Elimination of boiling incipience temperature drop in highly wetting fluids using spherical contact with a flat surface

S.J. Reed[1], I. Mudawar[2],*

Boiling and Two-Phase Flow Laboratory, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, U.S.A.

Abstract

This work examines the effectiveness of the zero-angle cavities created by curved contact with a flat surface in promoting vapor embryo capture, low temperature boiling incipience, and reduction or elimination of the incipience temperature overshoot with highly wetting liquids. Using FC-72 as a test liquid, both single and multiple spherical point contacts on a flat heater in both horizontal and vertical orientations are examined. The effects of contact force, material conductivity, and fluid flow obstruction as well as overall boiling behavior resulting from the surface contact are addressed. Boiling incipience behavior, for contact forces between 4.45 and 26.7 N, showed independence of force for all contact materials. Multiple contact points of insulative material with conductive tips showed the greatest improvement, virtually eliminating the temperature excursion often associated with incipience while still allowing sufficient liquid access to the boiling surface such that the critical heat flux was within only 6% of that for a bare surface. Because such features are large, it is unlikely that prolonged boiling or submersion would significantly degrade the boiling enhancement effects, as is the case with the small features resulting from surface roughening techniques. © 1999 Elsevier Science Ltd. All rights reserved.

Nomenclature

CHF critical heat flux
k thermal conductivity
P pressure
q_s'' heat flux across heater surface
T temperature.

Greek symbols
ϕ cavity angle
θ contact angle.

Subscripts
b bulk liquid

s heater surface
sat saturation.

1. Introduction

In many devices, improving performance often requires increased power densities which translate to needs for greater cooling. Where heat fluxes are too high to be easily handled by air cooling, alternative means are sought. Sophisticated schemes, including forced liquid, jet impingement, spray, and flow boiling have received considerable attention in the literature and have been shown capable of handling the highest predicted heat fluxes in electronic cooling and other areas. Pool boiling heat transfer is an attractive alternative to many of these because its passive, buoyancy-driven flow creates extremely high heat transfer coefficients while requiring no external power or cooling lines. In recent years, pool boiling has come to the forefront of high-heat-flux ther-

* Corresponding author. Tel.: +1 765 494 5705; fax: +1 765 494 0539; e-mail: mudawar@ecn.purdue.edu

[1] Graduate Research Assistant.

[2] Professor and Director of the Purdue University Boiling and Two-Phase Flow Laboratory.

mal management research for many applications, including X-ray devices, lasers, power supplies, and electronic components. Effective use of boiling requires that the repeatability and effectiveness of the boiling process be maximized and the thermal resistance between the heat dissipating component and the liquid minimized.

Except for high temperature, homogenous nucleation, nucleate boiling involves bubble growth from existing vapor embryos trapped in surface cavities during the initial filling with liquid or prior boiling. Conditions for thermo-mechanical equilibrium and growth of a bubble interface show that the fluid surrounding the bubble is superheated above its saturation temperature by an amount inversely proportional to the radius of curvature of that interface. For a given cavity, the radius of curvature of the bubble interface is related to the size of the trapped embryo. Figure 1 shows surface filling with liquid for different cavity and liquid contact angles. For large-angle cavities or relatively small contact angle liquids, cavities are flooded or trapped embryos are small, requiring large superheats for bubble growth. Decreasing the

cavity angle or increasing the liquid contact angle increases the size, and radius of curvature, of embryos.

1.1. Fluorocarbon liquids

The availability of inert, highly-dielectric liquids has made direct immersion of many heat dissipating devices, including electronic components, a promising possibility for eliminating the thermal resistance between the device and the coolant liquid encountered in indirectly cooled systems. 3M Company's [1] family of such liquids has recently taken a place of interest in two-phase cooling research and applications. Collectively known as Fluorinerts or FCs, they are environment-friendly coolants with saturation temperatures at atmospheric pressure ranging from -2.25 to 253°C. The disadvantages of the FCs, for cooling purposes, are that they possess relatively poor heat transfer characteristics and are highly wetting, making extremely small contact angles with most surfaces. Because the FCs wet surfaces so well, conventional cavities, which may be measured by surface
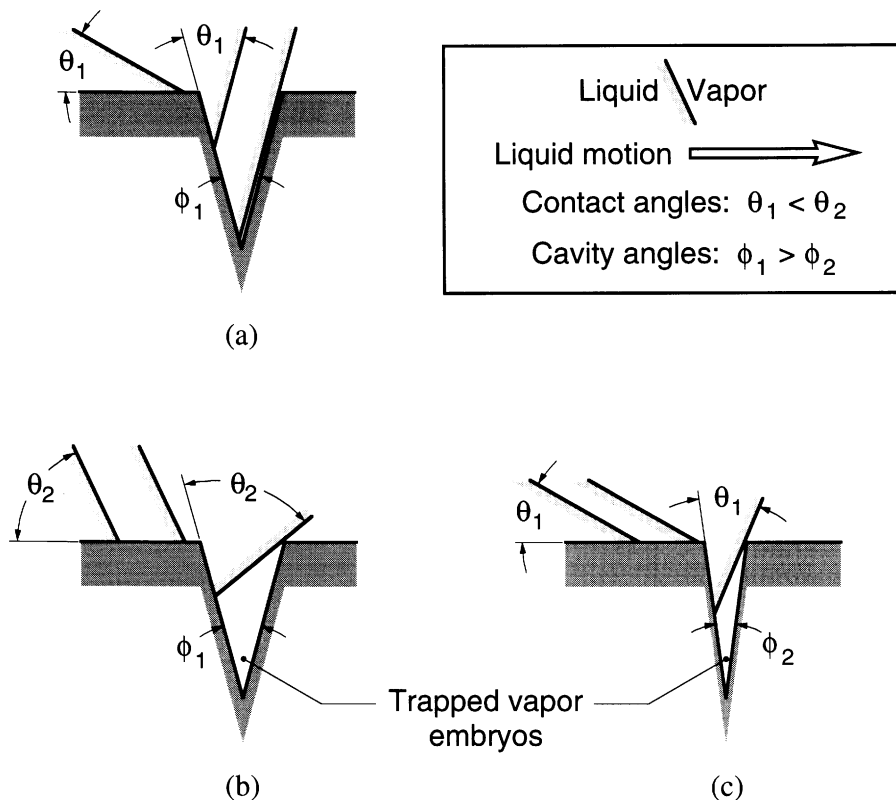

Fig. 1. (a) Cavity flooding because of a large cavity angle and small contact angle; (b) trapping of embryo with a less wetting fluid; (c) trapping of embryo because of a small cavity angle.

profilometry or scanning electron microscopy, and could serve as nucleation sites for less-wetting fluids, are flooded. As a result, embryos are trapped only in tiny cavities on the surface between, or on the walls of, the larger cavities and are themselves small, delaying the onset of boiling to high heater temperatures.

Studying FC-72 boiling on a variety of polished and roughened copper heater surfaces, Anderson and Mudawar [2] showed that conventional nucleation theory, which uses the cavity size and temperature gradient in the liquid near the wall to determine the superheat required for boiling incipience, does not apply to highly wetting fluids. With highly wetting fluids, the minimum embryo radius, which corresponds to the minimum superheat temperature required for bubble growth, is much smaller than the cavity size. You et al. [3] examined incipience of FC-72 on sputtered surfaces of various materials with cavities on the order of 1 μm. Based on a distribution of measured incipience superheats between 18–51°C, and using the bubble growth criteria mentioned earlier, they determined that corresponding embryo sizes ranged from 0.150–0.025 μm in radius, considerably smaller than the visible cavities. For real devices, such high incipience temperatures, which occur at low powers where the devices may operate for a considerable time, can mean seriously reduced component reliability and shortened lifetime. Thornell et al. [4] showed that the failure rate of electrical circuit components is nearly exponential with increasing operating temperature.

