing to evaporation of menisci associated with vapor stems.

We should point out once again that the objective of the current study is more to explore boiling models rather than to propose a model itself. It is hoped that information gained from this study will help to focus future efforts toward developing mechanistic models of boiling. This has been discussed in the Introduction section in Part I.

Having discussed the background and objectives of this study, we will now present the results of calculations carried out using MACRO3D.

PROBLEM

A typical problem we have investigated is a portion of a copper heater that is 5 mm on a side (25 mm² area). Saturated water at atmospheric pressure is assumed to be the boiling fluid. Heater thicknesses between 50 μm and 1 mm have been used so far. Computational costs and hardware limitations have restricted the maximum thickness we have been able to use so far. One hundred eighty (180) potential nucleation sites have been located on the heater surface. All sites are assumed to have geometries conducive for activation; that is, we assume that activation and deactivation of sites are controlled solely by local superheat values. Wetting angle effects are not considered in determining site activation and deactivation. Figure 1 indicates site locations on the modeled portion of the boiling surface. The different cavity sizes shown in the figure are intended only to give an indication of the relative variation in size; they are not drawn to scale.

The site spatial distribution is assigned randomly in a manner that satisfies a Poisson distribution

$$P(x) = \frac{e^{-\mu} \mu^x}{x!} , \quad (1)$$

where $P(x)$ is the probability of occurrence of event x and μ is the average value. In the present case, we divided the heater surface into 36 divisions so that there are an average of 5 sites per division. $P(x)$ then denotes the probability of having x sites in a division. The calculated probability distribution is compared with the exact Poisson distribution (for a mean of 5) in Fig. 2. The results are in fair agreement. This is consistent with results of Gaertner (1963), Sultan and Judd (1978), and other studies.

Wang and Dhir (1993) found that the surface site density, N_s , can be correlated with the cavity diameter, D_c , as

$$N_s = C_1 D_c^{-n} , \quad (2)$$

where the exponent n varied between a value of 2.0 for cavities with diameters greater than 5.8μ and a value of 5.4 for those with diameters less than 3.5μ . For a heater of area 25 mm^2 , their equations suggest that there will be approximately 250 cavities of diameter 6μ , and almost 8000 cavities of diameter 3μ . Computational limitations preclude us from simulating such a large number of cavities. In the present example, we have chosen to simulate a surface with a much lower surface site density. Results presented in this paper were obtained for two different size distributions. Most of the results presented here were obtained for a cavity distribution where the cavity radius varied from 0.5μ to 6.0μ in steps of 0.1μ . Some results were obtained using a distribution where the size variation was more coarse—the cavity radius varied from 1μ to 6μ in steps of 1μ . The number of sites of each size are chosen in approximate qualitative agreement with Eq. (2). The size distribution of cavities is listed in Tables I and II, respectively, and shown in Figs. 3a and 3b, respectively; the relevant temperature data are listed in Tables I and II. Unless otherwise mentioned, the results were obtained using the finer size distribution (Table I and Fig. 3a).

RESULTS

The configuration described in the above section was solved for the case of water boiling on a 50- μ -thick copper heater. This configuration may appear to be an awkward choice because the usual practice in experiments is to use relatively thick copper heaters, or to use very thin heaters of relatively low thermal conductivity. Prohibitive costs involved in computations have prevented us from running our calculations for thick heaters. However, by using a very thin heater of high thermal conductivity, we will be able to extend our results qualitatively to thicker heaters of lower thermal conductivity. We will discuss the results obtained for heat fluxes of 0.85 MW/m², 0.975 MW/m², and 1.04 MW/m². Results of calculations for heaters with thickness up to 1 mm will be discussed in subsequent sections.

Surface-Averaged Temperature

The transient variation of the temperature averaged over the full heater surface, T_{SA} , is shown in Fig. 4 for the three heat fluxes considered. The time series from $t = 100$ to $t = 400$ ms has been shown in the figures for purposes of comparing the overall characteristics.

We can see in the figure that the T_{SA} time series exhibits markedly different characteristics depending on the heat flux. For $q = 0.85$ MW/m², the surface-average temperature varies almost periodically with a period equal to that of the driving process—the departure of the mushroom bubble—as determined from Eq. (24) in the formulation (Part I of this paper). At the heat flux of 0.975 MW/m², the resulting T_{SA} time series still shows a periodic behavior, but now the period is twice that of the driving frequency. At a heat flux of 1.04 MW/m², the T_{SA} time series suggests aperiodic behavior. Similar time series were obtained for other heat flux levels as well. The range of temporal variations of the average temperature is about 2.5°C at the highest flux used in the current calculations.

