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T. Hinrichs

E. Hennecke

H. Yasuda
Missouri University of Science and Technology, yasudah@mizzou.edu

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THE EFFECT OF PLASMA-DEPOSITED POLYMERS ON THE NUCLEATE BOILING BEHAVIOR OF COPPER HEAT TRANSFER SURFACES

T. HINRICHS,* E. HENNECKE and H. YASUDA

Department of Chemical Engineering and Graduate Center for Materials Research,
University of Missouri-Rolla, Rolla, MO 65401, U.S.A.

Abstract—The effect of plasma deposited polymers on the nucleate boiling behavior of copper heat transfer surfaces, using water as the boiling liquid, was determined. The monomers used were tetrafluorethylene (TFE) and methane.

It was found that an 18 nm thick coating of TFE enhanced the nucleate boiling, while a 150 nm thick coating reduced the nucleate boiling. Both 15 nm and 150 nm thick coatings of methane reduced the nucleate boiling, with the effect being more pronounced with the thicker coating. A surface energy effect is postulated to explain the enhanced boiling observed.

NOMENCLATURE

a_i,	activity;
P,	vapor pressure for liquid with curved surface [Pa];
P°,	bulk liquid vapor pressure [Pa];
ΔP,	pressure difference [Pa];
r,	droplet or bubble radius of curvature [m];
T,	liquid temperature [K];
ΔT,	temperature difference between liquid and surface [K];
V,	liquid molar volume [m³ mol⁻¹].

Greek symbols

β,	contact angle [deg];
θ,	cavity apex angle/2 [deg];
μ_i,	chemical potential of liquid with curved surface [J mol⁻¹];
μ_i°,	chemical potential of bulk liquid [J mol⁻¹];
σ_{LV},	interfacial surface energy of liquid–vapor interface [kg s⁻²];
σ_{LS},	interfacial surface energy of liquid–solid interface [kg s⁻²];
σ_{SV},	interfacial surface energy of solid–vapor interface [kg s⁻²].

1. INTRODUCTION

NUKIYAMA [1] observed that several distinct modes of boiling exist. Nucleate boiling is the first type of boiling encountered as the heat flux is increased, followed by the unstable and film boiling regions. Nucleate boiling is characterized by the growth of vapor bubbles at specific sites on the solid surface. When the bubbles reach a certain critical size they detach themselves, being replaced by the start of a new bubble. This method of boiling heat transfer is of great interest industrially, since it is the most economical way of transferring large amounts of heat.

Although nucleate boiling has been phenomenologically understood for many years, the actual mechanism remains largely unclear. Corty and Foust [2] varied the surface roughness on the samples tested, and observed that a small change in roughness produced relatively large changes in both the slope and position of the boiling curve. This effect has been observed by many authors [3–6]. Clark, Strenge and Westwater [7] used high speed photography to identify actual bubble producing sites. The photographs showed that both pits (with diameters between 7.6 and 76.2 μm) and scratches were active nucleation sites. The fact that scratches produced active boiling sites was later verified by Bonilla, Grady and Avery [5]. They boiled water on polished copper surfaces both with and without sharp parallel scratches. They found that the scratches provided active nucleation sites, as the boiling curve was shifted to lower ΔT values.

It has also been suggested that surface chemistry may be an important parameter in determining the boiling behavior of a heat transfer surface. Griffith and Wallis [8] have stated that the contact angle of the liquid on the boiling surface, β, will affect the wall superheat required to initiate bubble growth. They based their analysis on an ideal vapor filled conical cavity. The authors state that when the contact angle between the liquid and the solid surface lies within the limits $\theta < \beta < 90°$, where θ is one half the cavity apex angle, the superheat required to initiate boiling will be constant for a particular surface. If β is greater than 90°, however, they claim that the wall superheat will be reduced. It follows that a lower temperature will be required to deactivate a site having a contact angle greater than 90°, so the cavity will be more stable.

The above analysis implies that the surface chemistry of the boiling surface, which directly affects the contact angle, will partially determine the boiling characteristics of the surface. One might therefore expect that low and high energy surfaces would behave differently during boiling.