A second threat to the longevity of sensitive components is the large temperature drop that often coincides with the onset of boiling of the FCs. Bernardin and Mudawar [5] showed that the number of cavities of a given size on a surface is inversely proportional to the cavity size. Because the small cavities that are able to trap embryos with the FCs are so numerous, bubble growth from one cavity can activate a neighboring one which has no embryo or whose incipience superheat has not yet been reached. When the bubble is released and the liquid flows to take its place, the contact angle of the liquid is greater, allowing a larger embryo to be trapped in the previously-inactive cavity. This can cause boiling to spread over the entire surface very quickly, dramatically increasing the heat transfer coefficient, and is manifested in a temperature drop, or 'excursion'. While the rate at which this excursion occurs depends on the mass and thermal properties of the heater, the end result is that the temperature of the device has gone through a cycle. For devices made of various materials with different thermal expansion properties, this thermal cycling can fatigue bonds, ultimately resulting in failure. Reduction of the superheat temperature required to induce boiling offers the advantages of entering the high heat transfer coefficient nucleate boiling region at low heat fluxes and decreasing the likelihood of such temperature drops. The goal, then, of schemes to enhance boiling heat transfer in highly wetting fluids, is to maximize the size and number of the trapped embryos to promote early boiling incipience and the gradual spread of boiling with increasing heat flux while increasing the area available for heat transfer.

1.2. Boiling enhancement

There are two popular methods for enhancing boiling heat transfer from a flat surface; surface extension and surface roughening. Surface extension, or finning, mainly increases the highest nucleate boiling heat flux, relative to a bare surface, by increasing the area available for boiling heat transfer. Surface roughening, as with sanding or particle blasting, leaves a wide range of cavity sizes capable of trapping embryos and growing bubbles in many liquids. This promotes early nucleation and increases the nucleate boiling heat transfer coefficient, which is manifested as a left-ward shift in the boiling curve. Artificial cavities for promoting vapor entrapment, nonwetting surface coatings, and surface attachments have also been used to cause boiling to begin at low fluxes and control boiling spread.

In many cases, a combination of the various enhancement concepts is essential for optimal cooling. However, advancement in one area sometimes comes at a cost to one of the others. Anderson and Mudawar [2], in a study that examined boiling of highly wetting liquids on surfaces with two levels of enhancement, showed that roughening surfaces by blasting with particles ranging between 1–7 μm in size resulted in reduced incipience temperature excursion and a greater heat transfer coefficient in nucleate boiling. They also found that adding features or cavities on the order of 1 mm in size increased the heat flux in the nucleate boiling regime and the maximum, or critical, heat flux (CHF), but resulted in large incipience temperature excursions.

Many schemes that have been developed to promote vapor entrapment and early boiling incipience are not applicable to highly wetting fluids because the features associated with those schemes would be flooded. One early idea for promoting boiling on evaporator tubes, proposed by Schmittle and Starner [6], involved wrapping the tubes with wire as a means of creating an array of infinitesimally small-angled cavities. Chyu and Mghamis [7] made quantitative measurements of the wall superheat temperature associated with boiling using a similar configuration, a cylinder held in contact with a flat plate, shown in Fig. 2. They found that, regardless of the conductivity of the cylinder material, boiling is always improved, beginning at lower wall temperatures with the cylinders than with a bare surface. They also reported that the larger diameter cylinders showed greater improvement than did the smaller diameter cylinders. They suggested that the flat plate and cylinder interface creates restricted regions which prohibit the fluid from
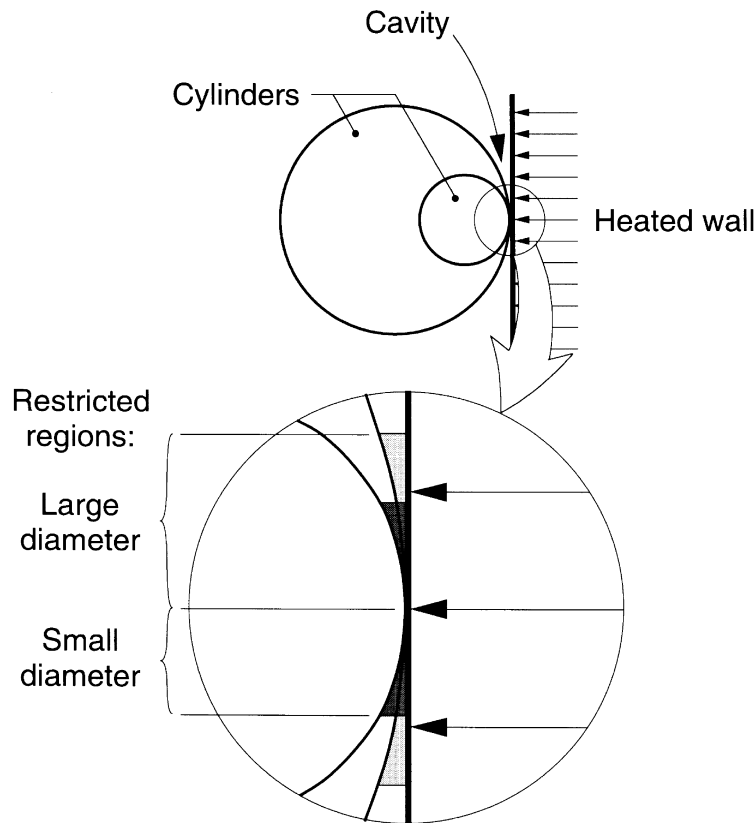
Fig. 2. Restricted regions created by interface of curved and flat surfaces.

circulating and causes it to superheat. The larger-diameter cylinder creates a larger restricted region, impeding fluid flow more and further flattening the temperature profile in the liquid close to the wall. Although they used water, the ideas may be extended to highly-wetting fluids because the cavity angle approaches zero degrees at the actual point of contact, permitting vapor entrapment in even the most wetting of liquids.

1.3. Study objectives

The goal of this work is to examine the effectiveness of the zero-angle cavities created by curved contact in promoting vapor embryo capture and low temperature nucleation incipience and reducing or eliminating the incipience temperature overshoot associated with highly-wetting liquids. Because such features are large, it is unlikely that prolonged boiling or submersion would significantly degrade the boiling enhancement effects, as is the case with surface roughening techniques. In this study, both single and multiple-spherical-point contacts on a flat heater are examined. The effects of contact force, material conductivity, and fluid flow obstruction are also addressed.

2. Experimental apparatus and procedure

2.1. Test chamber

All experiments reported herein used FC-72 ($T_{sat} = 56.6°C$ at 1 atm) and were performed in the pool boiling chamber shown in Fig. 3(a). The chamber was made of a G-10 fiberglass plastic frame, top and bottom, and had Lexan polycarbonate view windows on the front, back, and one side to provide convenient optical access. A smaller port, shown on the left side of the chamber, was used for making adjustments to the heater module while fluid was in the chamber. Atmospheric pressure was maintained during the experiments and noncondensible gases were released, using a vent on the top of the chamber. A copper coil condenser, with cold tap water circulating through it, recondensed nearly all the vapor, effectively making the chamber a closed system. A head of 6.35 cm of fluid above the submerged test heater, corresponding to approximately 0.3°C difference in the fluid saturation temperature, was maintained in all experiments.