In light of the apparent aperiodic behavior of the T_{SA} time series for $q = 1.04$ MW/m², we continued the calculation of that time series for up to 10000 ms. Segments of the T_{SA} time series between 0 and 1500 ms and between 3000 and 4500 ms are shown in Fig. 5. Careful examination of the time series indicates that there are pockets of aperiodic behavior interspersed by segments

that show a higher-order periodicity. Similar calculations for the lower heat fluxes showed that the periodic behavior was not disrupted at any time.

Qualitatively similar results were obtained in calculations using the cavity size distribution shown in Fig. 3b and detailed in Table II. Time series at different heat fluxes showed period-doubling as well as loss of periodicity. The values of the heat fluxes at which periodicity characteristics changed were different from those cited above for the size distribution of Fig. 3b. This is hardly surprising as the thermal interactions among the sites are altered as a result of the change in the size distribution. For purposes of brevity, further details of the results of this set of calculations are omitted here. However, they provide evidence that nonlinear effects could be present under different experimental conditions.

Site Intermittency

We saw in the previous section that the surface-average temperature can exhibit significantly different transient behavior than the single hydrodynamic-driven period one might expect. Although the vapor mushroom bubbles depart the surface with a constant period, the surface-average temperatures need not necessarily exhibit the same periodic behavior. This suggests that some aspect of the process has a strong irregular component.

Kenning (1992) suggested that the nonuniformities in heater surface temperature as a result of the distribution of active and inactive sites cause a feedback effect such that activation of additional sites is influenced by which sites are already active. The irregular variations of the surface-average temperature could be another manifestation of this feedback. To examine this further, we will look at the behavior of all available sites on the surface. Figure 6 shows the map of the surface with surface sites labeled according to their participation in the boiling process for the 50- μ -thick copper heater.

For this size and spatial distribution of sites, only about 35% of all surface sites activate. As seen in Fig. 6, about 12 sites (or about a fifth of all active sites) show intermittent behavior; some of these operate highly intermittently. The numbers marked on the figure are the site identification numbers.

Figure 7 shows the transient behavior of sites 9, 58, 128, and 137. For purposes of clarity, data are presented only for the segment of time between 300 ms and

2000 ms. This is representative of the behavior over the entire time duration for which calculations were made.

Figures 6 and 7 show that the behavior of individual sites can differ widely from one site to another. While many sites activate and remain active throughout the process, other sites activate and operate intermittently. Among intermittently operating sites, the degree of intermittency varies widely from one site to another. Site 58 for example, is active for a substantial portion of the time, while site 137 shows extremely intermittent operation. Site 137 shows what could be interpreted as bursts of activity, while site 135 shows a fairly regular pattern of activation and deactivation. These activity patterns are similar to those observed experimentally by Raad and Myers (1971) for low flux boiling.

We can note from Fig. 6 that sites with highly intermittent activation and deactivation patterns are located in regions of relatively high active site density. Each active site causes local cooling, which in turn could prevent or delay the activation of neighboring sites. By the same token, a site that has been continuously active for a certain duration can cool sufficiently so as to be deactivated. When this happens, one or more neighboring sites that have previously been inactive would activate. It is interesting to compare the behavior of sites 128 and 137. As seen in Fig. 6, these sites are located fairly close to each other. Site 137 is located among a cluster of sites that remain active at all times, and thus its temperature remains below the activation value. However, the interaction between sites 128 and 137 results in site 128 showing bursts of inactivity, which corresponds with bursts of activity in site 137. This is a clear example of the way feedback between the thermal state of the surface and the sites affects the behavior of the individual sites. Thus thermal interactions among sites is one possible cause for their intermittent operation. We do not imply that this is the only cause; it is merely suggested that this is one possible cause. Our model currently assumes that all surface sites are potential active sites; relaxation of this assumption as well as the inclusion of other effects such as hydrodynamic site seeding could further enhance the intermittent behavior of sites.