The most convenient way of investigating the effect of surface chemistry on the nucleate boiling character-

istics of a surface is through the application of a thin
coating. Young and Hummel [9] reported a dramatic
case of coating enhanced nucleate boiling. They ap-
plied tetrafluorethylene in the form of an enamel in two
different ways to stainless steel boiling surfaces. The
first method involved applying the enamel to a pitted
surface and wiping off the excess. This left only the pits
filled with the polymer. The second type was prepared
by spraying the enamel on a smooth surface, which
produced a large density of Teflon spots. The boiling
curve for both surfaces was located far to the left when
compared with untreated surfaces. It is worth noting
that the second method of surface preparation pro-
duced enhanced boiling without affecting the cavities
in any way. This is in contradiction to most of the
previous literature which suggested that pits and
scratches were necessary for the formation of active
boiling sites. They postulated that the enhanced
boiling was caused by the presence of a large density of
poorly wetted spots, on a surface that was wetted by
the boiling water.

There have been several other studies which in-
vestigated the effect of thin polymer coatings on the
boiling behavior of a surface. However, some discrep-
ancy exists in the literature, as some authors indicate
that the coatings enhance the nucleate boiling [9–12]
while others indicate that the boiling is hindered or
unchanged [3, 12–14].

This study examines the effect of a change in the
interfacial surface energy between the liquid and the
solid surface. Water, which has a high surface energy,
was used as the boiling liquid. The two coatings used
were plasma deposited polymers of methane and
tetrafluoroethylene, which have a high and low surface
energy respectively. By using a high energy liquid in
contact with both a high and low energy surface, the
effect of nonwetting on the boiling behavior of a
surface could be observed.

2. EXPERIMENTAL EQUIPMENT

2.1. Heat transfer surfaces

The heat transfer surfaces were fabricated according
to the specifications in Fig. 1. The surfaces were made
from alloy 110 hard drawn copper.

The thermocouple wells were drilled with a no. 55
drill bit to a depth of 0.76 mm (0.030 in.) from the
boiling surface. One hole was drilled in the center of the
surface, and one each at a radius of 0.76 cm (0.30 in.)
and 1.02 cm (0.40 in.). The thermocouples were in-
serted to the bottom of the hole and soldered in place
to prevent movement.

As illustrated in Fig. 2, two O-rings were used. The
O-ring at the base of the surface was 0.32 cm (0.125 in.)
thick, with an inside diameter of 3.02 cm (1.19 in.). It
made a water tight seal with the Teflon plate and
stopped any leakage into the heater core. The smaller
O-ring was 0.24 cm (0.094 in.) thick, with an inside
diameter of 2.54 cm (1 in.). Without this O-ring pres-
ent, it was found that the water preferentially boiled
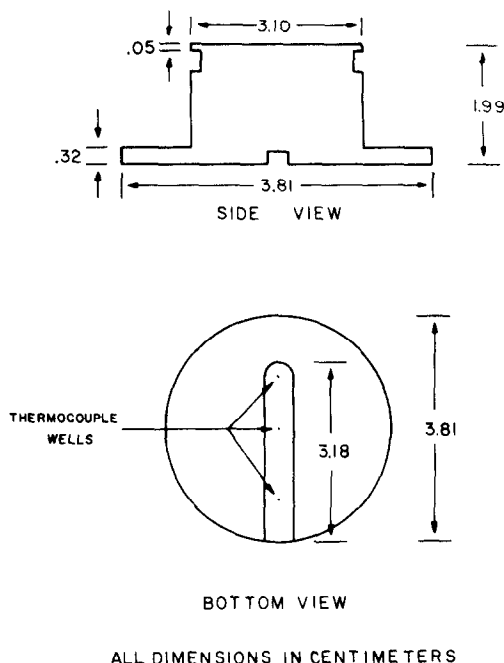around the periphery of the surface due to water

FIG. 1. Copper heat transfer surface.

leaking in the narrow channel between the copper and
the Teflon plate. The use of this O-ring near the boiling
surface greatly reduced the edge boiling.

The depth of the groove in the heat transfer surface
was critical in maintaining a good fit between the small
O-ring and the Teflon plate. The surface was initially
made with the groove 0.241 cm (0.095 in.) wide and
0.089 cm (0.035 in.) deep, with small corrections made
on the individual surfaces if required.

The channel on the bottom side of the heat transfer
surface was 0.25 cm (0.1 in.) deep and 0.475 cm
(0.187 in.) wide.