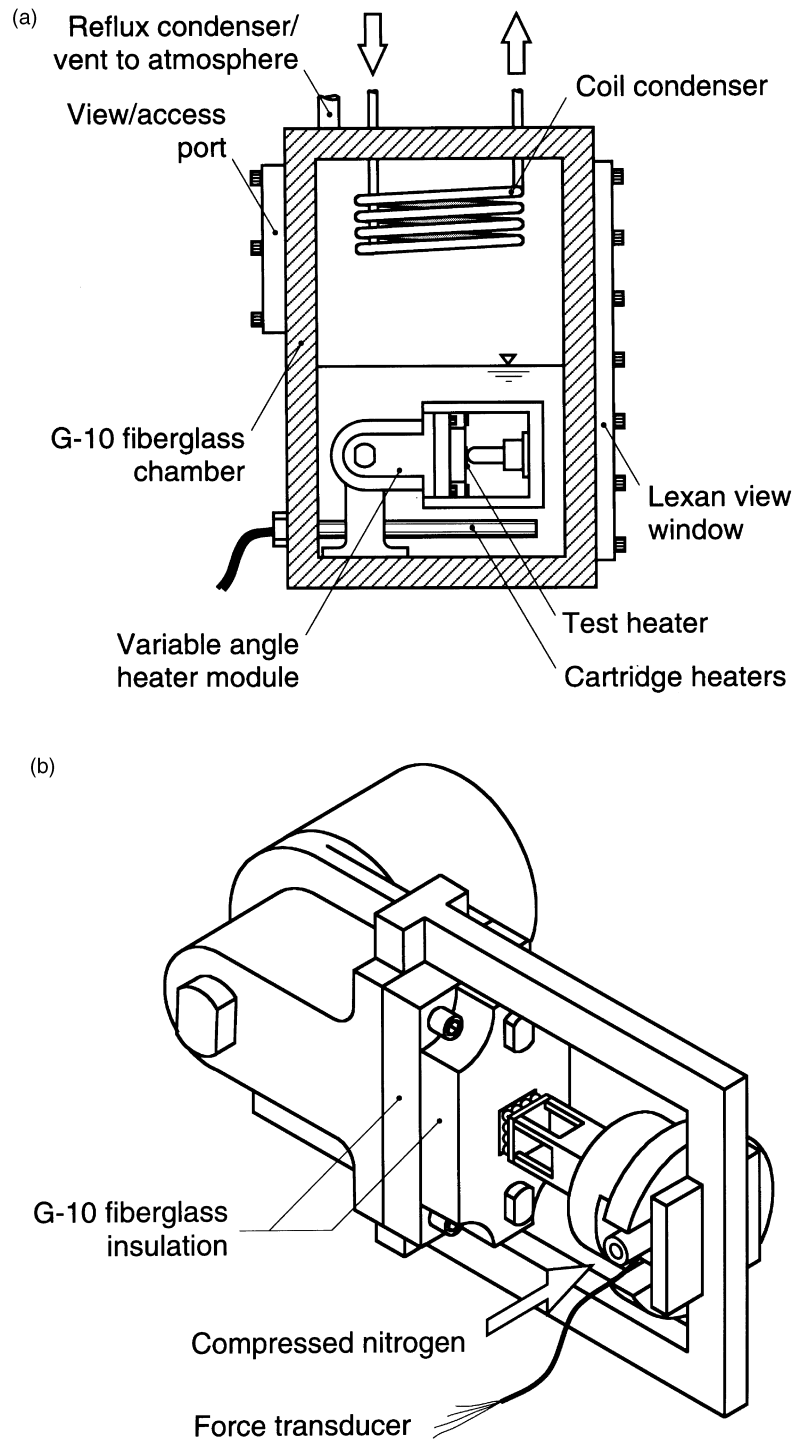The bulk fluid temperature was measured by two thermocouples positioned near the test heater. Heat lost

Fig. 3. (a) Test chamber and heater module; (b) heater module with surface attachment; (c) detail of surface attachment.
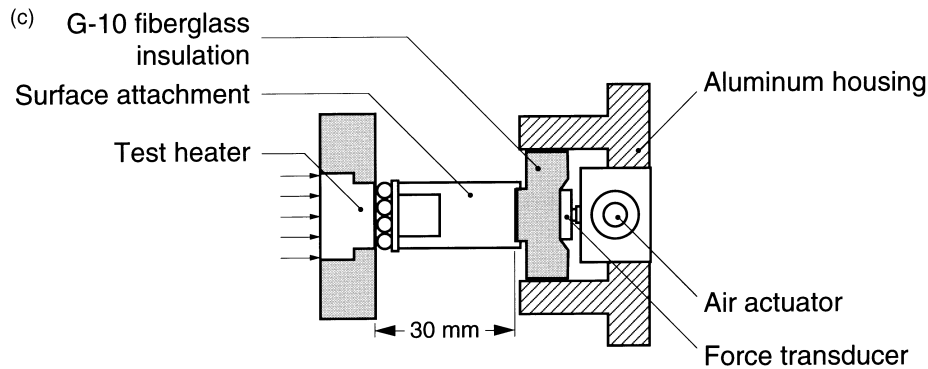
(c)

G-10 fiberglass insulation

Surface attachment

Test heater

Aluminum housing

Air actuator

Force transducer

|← 30 mm →|

Fig. 3. *Continued.*

through the chamber walls was replaced with heat from the test heater and three cartridge heaters which were connected to a variable-voltage source and were manually operated. The cartridge heaters were positioned at the back of the chamber to prevent the bubbly flow from interfering with the test heater. Experiments were run with the bulk fluid subcooled 1.5°C to eliminate the vigorous bulk fluid motion and vapor entrainment which occurred, even with a baffle installed, when the liquid was saturated. A thirty minute deaeration procedure, during which the fluid in the chamber was vigorously boiled and recondensed, was performed prior to each set of tests to remove all noncondensible gases from the liquid.

Figure 3(b) shows the sealed heater module and surface attachment with the square test heater in a vertical position. The test heater, detailed in Reed and Mudawar [8], consisted of an oxygen-free-copper block ($k = 398$ W m^{-1} K^{-1} at 20°C) with a 90 Ω, thick-film resistor soldered to the back. A thermocouple, located 0.81 mm beneath the surface, and a power transducer, measuring electrical power provided to the resistor, were used to determine the surface heat flux and for extrapolation to determine the surface temperature. To reduce losses, the heater was insulated on its perimeter and back, as shown. Finite element analysis of the insulated heater showed less than a 2% variation in heat flux across the surface, justifying the assumptions of one-dimensional conduction through the heater and uniform heat flux across the surface. Maximum uncertainty in heater surface temperature due to uncertainty in thermocouple position, heat flux measurement, and thermocouple uncertainty, was around 0.3°C. A linear calibration curve provided an excellent fit for the power transducer data and had less than 0.5% uncertainty. Because the linear fit had around a 0.49 W offset at zero power, considerable uncertainty is present in very low power measurements. As a result, heat fluxes less than 1 W cm^{-2} are to be regarded with caution and those below 0.4 W cm^{-2} are excluded from results.

2.2. Contact geometries

Like Chyu and Mghamis' [7] cylinder in line contact with a flat plate, a spherical surface in contact with a flat surface creates an array of nucleation sites with angles approaching zero degrees at the point of contact. In theory, the spherical contact neither decreases the heater surface area nor provides an additional route for heat flow because the area of contact is an infinitesimally small point. For true point contact, any contact force would result in infinite contact pressure. In reality, however, some deformation of the spherical contact point occurs, resulting in finite pressure and area of contact. The effects of contact force, contact material, and number of points of spherical contact were examined for their contribution to incipience enhancement.

Contact force for holding the various attachments to the heater surface was applied using the attachment shown in Fig. 3(b) and (c). Compressed nitrogen was connected to the pneumatic actuator shown in Fig. 3(c) through a pressure regulator, which was positioned outside the test chamber to allow remote adjustment of the contact force. A small, 53 N load cell was connected in series with the actuator to measure the applied contact force, as detailed in Fig. 3(c). Uncertainty in the applied force measurement due to inaccuracy in the force transducer output and regulator adjustment varied from less than 2% at the highest to around 10% at the lowest force, 4.45 N, measured. Except for the tests to determine the effect of contact force on the boiling performance, all tests were run with this minimum loading on the attachments.