One consequence of site intermittency is that the total number of active sites, and therefore the active site density, varies with time. Figure 8a shows the variation of the number of active sites with time for different heat fluxes. Data for one representative hovering period are shown for each heat flux. The x-axis

represents time, but in a discontinuous manner. The data for each heat flux are shown contiguous to each other for purposes of clarity.

The results of Fig. 8a show that the active site density varies considerably at a given heat flux. This points to the futility of attempting generalized correlations for active site density as functions of heat flux alone or wall superheat alone. These results raise a very fundamental question—what is N_a in such attempts? Is it the maximum number of sites activated? Or is it a time- and area-averaged value? It is hardly surprising that previous attempts to correlate the active site density with heat flux or wall superheat in the form

$$N_a = C_1 q^m \quad (3)$$

$$\text{or } N_a = C_2 \Delta T^n \quad (4)$$

have generally led to a broad range of values for the exponents m and n .

Figure 8b shows the maximum number of active sites for each heat flux. The data are correlated sufficiently well by Eq. (3) with exponent $m = 0.925$. However, as based on Fig. 8a, the use of such an equation in a linearized model will inevitably lead to over- or underestimation of the heat transfer characteristics.

If the transient variation in the number of active sites is important, experimental efforts in this area need to be refined so as to be able to discern the variation better. Active site counting methods of Gaertner (1963) employing salt-deposition and Wang and Dhira (1993) employing subcooled water injection might not yield sufficiently accurate pictures of the variation in active site density. Liquid crystal techniques might provide some information necessary to clarify these characteristics, at least for thin heaters, if the necessary temporal resolution can be achieved.

As observed by Kenning (1992), site intermittency and the variation in the site density have further consequences for modeling efforts. Modeling efforts thus far typically use a linearized approach—physical phenomena are analyzed on the basis of a single stem or site, and the results are extrapolated by assuming some uniform spacing considerations to obtain results for actual surfaces with a known active site density. Possible variations in active site density and their associated spacing are thus ignored. The present calculations further support the notion

that a linearized approach ignoring the possibility of thermal interactions could yield inaccurate results. The effects would be especially adverse in situations where the heater characteristics—thickness, thermal conductivity, and size and spatial distribution of surface sites—are such that thermal interactions are increased.

Spatial Variations

We have seen in the discussion thus far that fairly significant temporal variations in the average temperature can occur on the heater surface. We turn next to the issue of spatial temperature variations on the surface. The possibility of significant spatial variations in temperature has already been demonstrated at low fluxes by Kenning (1992).

Figure 9a shows the spatial temperature variations on the surface of a 50- μ -thick copper heater at heat flux levels of 0.8, 0.9, 1.04, and 1.2 MW/m². Data are presented as curves of surface superheat versus area fraction. These are instantaneous temperature distributions, and correspond to the end of a randomly chosen hovering period. The highest and lowest temperatures on the surface for each of the heat fluxes shown in Fig. 9a are shown in Fig. 9b. There is a fairly broad temperature range on the surface even at the relatively low heat flux of 0.8 MW/m². It can be seen that a small fraction of the surface is close to saturation for all heat flux levels shown. This area corresponds approximately to the annular area around each active nucleation site where meniscus evaporation contributes to heat dissipation.

Modeling efforts in nucleate boiling and critical heat flux (CHF) have typically ignored the possibility of spatial variations as we have shown above. Correlations usually require the specification of time- and area-averaged heat flux or heater surface superheat. The possibility of substantial spatial variations on the surface raises questions about the validity of using such an approach. Spatial variations in surface temperature also have consequences on experimental methods. This issue is discussed in the next section.

Spatial Temperature Variations: Consequences of the Measurement Technique

Nucleate boiling experiments employ different approaches to monitor heater temperatures. The first approach adopted in the earliest experiments of

Nukiyama (1934) and subsequently by many other investigators is to use ohmic heating and to deduce the heater temperature from measurements of the resistance of the heater. This method essentially yields temperature values that are averaged over time, and over the entire volume of the heater. Thus it is virtually impossible to detect any spatial variation on the heater surface using this approach. Another method is to use techniques such as liquid crystal thermography [Raad and Myers (1971)], or infrared mapping [Sgheiza and Myers (1985)]. However, this approach suffers from limitations in the range of temperature that can be detected.