2.2. Boiling apparatus

The heat source bundle was prepared by installing
cartridge heaters in a cylindrical copper sink. Six
Watlow Firerod cartridge heaters (J2E56) were used,
each with a brass 3/8 in. NPT fitting welded to the end.
The copper core was 7.62 cm (3 in.) in dia. and 7.30 cm
(2.88 in.) in length. Six 1.27 cm (0.50 in.) holes were
drilled symmetrically in the copper core at a radius of
2.22 cm (0.88 in) and then tapped. A thin layer of
General Electric Insulgrease G-641 was applied to the
heater sheaths before they were screwed into the holes.
This was to insure that no void space existed between
the sheath and the copper core. On the top of the
copper core, a 3.81 cm (1.5 in.) diameter circle was
machined to a depth of 0.32 cm (0.125 in.) to accom-
modate the heat transfer surfaces. In order to allow for
handling of the surface thermocouples, a 0.64 cm
(0.25 in.) wide channel was machined to the same
depth as the circle, extending from the outer radius of
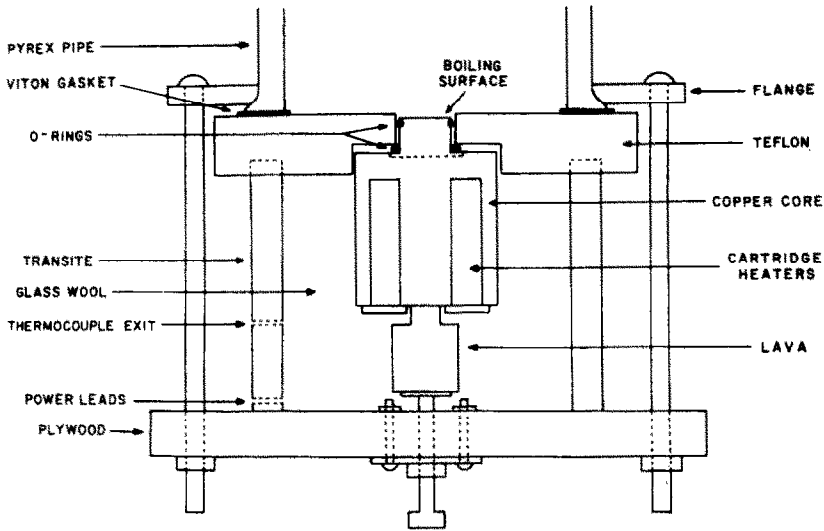the circle to the copper core edge.
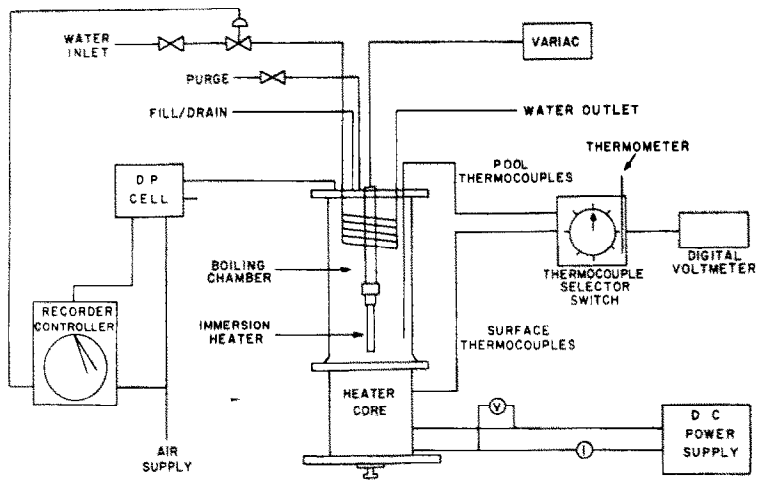
FIG. 2. Heater core and surrounding assembly.

FIG. 3. Experimental equipment.

Power was supplied to the heaters with a Sorensen DC Power Supply DCR60-40A. The voltage was read with a Keithley 177 digital multimeter, and the current with a Simpson 0–5 amp panel meter.

The heater core was surrounded by 3.5 cm (1.4 in.) of glass wool, followed by a 1.75 cm (0.69 in.) thick piece of Transite pipe. The Transite pipe rested on a 28 cm (11 in.) square piece of 1.9 cm (0.75 in.) thick plywood.