Figure 4(a) summarizes the single and multiple point contact configurations and the materials used. Single point 'fins' of solid copper and G-10 fiberglass ($k = 0.26$ W m^{-1} K^{-1}) represent thermally conductive and insulative attachments, respectively. The composite aluminum foil ($k = 237$ W m^{-1} K^{-1}) and G-10 attachment provides a small, thermally conductive region at the tip while retaining the overall insulative properties of the G-10
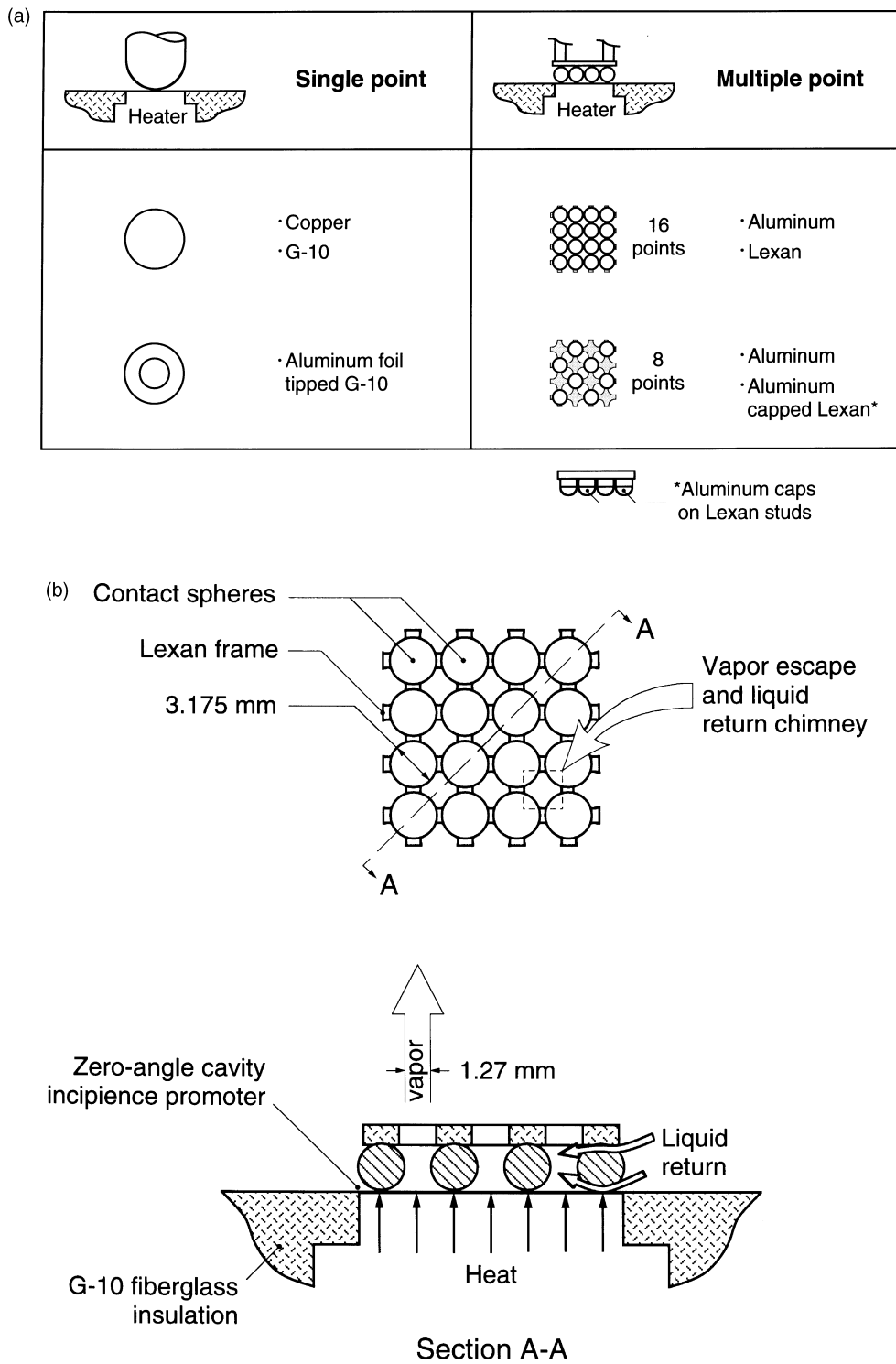
(a)

Single point		Multiple point	
○	· Copper · G-10	▦ 16 points	· Aluminum · Lexan
◎	· Aluminum foil tipped G-10	▨ 8 points	· Aluminum · Aluminum capped Lexan*

*Aluminum caps
on Lexan studs

(b) Contact spheres
Lexan frame
3.175 mm

Vapor escape
and liquid
return chimney

A

A

Zero-angle cavity
incipience promoter

vapor ← 1.27 mm

Liquid
return

G-10 fiberglass
insulation

Heat

Section A-A

Fig. 4. (a) Contacting geometries and materials used in this study; (d) detail of multiple point contact attachment.

fiberglass. For the multiple point contact attachments shown in Fig. 4(a) and detailed in Fig. 4(b), a Lexan frame held arrays of Lexan spheres ($k = 0.20$ W m^{-1} K^{-1}), aluminum spheres, and Lexan studs with sections of aluminum spheres representing insulative, conductive, and conductively tipped insulative attachment cases, respectively.

Two densities of packing of the 3.175 mm diameter spherical contacts were used, as Fig. 4(a) shows, to examine the effect of spacing for this experiment. Klein and Westwater [9] showed that the minimum spacing in arrays of fins, without loss in fin performance, is on the order of the fluid's nucleate pool boiling bubble departure diameter. Departure diameters for FC-72, using various correlations for the departure diameter of bubbles in nucleate boiling, given in Carey [10], average around 0.4 mm. The property data and boiling curves needed for these correlations are given in Reed and Mudawar [8]. For both the eight- and sixteen-sphere arrangements, vapor release and fluid replacement were achieved with chimneys drilled through the Lexan frame and gaps between the spheres. The minimum diameter of the vapor escape chimney, shown in Fig. 4(b), is 1.27 mm, the distance between two of the contacting spheres. This is more than three times the average departure diameter of bubbles in saturated pool boiling of FC-72. The eight-sphere arrangement formed by simply eliminating every other sphere provided additional routes for vapor and liquid flow in the vacancies of the other spheres.

2.3. Test procedure

Surfaces subjected to prolonged boiling and immersion can experience changes in their boiling behavior, dramatically affecting the repeatability of boiling tests. This effect, known as 'aging', was first observed by Jakob [11] and has been attributed to several causes including surface erosion, oxidation and contamination, as well as release of gases adsorbed by the heater surface and vapor embryo condensation. Anderson and Mudawar [2] showed that, for highly wetting liquids, the pre-boiling experience of the heater surface greatly influences the incipience temperature and overshoot magnitudes. To ensure uniform and repeatable boiling surface properties, the test heater surface was blasted with a silica particle and water slurry prior to each set of tests. Electron microscope photos of particle-blasted surfaces, presented by Anderson and Mudawar [2], show that such treatment replaces small-scale roughness features with a randomly-distributed, dendritic surface texture with cavities on the order of 10 μm. Degradation of this surface occurs quickly at first, as the sharp features erode, and then much more slowly. To avoid the region of rapid change and to achieve quasi-steady boiling behavior, the heater surface was boiled vigorously for thirty minutes at one-fourth the critical heat flux prior to each set of tests and

in conjunction with the bulk fluid deaeration procedure described earlier.