The most commonly used approach is to use sensors such as thermocouples at one or more locations on the surface or below the surface. Such "point" measurements of temperature essentially measure the average temperature over a small area on which the sensor is mounted. The issue then is to assess how much influence spatial variations have on experimental data obtained using point or small-area sensor measurements.

We will return to the results presented earlier for a 50- μ -thick copper heater at a heat flux of 1.04 MW/m². The map of active, inactive, and intermittent sites was shown in Fig. 6. We will consider a square sensor of side 1 mm, and locate it at different regions of the surface. Such a sensor has 25 possible nonoverlapping locations on the surface of side 5 mm, as shown by the grid overlay in Fig. 10.

Figure 11 shows segments of the time series of window-averaged temperatures for three windows (labeled A, B, and C in Fig. 10) and for the full surface. It is clear that different locations of the sensor can result in substantial differences in the readings obtained. Window A is in one corner of the surface and contains one active site, while window B has four active sites. A comparison of the temperature time series data shown in Fig. 11 for windows A and B suggests that experimental data are highly dependent on local values of active site density.

It can also be seen in Fig. 11 that the magnitude of temporal variations in the surface temperature varies substantially from one location to another. The temperature data on window C show more temporal variations than those for A or B. The reason for this can be understood by examining the behavior of the sites on the surface. It can be seen in Fig. 9 that window C contains one intermittently active site, while windows A and B do not contain any

intermittent sites. The intermittent operation of sites thus is responsible for increasing the local variation of temperature. Under experimental conditions that enhance chances for intermittent operation of sites, point or small-area sensor measurements of temperature could be in considerable error unless adequate steps are taken.

The foregoing discussion raises the issue of whether there is a suitable sensing area that will ensure approximate ergodicity. In other words, what is the smallest sensing area required to ensure that the average temperature on the sensing area is independent of the sensor location? We repeated the calculations for different window sizes and found that, for the problem under consideration, any sensor area less than the full surface area yields different average values. This could be attributed to the fact that the highly intermittent sites are not distributed uniformly over the full surface. Surfaces with different site distributions may or may not yield sensing areas that will ensure ergodicity. Based on our current calculations, the only approach that we can suggest to minimize error due to spatial variations is that surface temperature data must be based on an ensemble average of values obtained at multiple locations.

The preceding discussion focused on the location of temperature sensors on the boiling plane. A related issue that becomes especially important in relatively thick heaters is that of axial variations in temperature. Previous calculations [Sadasivan et al. (1993)] indicate that the spatial variations in temperature decay considerably at small depths below the heater surface, especially when the heater material has a high thermal conductivity. This has implications for the most suitable axial location for temperature sensors. As a result of inherent difficulties in locating sensors on the surface, boiling experiments tend to employ sensors at a certain depth below the surface; the surface data are then obtained by extrapolation. Our results suggest that such an approach will mask some of the spatial variations at the surface and may lead to erroneous conclusions.

The Boiling Problem as a Nonlinear Dynamical System

In Figs. 4 and 5, we saw that the time series for the surface-average temperature T_{SA} shows a single periodic behavior at $q = 0.85 \text{ MW/m}^2$, a bi-periodic behavior for $q = 1.075 \text{ MW/m}^2$, and an apparent lack of periodicity for $q = 1.2 \text{ MW/m}^2$. We stress again that such results are for the specific combination of experimental

conditions that are simulated in these calculations but did occur within both distributions represented in Fig. 3.

Period-doubling is a hallmark characteristic of many nonlinear processes in nature. Indeed, it is well established that period-doubling is a classical route to chaotic behavior. The period-doubling and subsequent breakdown of periodicity that we see for the problem under consideration strongly suggest the presence of a nonlinearity in the system.

Nonlinear and chaotic behavior of the system could have significant consequences. Such behavior can explain some of the data scatter that is a hallmark of typical boiling experiments. It could also have consequences for our ability to predict nucleate boiling characteristics accurately. We have already pointed out that the governing equation in our system is linear. Therefore, the nonlinearity must enter the process through the boundary conditions.

The analogy between the on-off behavior of the diode in the resonator circuit and the on-off behavior of nucleation sites in a boiling system is self-evident. Nucleation sites turn on when the local superheat exceeds the activation superheat of the site. When the local superheat is less than the deactivation value, at the beginning of a hovering period, the site turns off. We believe that the on-off behavior of sites as a result of thermal interactions is the main source of nonlinear effects observed in our calculations. The greater the chances of interactions among sites, and intermittent behavior of sites, the greater the chances for nonlinear behavior. As we mentioned earlier, all modeling efforts in nucleate boiling and CHF thus far have assumed a linearized approach, and thus would not be able to account for or detect nonlinear, or possibly chaotic, behavior.