The Teflon plate was 2.54 cm (1 in.) thick and had a diameter of 21 cm (8.25 in.). A centred 3.30 cm (1.30 in.) hole was machined through the plate, and a 1.27 cm (0.50 in.) deep by 7.75 cm (3.05 in.) dia. circle was machined on the underside of the plate for the heat source bundle to fit in. Also on the underside of the

plate, a 0.64 cm (0.25 in.) deep groove was machined for the Transite pipe.

It was necessary to have an upward force acting on the heat source bundle in order to get the large O-ring to seal against the Teflon plate. A 0.95 cm (0.375 in.) nut was welded onto a small iron plate, which was then bolted onto the underside of the plywood. A bolt was then screwed into the nut until it projected through a 2.86 cm (1.125 in.) hole that had been drilled in the plywood. A 2.54 cm (1 in.) washer was welded onto the top of the bolt, and ground smooth. A piece of Lava was used to span the distance between the washer and the heater core. Therefore, by tightening the bolt on the underside of the plywood, the required pressure to seal

the O-ring could easily be obtained.

The boiling chamber consisted of a 15.2 cm (6 in.) dia. by 45.7 cm (18 in.) long piece of Pyrex pipe. A 15.2 cm (6 in.) metal flange and Viton gasket were used on both ends of the vessel. The bottom seal was made using bolts that extended from the flange to the plywood.

A Watlow immersion heater (L6EX16A) with a stainless steel fitting was used to insure that saturated conditions remained in the chamber while boiling was carried out.

The top plate of the vessel was 0.95 cm (0.375 in.) thick brass. A hole was tapped in the plate to accommodate a Whitey B-1VS4A regulating valve, through which the system was purged. Two 3/8 in. Ultra-Torr bore-through male connectors were used to hold the glass condenser in place.

2.3. Pressure control system

The pressure in the boiling chamber was held constant at 0.101 MPa (1 atm) ± 0.003 MPa (0.03 atm) during all runs by controlling the cooling water flow rate to the condenser. The Foxboro DP cell used was calibrated using a standard gauge, so that a 6.89 kPa (1 psi) pressure difference caused a full scale deflection of the recorder–controller. The controller sent a pneumatic signal to an air-to-close Research Control Valve, equipped with size D trim.

2.4. Temperature measurement system

Two stainless steel sheathed copper–constantan thermocouples were used to measure the liquid pool temperature. The thermocouple sheath was held in place in the top plate with a Swagelok male connector. The heat transfer surface thermocouples were stainless steel sheathed copper–constantan wire. Both surface and pool thermocouples were obtained from Omega Engineering Inc.

The thermocouple millivolt values were read using a Keithley 177 multimeter.

2.5. Plasma polymerization reactor

Morosoff, Newton and Yasuda [15] have published details of the design of the plasma polymerization unit used in this study. The reactor operating conditions present for the coating of the samples are listed in Table 1.

All surfaces were treated in an argon plasma for 5 min prior to coating. The argon flow rate was 2.0 cm^3 min^{-1}, the power input was 70 ± 5 W, and the pressure was 34 ± 1 μm.

3. EXPERIMENTAL PROCEDURE

3.1. Apparatus set-up

With both O-rings in place, the heat transfer surface was inserted into the Teflon plate. A thin layer of Insulgrease was applied to the bottom of the heat transfer surface in order to insure good contact with the heater core. The surface thermocouple wires were fed through a small hole in the Transite pipe before the assembly was bolted to the flange. The bolt on the plywood was tightened only 3/4 turn past hand tight in order to minimize flow deformation of the Teflon plate.

3.2. Data acquisition

After the heater surface was installed and the apparatus assembled, two liters of freshly distilled water were added to the boiling chamber.

Before data were recorded, the system was purged ten times to remove any noncondensable gases in the boiling chamber, as well as dissolved air in the water. The purging was carried out by letting the pressure in the chamber rise to a value 6.89 kPa (1 psi) above the ambient pressure and venting through the valve on the top plate.

The first data point was obtained with the power to the heater core corresponding to a flux of about 55 000 W m^{-2} (17 500 Btu hr^{-1} ft^{-2}). Remaining data were obtained by increasing the power input by 25 W increments until a flux of about 210 000 W m^{-2} (66 500 Btu hr^{-1} ft^{-2}) was reached.

Some hysteresis was observed when the data points were taken with increasing flux, as compared with the same data for decreasing flux. However, since this study was concerned with characterizing the boiling behavior of differently treated surfaces, all data points were obtained with increasing flux.