Data acquisition and system control, except for the manual operation of the bulk fluid cartridge heaters, was achieved using a Keithley data acquisition system (DAS). The DAS monitored the heater and bulk fluid temperatures, heater power, and contact force and recorded the values when the system reached steady state. Steady state was determined to occur when the standard deviation of the heater temperature measurements fell below limits set by the user. The power provided to the test heater was controlled using solid state power relays, operated by the DAS, in conjunction with a resistance ladder. Upon reaching steady state, the temperature, power, and force measurements were recorded and the heater power was incremented by opening and closing various power relays to change the net ladder resistance. For the complete boiling curves given, this process continued until the critical heat flux was reached. Tests were terminated when the heater reached critical heat flux, the point when the heater temperature did not achieve a steady value, or reached 130°C, a limit set to prevent the resistive heater from burning. In the multiple point contact cases, where only the boiling incipience point was reported, the tests were not run to critical heat flux but were terminated after slowly incrementing the power in the same manner as in the complete tests but only two data points past incipience.

3. Experimental results and discussion

Conditions for boiling incipience, particularly when highly-wetting fluids and finite-sized heaters are used, are difficult to predict and can even vary between successive tests. You et al. [3] suggested that data for fluids such as the Fluorinerts be presented in terms of the probability of boiling occurring at corresponding wall superheat temperatures. Results of the present study are given in accordance with this convention. Table 1 summarizes the different surface contact geometries tested and gives the number of runs for each geometry.

A problem associated with the probability method of presenting incipience data is that it makes no account for the magnitude of the temperature excursion which occurs at the onset of boiling. In general, the delay of boiling to higher incipience temperatures corresponds to greater temperature drops when boiling finally does begin. This is not always the case, however, and sometimes high incipience temperatures are followed by relatively small temperature drops at the onset of boiling. To better characterize the incipience behavior, data for the multiple point contact geometries are presented both in terms of the incipience temperature and the magnitude of the accompanying temperature drop.

Table 1
Number of test runs used for determining incipience probability

Heater orientation	Bare surface	Single point contact		
		Copper	G-10	Aluminum-tipped G-10
Vertical	12	35	7	9
Horizontal	6	19	12	17
		Multiple point contact		
		16 point Lexan	16 point aluminum	8 aluminum spheres	8 aluminum caps
Vertical		3	3	12*	12*
Horizontal		3	3		

* Incipience only.

3.1. Force dependence

A series of contact force runs was made with the single copper point contact and various contact forces on a vertical heater surface, increasing the force from zero (contact only) to 26.7 N and decreasing it back to zero. The copper attachment was used because its high conductivity would cause it to show the greatest dependence of incipience and boiling behavior on contact force. Similar contact force runs conducted with the G-10 and aluminum-foil-tipped G-10 attachments showed no change with varying force and are not included here. The boiling surface received the particle blasting and aging treatment only once for this series, prior to the first test. Figure 5(a) shows results for three loadings with increasing force while Fig. 5(b) gives results for the same three loadings with decreasing force. Figure 5(c) compares the first two runs of the series with the final two.

In this series, and also in a second series of tests using the copper attachment but with a horizontal heater surface, there was no discernible dependence of incipience temperature or excursion upon contact force. Also, the shift in the point at which the transition out of nucleate boiling began to occur and the rightward shift of the nucleate boiling portion of the curve, seen in Fig. 5(c), appear to result from the aging that occurred across multiple, successive tests. Neither the critical heat flux nor the temperature at which it occurred were greatly affected by the contact force. The CHF value varied between 18.1–19.3 W cm^{-2} for the different loadings, showing slightly more heat dissipation at the high contact force.

In nucleate boiling, the extremely high heat transfer coefficient overshadows the relatively poor conduction heat transfer through the point of contact. Even the natural convection regions of the curves, excepting the seem-ingly anomalous first run, appeared to be little affected by contact force. Because the area of contact was so small, very little heat could be conducted through it. Increasing the force, for the range of forces used, did not significantly increase the area of contact or decrease the contact resistance. As a result, the effect of contact force on the incipience and overall boiling behavior was quite small.

3.2. Single point contact

Figure 6(a) shows a comparison between boiling on a bare, horizontal copper heater and on the heater with the single conductive, insulative, and conductively tipped insulative point contacts described earlier. Figure 6(b) shows the same cases for the vertical heater surface. These curves are representative of several runs with each type of attachment. Figure 7(a) and (b) shows the relative cumulative frequency of obtaining boiling vs wall superheat for the bare heater surface and the three single point contact cases.

The relative cumulative frequency plot is the discrete version of the integrated probability density distribution. The plotted points represent the number of boiling incipience occurrences (from $T_s - T_b = 0$ to the corresponding wall superheat) divided by the total number of incipience data points. For example, Fig. 7(a) shows a wall superheat temperature of 14°C on a copper surface corresponds to approximately a 90% likelihood that boiling would begin at that temperature. Bins used for determining the frequencies were of uniform width. However, because relatively small numbers of incipience data points were taken for some cases as indicated in Table 1, some frequency bins were empty. When this occurred, the corresponding frequency data point, which has the same value as the previous bin, was eliminated from the plot.
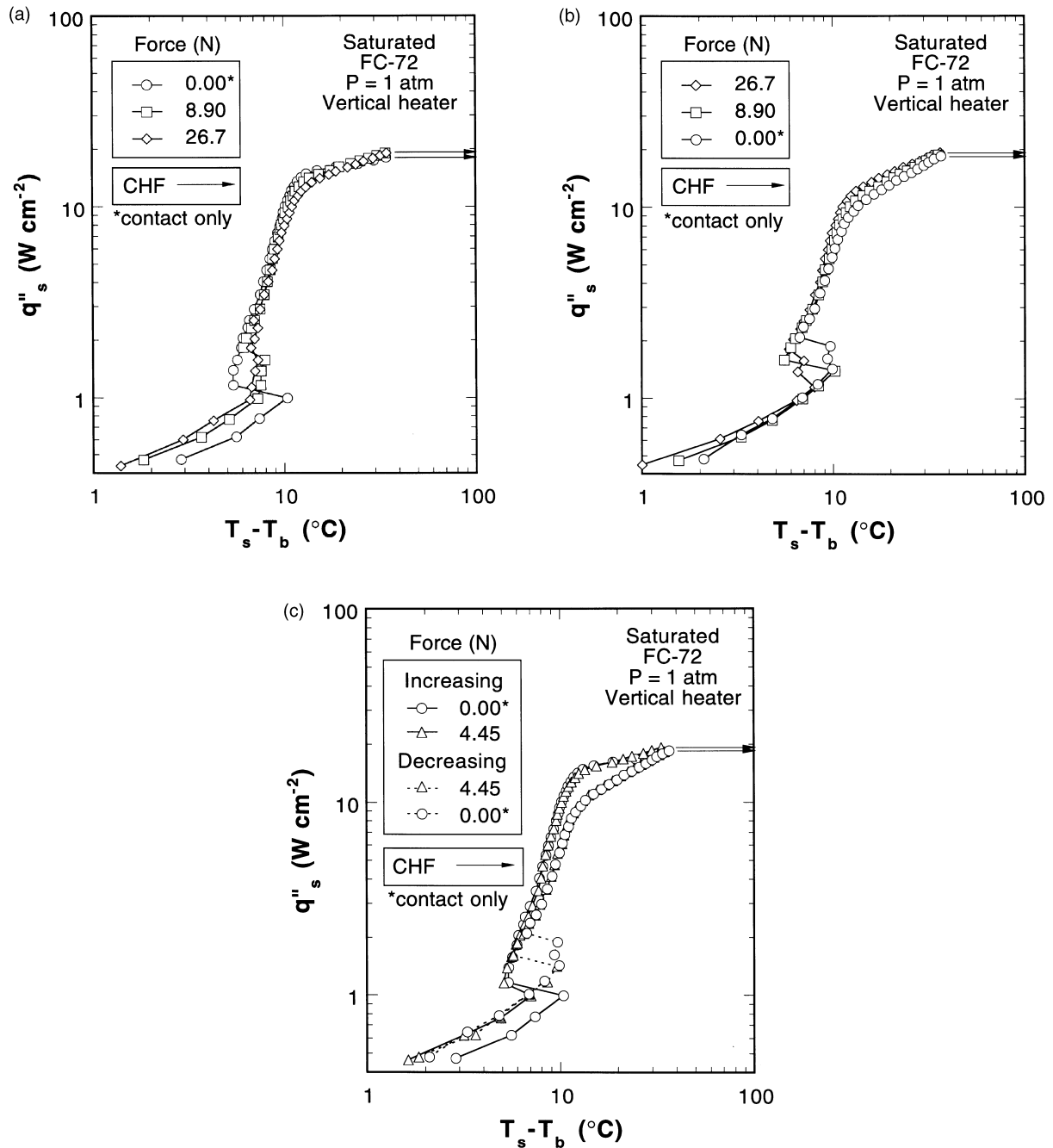
Fig. 5. Contact force dependence using single copper point contact on vertical heater with (a) increasing and (b) decreasing contact force; (c) shows effect of surface aging.