We will use the T_{SA} time series of Figs. 4 and 5 as prototypes to explore the possibility of nonlinear and chaotic behavior of the boiling system. One fundamental issue is to identify the type of recurrence exhibited by the system. The simplest form of recurrence is equilibrium where the system approaches a time-invariant state asymptotically. The current boiling model will clearly not yield such a recurrent behavior owing to the inherent periodicity in the boundary conditions—the macrolayer is reestablished periodically. We will refer to the frequency as the fundamental frequency of the system. The next higher form of recurrence is periodicity, also called a limit cycle. The time series shown in Fig. 4a

for a heat flux of 0.85 MW/m^2 exhibits this type of limit-cycle behavior. However, the time series of Fig. 5 does not.

The time series of Fig. 5 clearly indicates segments of apparent higher-order periodicity interspersed with segments of apparent aperiodicity. There are three possible explanations for this. One possibility is that it is generated by the superposition of the fundamental frequency and one or more subharmonics. A second possibility is that it represents a quasiperiodic pattern—composed of two incommensurate frequencies together with their harmonics. The third possibility is that it represents a chaotic pattern. We will primarily use phase plots, Poincaré sections and Fourier analysis to study the time series in more detail.

One possible representation of the current data in phase space is a continuous trajectory plot of T versus T' ($= dT/dt$). For a single-periodic system such as Fig. 4a, the phase trajectory approaches a single closed-loop limit cycle. When period-doubling occurs such as shown in Fig. 4b, the phase trajectory approaches a limit cycle composed of two lobes. For chaotic motion, the phase trajectory will fill up a portion of phase space in an irregular manner.

If we confine our attention to portions of the phase trajectory that are spaced at equal time intervals, the result will be a series of points. This yields the Poincaré section. The Poincaré section is obtained easily in the present case because the system has a natural forcing function—that of the departure of the vapor mushroom, and of the resulting resupply of liquid to the near-heater region. An alternative representation of the data would be in first return maps where some metric of the system at one time is plotted against the same metric at a fixed time phase shift. We will use first return maps to look at our data more closely. The first return map of a single-period system such as Fig. 4a is essentially a single point in phase space. The first return map for Fig. 4b would exhibit two points. For a chaotic system, the first return map appears as a cloud of points or as an infinite set of points that appear to have an overall structure. When plotted as a Poincaré section, these are usually referred to as strange attractors. The classical Lorenz attractor obtained for the case of Bénard convection in horizontal liquid layers is a classic example of a strange attractor.

The first return maps for the data of Figs. 4a, 4b, and 5 are shown in Fig. 12. The time series of Fig. 5 contains data for 190 hovering periods; thus the corresponding first return map contains 190 points. It is clear that there is a considerable overlapping of points in the first return map. This again indicates that there are segments of periodic behavior interspersed with segments of aperiodicity. The considerable overlapping seen in the first return suggests that while the system is not simple-periodic, the data do not provide sufficient evidence for a chaotic behavior.

The time series presented in Fig. 4 and others consist of temperature data obtained at unevenly spaced samples. This is because the time step size used in the computations varies from one time step to another. Because of the uneven sampling, conventional Fourier analysis methods such as the Cooley-Tukey algorithm cannot be used directly. One approach is to smooth the data into even samples by interpolation. Another approach is the Lomb normalized periodogram. Press et al. (1992) provide a good discussion of this technique; they also provide a computer code for implementing the Lomb algorithm. In the present study, we have used this approach to carry out the spectral analysis of the temperature data.