4. RESULTS AND DISCUSSION

One set of the experimental results is illustrated in Fig. 4, which shows representative boiling curves obtained for a 150 nm thick methane plasma polymer coated surface. One observes that the surface aged with successive runs, with the curve being shifted to higher ΔT values. This aging effect was observed with all the surfaces studied.

Boiling curves for each surface were obtained until the shift due to aging was less than approximately 0.2 K. This point was generally reached after about five curves were obtained. A minimum of two samples were used for each type of surface studied. If the experimental data for similarly treated surfaces are averaged, Fig. 5 is obtained. This figure shows that the 18 nm thick TFE coating enhanced the nucleate boiling, as the curve was located to the left of the untreated machined surfaces. The 15 nm methane coating hindered boiling, with the curve being shifted to the right. The shift to higher ΔT values was more pronounced with the 150 nm thick TFE and methane coated samples.

The presence of the coatings has clearly affected the nucleate boiling behavior of the surfaces. Before attempting to explain the observed results, it is beneficial to first consider how the coatings may affect the surface. The application of a coating certainly changes the topography of the surface. In the case of thin plasma polymer coatings, this effect would be

Table 1. Plasma polymerization reactor conditions

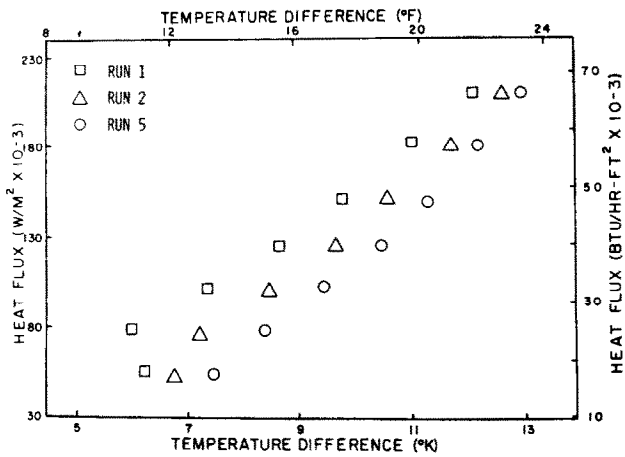| Surface number	4, 5	6, 7	8, 9	10, 11
Monomer	$CF_2 = CF_2$	CH_4	$CF_2 = CF_2$	CH_4
Thickness (nm)	150 ± 10	150 ± 10	18 ± 2.5	15 ± 2.5
Monomer flow rate (cm^3 min^{-1})	1.9	2.0	1.5	0.5
Power input (W)	75 ± 5	69 ± 5	21 ± 5	81 ± 5
Pressure during reactions (μm)			16 ± 1	16 ± 1

FIG. 4. Nucleate boiling curves for surface 6, obtained with boiling water at 0.101 MPa (1 atm).
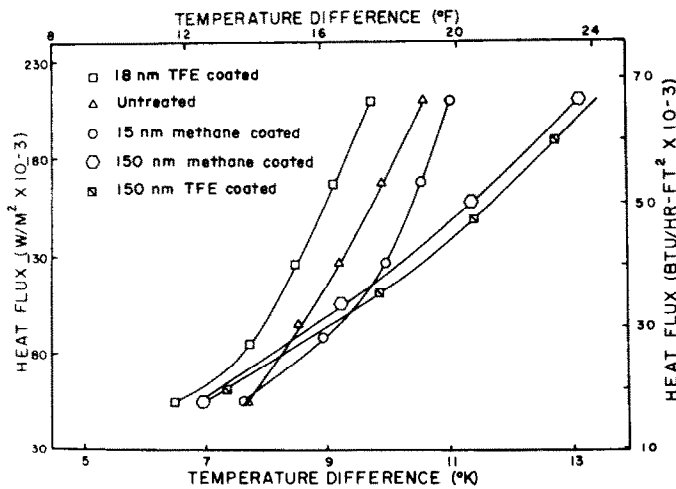

FIG. 5. Comparison of nucleate boiling results.

small. However, with increased coating thickness, one might expect some of the cavities to be filled or covered over with the polymer.