While this reduces the clutter in the frequency plots, it makes the bins appear nonuniform in width.

Notice that, for both horizontal and vertical heaters, the bare heater and heater with copper in point contact showed higher incipience temperatures than the cases of the G-10 and the aluminum tipped G-10 attachments. Correspondingly larger temperature excursions resulted from the higher incipience temperatures in the bare and copper attachment cases, as the curves in Fig. 6(a) and (b) indicate. The aluminum-foil-tipped G-10 attachment
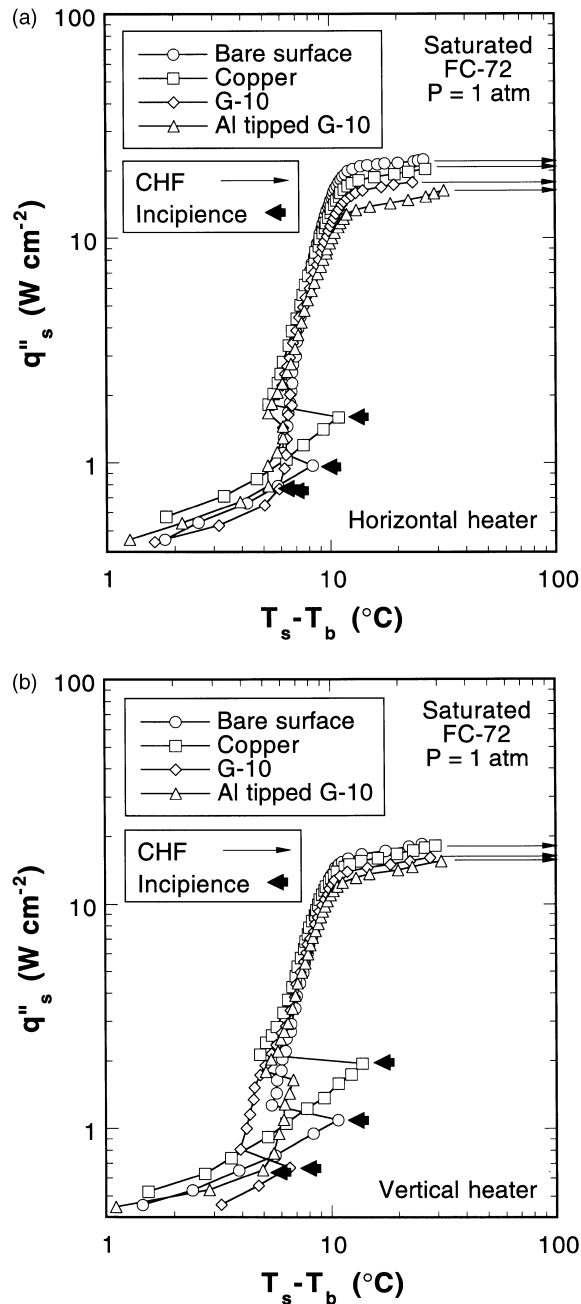
Fig. 6. Comparison of boiling for various single point contact materials on (a) horizontal and (b) vertical heater surfaces.

for the bare surface when the heater was horizontal. Although the area of contact was small, at low heat fluxes conduction into the cold, conductive copper constituted a lower resistance to heat flow than that of natural convection from the surface of the test heater into the liquid. This keeps the temperature of the area on the heater surface local to the contact point relatively cool, and the nucleation sites created by the point contact actually colder than other parts of the test heater surface, delaying the superheating of the liquid to higher heater heat fluxes. Tests with the bulk liquid subcooled 10°C showed this effect even more dramatically. In those cases, boiling began on the bare heater surface, away from the artificial nucleation sites that were created at the point of contact. Figure 8 shows computed values of the isotherms in the test heater and the copper attachment at (a) low and (b) high heat fluxes. At high heat fluxes, with the large boiling heat transfer coefficient occurring on the heater surface, the resistance to heat flow was lower for boiling at the heater surface than for conduction to the copper attachment. Notice that the computed isotherms in the heater are inverted in the high-flux case, Fig. 8(b), showing the contact point as a local hot spot.

Presumably, an insulative attachment would locally overheat the test heater at the point of contact, even at low heat fluxes, causing early nucleation and reducing the temperature overshoot. The insulative G-10 attachment also demonstrated some incipience excursion, however. For some runs with the G-10 attachment, as with copper, the spread of boiling to the interface was delayed to higher heater temperatures, causing the temperature to drop at incipience. While the copper attachment conducted too well and thus was effective in drawing the heat from the site at the contact point, the G-10 attachment did not conduct well enough and the heated area was confined to a region which was too small to effectively superheat the liquid. In this case, only one side of the artificial nucleation site was heated and nucleation was again delayed.

The aluminum-tipped G-10 attachment represents a more optimum balance between the conductive and insulative cases. Because the foil was very thin and insulated on the back by the G-10, it did not conduct much heat away from the heater surface in the vicinity of the contact point, as was the case with the copper attachment. The foil also spread the heat outward from the contact point, heating all sides of the nucleation site. The liquid flow in this region was restricted, causing it to superheat and begin boiling early. Boiling spread outward from the point of contact was, in general, gradual. However, some small temperature drops occurred, Fig. 6(a) and (b), as the boiling spread in discrete steps with steps in heat flux to regions away from the interface and below the contact point, for the horizontal and vertical heaters, respectively.

Natural convection and CHF behaviors also showed dependence on attachment material. Where conductive

demonstrated the earliest and most repeatable boiling incipience, in most cases resulting in no temperature drop at incipience.