The Lomb periodograms of spectral power versus frequency for the time series of surface-average temperature for the three heat fluxes shown in Fig. 4 are shown in Fig. 13. It is clear that the spectral components vary dramatically from one case to another. For a heat flux of 0.85 MW/m^2 , we saw earlier that the T_{SA} time series showed a single periodic behavior. This is borne out in Fig. 13a—the dominant component is at 20.7 Hz, which corresponds exactly to the driving frequency [the time period predicted by Eq. (24) in Part I is 48.26 ms]. Figure 13b is for a heat flux of 0.95 MW/m^2 , and it shows dominant components at 20.3 Hz (the driving frequency of the system) as well as 10.15 Hz (corresponding a 2-periodic behavior). Figure 13c shows the results for a heat flux of 1.04 MW/m^2 , and shows a dominant frequency at 19.9 Hz. But unlike in Figs. 13a and 13b, it shows a broad spectrum of low-frequency components. There is no evidence of chaotic behavior, but the presence of the spectrum of low-frequency components does suggest the presence of nonlinear effects. It is also possible that the system exhibits long dominant periods of periodic behavior with bursts of chaotic behavior. More definitive tests are required to establish this fact. These include

evaluating the fractal dimension or the Lyapunov exponent based on the time series. However, these calculations typically require a much larger number of data points than we currently have.

Well-established chaotic systems such as the logistic equation and the Lorenz system exhibit chaotic motions only for some range of values of one or more control parameters. Our results thus far were obtained for a specific configuration—size and spatial distribution of sites. We do not imply that similar results will be observed in all cases; however, these results establish unequivocally that such effects are possible. We cannot rule out the possibility that the nucleate boiling model used in the present study can generate chaotic behavior for other experimental conditions. Indeed, if the source of the nonlinearity lies in the on-off behavior of the intermittently active sites, we can expect the nonlinear effects to increase significantly under conditions which lead to a larger number of such sites. These include changes in heater thickness, heater thermal conductivity, and nucleation site distribution.

DISCUSSION

The results presented in the previous sections reveal that, within the context of the model used, significant nonlinear effects are possible in nucleate boiling systems. Several aspects revealed by the numerical study are consistent, at least in a qualitative manner, with the experimental observations of previous studies.

We showed that one main manifestation of nonlinearity is in the transient activation and deactivation of sites. Such transient operation of nucleation sites has been observed by Kenning (1992) in his experiments with heaters having their undersurfaces coated with liquid crystals.

Yu and Mesler (1977) presented temperature measurements obtained using a microthermocouple embedded on the heater surface. Their results showed that local temperatures on the heater surface can vary widely during nucleate boiling. A portion of the surface temperature time series of Yu and Mesler (1977) is reproduced in Fig. 13a. The time series is qualitatively similar to those we presented earlier from our numerical studies.

It is not clear whether the thermocouple used by Yu and Mesler (1977) was below a single nucleation site or whether it covered a larger window on the surface

much like those we discussed earlier (see Fig. 10). For the moment, we will assume that the thermocouple sensed the temperature at a single nucleation site, and note that this discussion would be valid even if the thermocouple reading was an average over a larger area. We assume that an increase of the temperature reading of 1 °C or greater implies that the site has deactivated, and conversely, a drop of 1 °C or more implies that the site has deactivated. Using this rule, we can convert the temperature time series of Fig. 14a into a site activity time series. The result is shown in Fig. 14b. Again we see that the results are in qualitative agreement with transient site activity time series we presented earlier from our numerical studies (see Fig. 7). We should reiterate that we do not suggest that such qualitative agreement validates the model used in this study; such agreement merely provides further evidence to support that the model and numerical implementation mimic fairly well the actual behavior of systems.

One more point is worthy of discussion. This relates to the completeness of the model. It should be clear that the model used in the study focuses only on thermal interactions among nucleation sites. The model was developed to investigate this particular phenomenon separate from other potential effects. For example, we currently do not account for possible hydrodynamic and other interaction effects. Hydrodynamic interactions occur as the result of interactions among bubbles growing at neighboring nucleation sites. These interactions are fairly considerable at low heat fluxes where vapor removal is in the form of discrete bubbles; the bubbles grow to relatively large sizes before departure. Similar interactions in the macrolayer region would occur if the vapor stem associated with one site overlays a neighboring site which is previously inactive. Such vapor seeding during one hovering period could lead to activation of the latter site in the subsequent period. Chekanov (1977) proposed that acoustic propagation could be another mechanism of interaction among nucleation sites.