The application of a coating also alters the surface energy of a surface. Since a surface used for nucleate boiling is in contact with liquid, it is also important to realise that a coating changes the liquid–solid interfacial energy. This is shown in equation (1),

$$\sigma_{LV} \cos \beta + \sigma_{LS} = \sigma_{SV} \tag{1}$$

which was derived by Young [16]. The relationship between the surface energy terms appearing in equation (1) is illustrated in Fig. 6. One observes that the liquid–solid interfacial energy, σ_{LS}, is a function of both the solid and liquid surface energies. Before considering whether the surface energy of the liquid and the solid might affect the boiling behavior of a surface, the simplified case of a liquid droplet surrounded by its vapor will be considered.

It has long been recognized that a pressure difference exists across the interface between a liquid droplet and its surrounding vapor. This pressure difference is defined by the equation of Young and Laplace, which for a spherical droplet is

$$\Delta P = \frac{2\sigma_{LV}}{r}. \tag{2}$$

Using the equation of Young and Laplace, Davies and Rideal [17] derived equation (3). This equation illustrates that the vapor pressure of the liquid in a droplet, P, is somewhat greater than that of bulk liquid, $P°$, assuming a constant temperature. The magnitude of the vapor pressure difference is a function of the liquid surface energy, σ_{LV}, and the radius of curvature of the droplet

$$RT \ln \frac{P}{P°} = \frac{2V\sigma_{LV}}{r}. \tag{3}$$

From thermodynamics,

$$\mu_i = \mu_i° + RT \ln (a_i) \tag{4}$$

which relates the chemical potential of component i to its activity a_i. Assuming an ideal vapor, equations (3) and (4) can be combined to give
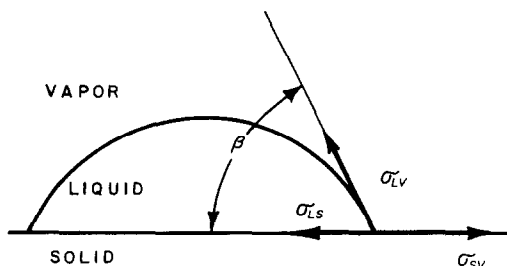
$$\mu_i = \mu_i° + \frac{2V\sigma_{LV}}{r}. \tag{5}$$

This equation illustrates that the curvature of the liquid acts to increase the chemical potential of the liquid in the drop, with the effect increasing with decreasing radius. In addition, an increasing surface energy will increase the chemical potential of the liquid in the drop.

The concepts presented above can now be used to qualitatively state how the liquid in a small cavity may be affected by the cavity's size and the surface energy of the liquid and solid. In the above discussion, the surface energy term was the interfacial energy of the liquid–vapor interface (i.e. σ_{LV}). If one now considers liquid in contact with solid cavity walls, the interfacial energy of the liquid–solid interface, σ_{LS}, becomes the important factor. Therefore, when applying the concepts presented in equations (3)–(5) to a liquid filled cavity, the liquid–solid interfacial energy must be used.

Using equation (5), it is possible to postulate why nucleate boiling is observed to occur from cavities and other surface imperfections. At any particular temperature, the chemical potential of the liquid in a cavity will be somewhat greater than the bulk liquid. Therefore, boiling will preferentially occur from the cavity. When applying this to the actual boiling process, it is necessary to assume liquid fills the cavity after each vapor bubble is released. Then during boiling, bubble formation will always occur at the cavity, which agrees with experimental observations.

At this point it is worth noting the difference between the analysis by Griffith and Wallis [8] and this study. Assuming an idealized vapor filled cavity, Griffith and Wallis [8] discussed how various parameters affect the superheat required for boiling. This study, however, considers a liquid filled cavity. More specifically, it attempts to answer the question of why bubble formation may preferentially occur at a liquid filled cavity, and how several parameters affect the relative ease at which a bubble will form.

It is now possible to consider how a thin coating on a heat transfer surface might affect the boiling behavior of a cavity. The chemical potential of the liquid in a cavity will depend on the cavity size, and the interfacial surface energy between the liquid and solid. A high interfacial surface energy will raise the chemical potential of the liquid in the cavity, so that the temperature required to initiate boiling will be lower compared to the bulk liquid. In addition, a high interfacial surface energy may allow a wider range of cavity sizes to boil at any particular temperature difference. This once again is because the surface energy effect may allow boiling to begin at a lower temperature difference than would otherwise be possible.

The TFE and methane coated samples had surface energies of 0.016 and 0.040 kg s^{-2}, respectively, as obtained using the method of Zisman [18]. Using these values in conjunction with the contact angle data for water on polymer-coated surfaces, it is possible to

Fig. 6. Sessile drop illustrating the contact angle, β, and the various interfacial surface energies present.