It is noteworthy that the copper attachment provided little improvement when the heater was vertical and actually increased temperature drops over those observed
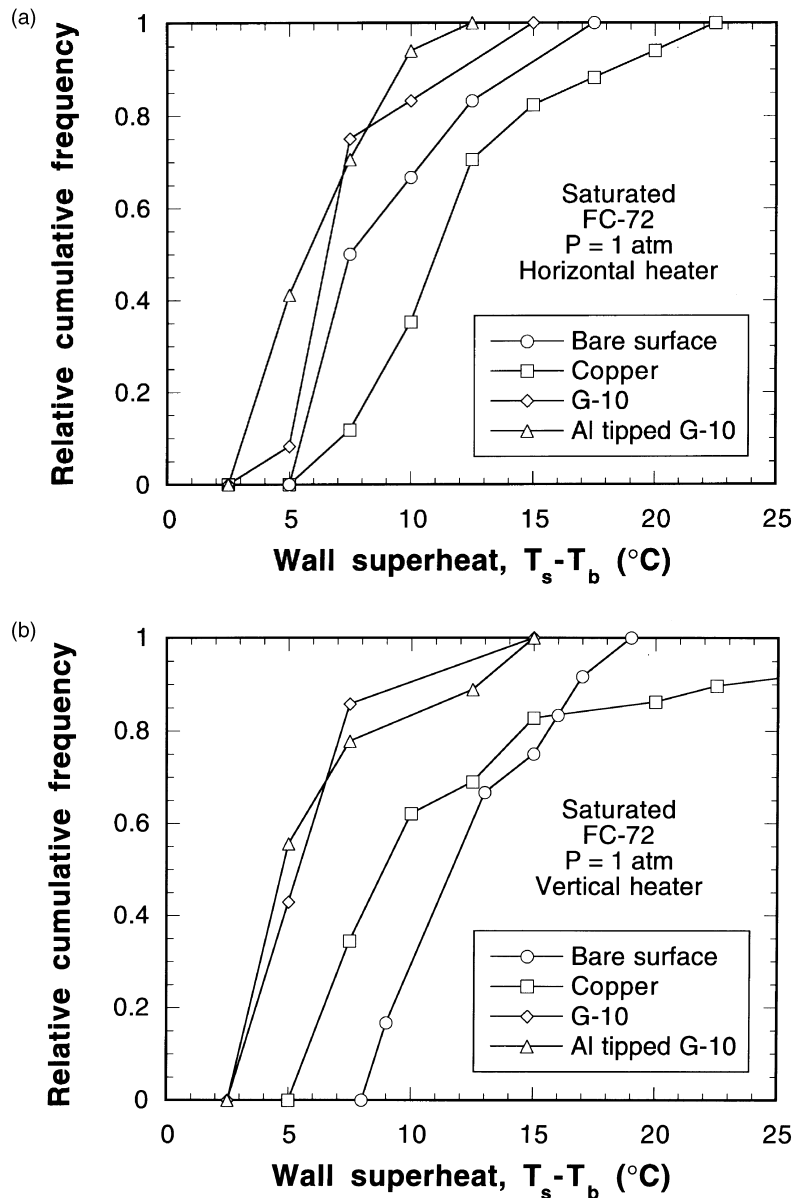
Fig. 7. Relative cumulative frequency ogive for boiling incipience with various single point contact materials on (a) horizontal and (b) vertical heater surfaces.

material such as copper and, to a small extent, aluminum tipped G-10 was used, some finning effect resulted and the natural convection was better than that for a bare surface. The CHF values for the different contact materials were all lower than CHF for the bare surface, which seems contrary to the idea that the point contact attachments do not significantly change the surface area. In fact, because the copper attachment did draw some heat, it actually added some amount of surface area, and it might be expected that the CHF would be higher than

that for the bare surface. The reason for its inferior CHF relative to a bare surface is that the attachment affected the fluid flow in the vicinity of the heater, blocking some of the area needed for liquid to flow to the surface to replenish that which was boiled away.

3.3. Multiple point contact

The success of the insulative and conductively-tipped insulative attachments in incipience temperature and
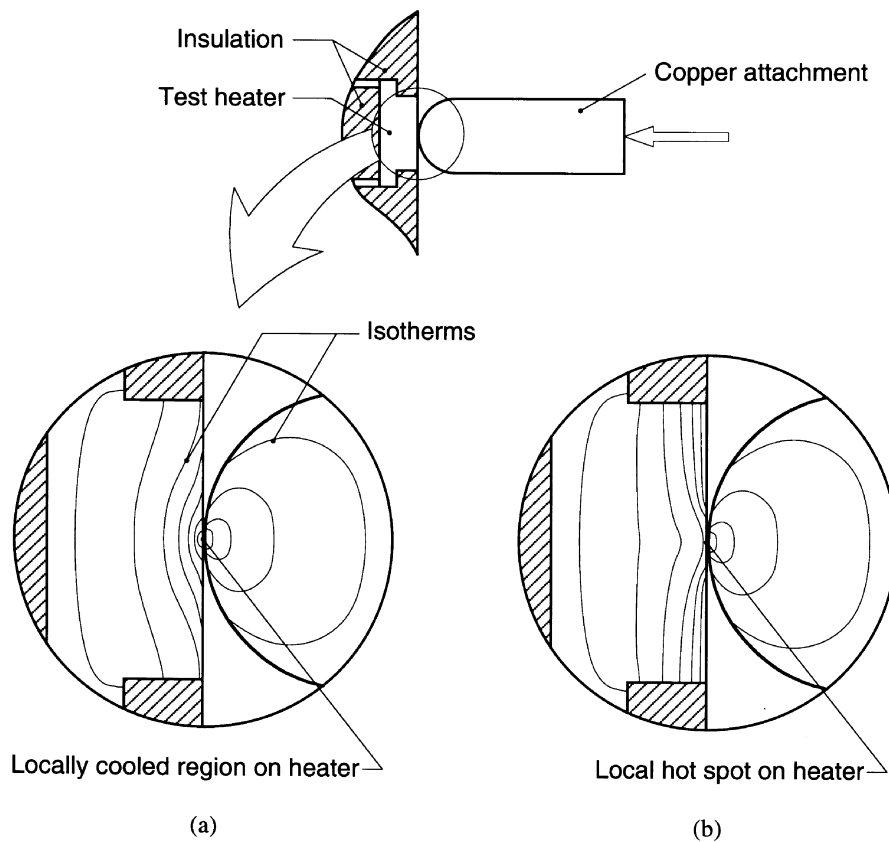
Fig. 8. Temperature gradients in heater and copper attachment for (a) low and (b) high heat fluxes.

overshoot reduction implied that multiple point contacts of similar design have the potential for providing even greater enhancement. With the single point contacts, the large area of bare heater surface allowed boiling to spread unpredictably at times. Multiple points of contact, conversely, would break up the bare heater surface into many smaller areas, reducing the likelihood of such boiling spread. The multiple points also provide more artificial, zero-angle cavities, increasing the probability of boiling occurring at lower temperatures.

Figure 9(a) compares the relative cumulative frequencies of boiling occurring for a bare vertical heater, eight contacting aluminum spheres, and eight contacting aluminum capped Lexan studs. Both the solid aluminum spheres and the aluminum capped studs showed reduction in the incipience wall superheat temperature over that of the bare surface. Like the single point contacts, the conductively tipped insulative attachment showed the greatest improvement because the conductive material maintained high surface temperatures on all sides of the cavity while the insulative back allowed little of the heat to be drawn from the heater surface. Figure

9(b), a histogram showing the incipience temperature excursions and their relative frequencies of occurrence, clearly shows the advantage of the conductively tipped insulative attachments for they effectively eliminate the incipience temperature excursion. For all tests with the aluminum capped Lexan, this excursion was less than 2°C and in ten of the twelve runs, less than 0.5°C.

The solid aluminum spheres, like the single copper point, could conduct heat away, locally cooling the heater and delaying incipience to higher heater temperatures. However, because the thermal mass of the aluminum spheres was small, this effect was not so pronounced as with the large, single copper point attachment. Figure 9(b) shows that the excursion of 6°C with the aluminum spheres was a reduction of the incipience excursion, compared to excursions as great as 12°C for the bare surface.