Judd and coworkers [see for example Calka and Judd (1985), Judd and Lavdas (1980), and Judd and Chopra (1993)] have studied the issue of interaction between bubbles formed at adjacent nucleation sites. Their studies do not consider the possibility of thermal interactions. Indeed, Judd and Chopra (1993) observe that thermal interactions are minimal compared to the bubble interaction effects. The results of the present study suggest otherwise. In macrolayer-controlled nucleate boiling, a realistic model would have to account for both stem hydrodynamic

interactions as well as thermal interactions. The present study has considered only thermal interactions; the computer model has been developed in such a manner that additional effects can be incorporated as better model elements are developed.

SUMMARY

This paper summarizes the preliminary findings of a study aimed at identifying the effects of transient activation and deactivation of nucleation sites on the overall characteristics of high heat flux nucleate boiling. The present results support and extend previous findings in the low-flux regime.

A simple heat-conduction model has been developed to simulate heat conduction within the heater and liquid macrolayer. The boundary conditions of the conduction problem vary with time depending on the instantaneous status of each nucleation site on the surface.

The numerical implementation of the model has been used to demonstrate that significant nonlinearities exist in the boiling system. It is proposed that the on-off behavior of the nucleation sites on the surface is the primary source of the nonlinearities. Such transient variations in the status of nucleation sites is the result of the thermal feedback between the sites and the heater surface temperature distribution. Different consequences of the nonlinearities in the system have been discussed.

Significant spatial and temporal variations in surface temperature can occur under appropriate conditions of heater thermophysical properties, heater thickness, and distribution of sites on the surface. The results of the present study with respect to transient variation in the status of nucleation sites, and with respect to spatial and temporal variations in surface temperature have been shown to be in qualitative agreement with experimental results of previous studies.

The spatial variations in temperature on the heater surface have been shown to have considerable consequences for experimental measurements. Local point measurements of surface temperature can yield widely different values of temperature depending on combined influence of sensor location and the spatial distribution of active sites and intermittently active sites.

For the problems discussed in this paper, the nonlinear effects in boiling have been shown to cause period-doubling in some cases, and a loss of periodicity in other cases. It is proposed that the nonlinear effects are responsible for some of the data scatter commonly seen in boiling data. The results do not indicate the evidence of chaotic behavior. However, it is argued that this possibility cannot be ruled out in other systems; the potential for nonlinearity increases as the potential for increased thermal interactions among sites increases.

ACKNOWLEDGMENT

We wish to acknowledge the excellent service provided by the Computing Information Center of Los Alamos National Laboratory in making these computations possible.

REFERENCES

- Calka, A., and Judd, R. L., 1985, "Some Aspects of the Interaction Among Nucleation Sites During Saturated Nucleate Boiling," *Int. J. Heat Mass Transfer* **28**, pp. 2331-2342.
- Chekanov, V.V., 1977, "Interaction of Centers in Nucleate Boiling," Translated from *Teplofizika Vysokikh Temperatur* **15** (1), pp. 121-128.
- Gaertner, R. F., 1963, "Distribution of Active Sites in the Nucleate Boiling of Liquids," *Chem. Engr. Prog. Symp. Ser.* **59**, pp. 52-61.
- Judd, R. L., and Lavdas, C. H., 1980, "The Nature of Nucleation Site Interaction," *J. Heat Transfer* **110**, pp. 475-478.
- Judd, R. L., and Chopra, A., 1993, "Interaction of the Nucleation Processes Occurring at Adjacent Nucleation Sites," *J. Heat Transfer* **115**, pp. 955-962.
- Kenning, D. B. R., 1992, "Wall Temperature Patterns in Nucleate Boiling," *Int. J. Heat Mass Transfer* **35**, pp. 73-86.
- Nukiyama, S., 1934, "The Maximum and Minimum Values of the Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure," *J. Jap. Soc. Mech. Eng.* **37**, pp. 367-374 (translation: *Int. J. Heat Mass Transfer* **9**, 1966, pp. 1419-1433).

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P., 1992, Numerical Recipes in FORTRAN. The Art of Scientific Computing, Second Edition, Cambridge University Press.

Raad, T., and Myers, J. E., 1971, "Nucleation Studies in Pool Boiling on Thin Plates Using Liquid Crystals," *AIChE Journal* 17, pp. 1260-1261.

Sadasivan, P., Unal, C., and Nelson, R. A., 1993, "MACRO3D—Discretization Schemes for Slender Geometries," Los Alamos National Laboratory document LA-UR-93-3233.

Sgheiza, J. E., and Myers, J. E., 1985, "Behavior of Nucleation Sites in Pool Boiling," *AIChE Journal* 31, pp. 1605-1613.