3.4. Overall boiling enhancement considerations

As noted earlier, all behavior resulting from use of a boiling promotion technique must be considered in evaluating its overall effectiveness. Because the heat flux
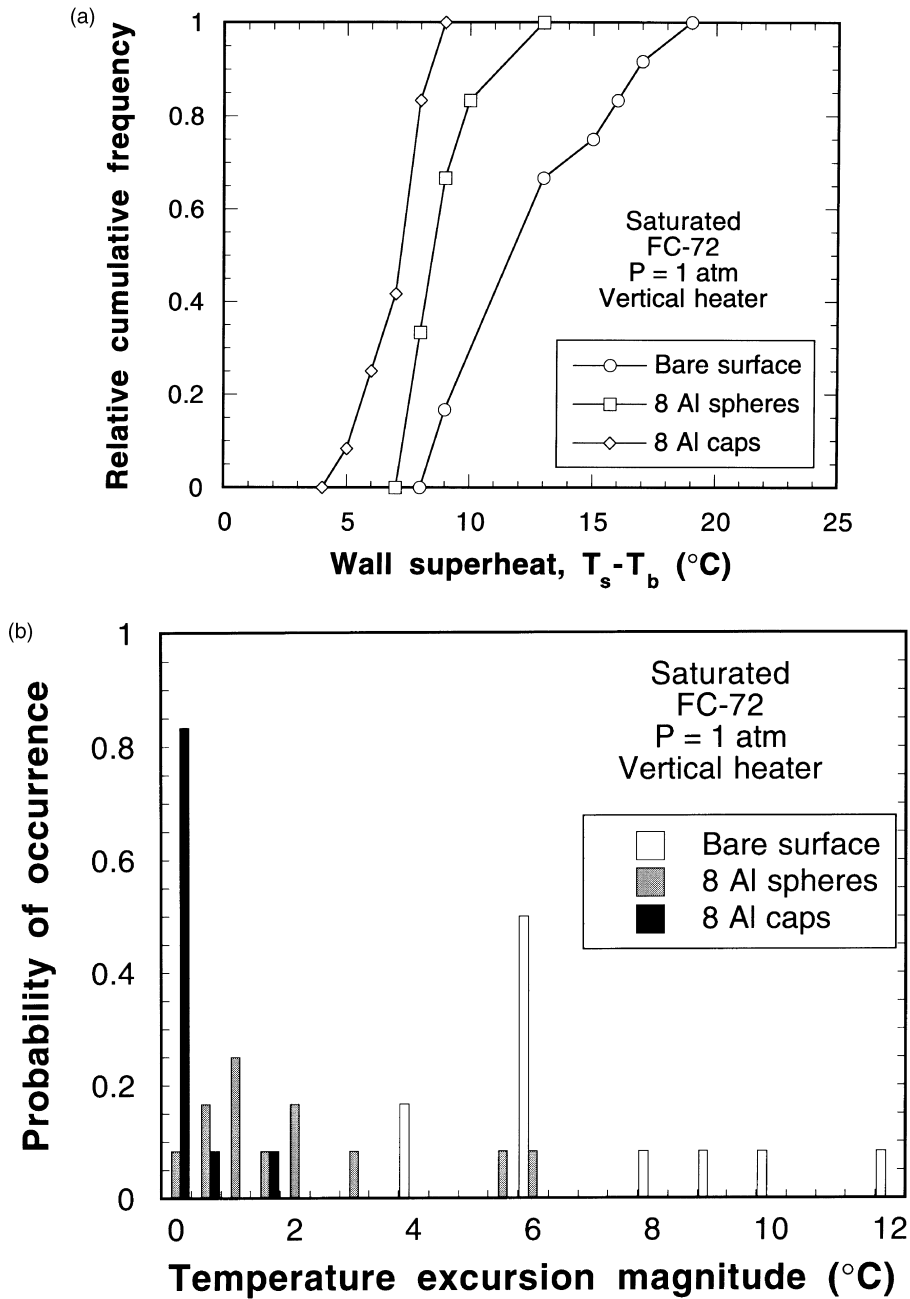
Fig. 9. (a) Relative cumulative frequency ogive of wall superheats and (b) relative frequency histogram of incipience excursion magnitudes for boiling incipience on vertical surface with multiple contact points.

into point contact materials is small, the finning effect is small and the only advantage to be gained through the use of these attachments is the promotion of incipience and a more gradual boiling spread. Figure 10 shows the effects of the multiple point contact geometries on natural convection and boiling up to CHF for a horizontal heater

surface. Aside from the reduction of incipience temperatures and excursions, the only noticeable effect of the surface attachments is the reduction in the CHF from that for a bare surface, because of the reduced liquid access to the heated surface.
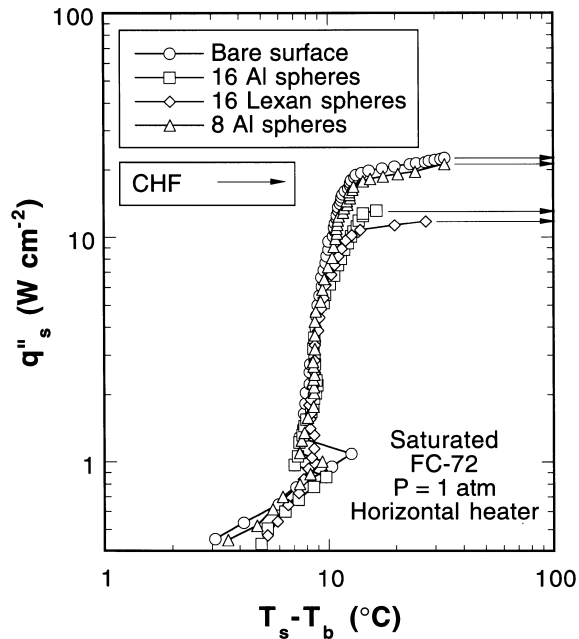
As expected, the most dense point contact packing

Fig. 10. Comparison of boiling for multiple contact points of various materials on horizontal heater surface.

showed the greatest decrease in CHF performance, over 41% for the sixteen aluminum spheres, because it provided the most obstruction to fluid access to the surface. Eight points of contact, had a considerably smaller effect on CHF and showed only a 6% reduction in CHF from that for a bare surface. Apparently, eliminating half of the spheres provided sufficient area for liquid to flow, unimpeded, that significant incipience enhancement advantage could be gained with little cost to boiling performance. Although the minimum vapor release jet size, the bubble departure diameter, was satisfied with the sixteen sphere geometry, too few chimneys were available for adequate vapor release and liquid return. Reducing the size of the contact spheres would also create more area for liquid flow. However, the radius of curvature at the point of contact must be kept large to create smaller cavity angles and allow better vapor embryo entrapment.

4. Conclusions

The goal of this study was to examine the usefulness of artificial nucleation sites, created by curved contact with a flat surface, in promoting early and repeatable boiling incipience. Cavities created by the spherical contact have angles which approach zero degrees at the point of contact and can trap vapor embryos in even highly wetting liquids. Unlike surface roughening, these artificial features are of large scale and therefore not sus-

ceptible to the degrading effects of prolonged boiling and surface aging. The important results follow:

(1) For the range of loadings tested, 4.45–26.7 N, the effect of contact force on nucleate boiling heat transfer using spherical copper point contact was small. Heat conducted from the heater surface into the cold copper attachment, because the area of contact is small and does not change significantly with increased load, is also small and is dominated by the high convection occurring on the exposed heater surface.

(2) Enhancement in the boiling incipience behavior is realized with use of the insulative and conductively tipped insulative point contact attachments. The conductively tipped insulative points show the greatest improvement over boiling on a bare surface, creating continuous nucleation sites, heated on all sides, at the point of contact. These cavities impede the natural convection flow of the liquid, causing it to superheat and begin boiling earlier. The multiple point aluminum tipped Lexan studs showed the greatest enhancement, giving the lowest incipience temperatures and smallest, nearly nonexistent, temperature excursions at the onset of boiling.

(3) Comparison between boiling with two densities of point contacts and boiling on a bare surface showed significant decrease in CHF with the sixteen point geometry. The eight point, however, showed only a slight decrease in CHF from that for a bare surface. This suggests that significant boiling incipience enhancement can be achieved at little cost to the boiling behavior by using the multiple contact point attachment.

(4) Because the enhancement effect of the spherical contact with the flat surface is dependent upon the zero-angle cavity at the point of contact, mechanical force, rather than epoxy or solder, must be used to hold the objects in contact. Applied contact force, which need not be great, as these results show, is currently being used in other electronic cooling devices such as IBM's Thermal Conduction Module, described by Goth et al. [12].

Acknowledgements

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