Sultan and Judd, R. L., 1978, "Spatial Distribution of Active Sites and Bubble Flux Density," *J. Heat Transfer* 100, pp. 56-62.

Wang, C. H., and Dhir, V. K., 1993, "Effect of Surface Wettability on Active Nucleation Site Density During Pool Boiling of Water on a Vertical Surface," *J. Heat Transfer* 115, pp. 659-669.

Yu, C. L., and Mesler, R. B., 1977, "Study of Nucleate Boiling Near the Peak Heat Flux Through Measurements of Transient Surface Temperature," *Int. J. Heat Mass Transfer* 20, pp. 827-840.

Table I Surface site data for distribution of Fig. 3a

Cavity size (μ)	Number of cavities	Activation temperature (K)	Deactivation temperature (K)
0.5	2	477.88	472.88
0.6	3	460.40	455.40
0.7	5	447.91	442.91
0.8	4	438.55	433.55
0.9	5	431.27	426.27
1.0	5	425.44	420.44
1.1	4	420.67	415.67
1.2	4	416.70	411.70
1.3	4	413.34	408.34
1.4	4	410.46	405.46
1.5	5	407.96	402.96
1.6	6	405.77	400.77
1.7	12	403.85	398.85
1.8	12	402.13	397.13
1.9	11	400.60	395.60
2.0	9	399.22	394.22
2.1	9	397.97	392.97
2.2	9	396.84	391.84
2.3	9	395.80	390.80
2.4	8	394.85	389.85
2.5	8	393.98	388.98
2.6	6	393.17	388.17
2.7	4	392.42	387.42
2.8	3	391.73	386.73
2.9	2	391.08	386.08
3.0	2	390.48	385.48
3.1	2	389.92	384.92
3.2	2	389.39	384.39
3.3	2	388.89	383.89
3.4	2	388.42	383.42
3.5	2	387.98	382.98
3.8	3	386.80	381.80
4.0	3	386.11	381.11
4.3	2	385.20	380.20
4.5	1	384.65	379.65
4.8	1	383.92	378.92
5.0	1	383.49	378.49
5.3	1	382.89	377.89
5.5	1	382.53	377.53
5.7	1	382.20	377.20
6.0	1	381.74	376.74

Table II Surface site data for distribution of Fig. 3b

Cavity size (μ)	Number of cavities	Activation temperature (K)	Deactivation temperature (K)
1	40	425.44	420.44
2	90	399.22	394.22
3	33	390.48	385.48
4	10	386.11	381.11
5	4	383.49	378.48
6	3	381.74	376.74

Fig. 1. Cavity location map.

Fig. 2. Spatial distribution of surface cavities (solid line shows Poisson distribution for a mean of five sites per division; solid circles correspond to distribution of Fig. 1).

(a)

(b)

Fig. 3. Size distribution of surface sites (a) fine variation (data in Table I) and (b) coarse variation (data in Table II).

Fig. 4. Transient variation of T_{SA} for three heat fluxes.

Fig. 5. T_{SA} time series for $q = 1.04 \text{ MW/m}^2$.

Fig. 6. Behavior of sites on the 50- μ surface for $q = 1.04 \text{ MW/m}^2$ (numbers marked are site labels of the intermittent sites).

Fig. 7. Examples of transient behavior of individual sites—from top, site 9, 58, 128, and 137, where numbers correspond to those marked in Fig. 6.

Fig. 8. (a) Variation of the number of sites during a hovering period, for different heat fluxes, and (b) variation of the maximum number of active sites with heat flux.

Fig. 9. Spatial temperature variations on the heater surface (a) superheat versus area fraction and (b) highest and lowest temperatures on the surface.

Fig. 10. Map of surface showing locations of 1-mm square sensors.

Fig. 11. Variation of window-average temperature for windows shown in Fig. 10.

Fig. 12. First return maps for the surface-average temperature at three heat fluxes.

Fig. 13. Lamb normalized periodogram of the surface-average temperature time series for three heat flux levels of Fig. 4.

(a)

(b)

Fig. 14. Data of Yu and Mesler (1977): (a) surface temperature time series and (b) qualitative interpretation of the data in Fig. 14(a) for on-off behavior of sites in the sensing area.

**DATE
FILMED**

10 / 12 / 94

END

1