Table 2. Results of calculation of liquid–solid interfacial surface energy, σ_{LS}, obtained using equation (1)

Monomer used for polymer formation	σ_{LV} (kg s^{-2})	σ_{SV} (kg s^{-2})	β	σ_{LS}
TFE	0.072	0.016	111°	0.042
CH$_4$	0.072	0.040	69°	0.014

calculate the liquid–solid interfacial surface energy using equation (1). As shown in Table 2, the interfacial surface energy for the TFE coated samples was greater than that of the methane coated samples. Therefore, a large interfacial surface energy arises when a high surface energy liquid contacts a low surface energy solid.

The application of a polymer coating can also hinder the nucleate boiling. As mentioned previously, the cavities may be partially covered over or filled with the application of a plasma polymer, thereby reducing the number of potential boiling sites. One might expect this effect to be more pronounced with increasing coating thickness.

In accordance with equation (5), the application of a very thin coating will affect the chemical potential of the liquid in a cavity by changing the liquid–solid interfacial surface energy. In agreement with the previous discussion, the high interfacial surface energy present with the 18 nm TFE coating may account for the enhanced boiling observed. The coating increased the chemical potential of the liquid in the cavities, thereby allowing more sites to be active at a particular heat flux. In the case of the 15 nm methane coated surfaces, the lower interfacial surface energy did not alter the chemical potential of the liquid in the cavity enough to enhance the boiling. Instead, some potential boiling sites were deactivated, as the boiling curve was located to the right of the uncoated machined surfaces.

The deactivation of potential boiling sites was more pronounced with the thicker coatings. This was observed experimentally with both the 150 nm TFE and methane coated samples. As observed in Fig. 5, the boiling curves for both surfaces are similar, and are shifted well to the right of the uncoated machined surfaces.

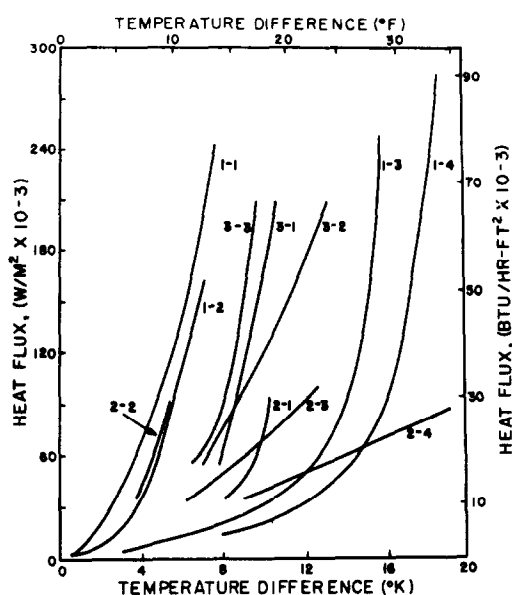Young and Hummel [9] and Vachon et al. [10] used Teflon coatings with water as the test liquid. Figure 7

FIG. 7. Comparison of nucleate boiling results for several authors that boiled water at 0.101 MPa (1 atm).

Table 3. Reference table to Fig. 7

Author	Surface characterization
1-1 Young and Hummel	Pitted, stainless steel surface possessing Teflon in the pits
1-2 Young and Hummel	Smooth, stainless steel surface possessing spots of Teflon on the surface
1-3 Young and Hummel	Pitted, stainless steel surface
1-4 Young and Hummel	Smooth, stainless steel surface
2-1 Vachon et al.	Uncoated stainless steel surface
2-2 Vachon et al.	7.6 μm Teflon coated surface
2-3 Vachon et al.	30.4 μm Teflon coated surface
2-4 Vachon et al.	35.6 μm Teflon coated surface
3-1 This work	Untreated surface
3-2 This work	150 nm TFE plasma polymer coated surface
3-3 This work	18 nm TFE plasma polymer coated surface

compares their results with the TFE coated samples used in this study.

Young and Hummel [9] observed a dramatic case of enhanced boiling due to the application of the Teflon coating. At the same time, however, it is worth noting that their uncoated samples are shifted far to the right of the uncoated samples used in this study, as well as those of Vachon *et al.* [10]. Therefore, although the absolute magnitude of the shift of their coated surfaces is quite large, the actual position is reasonably close to the 18 nm TFE coated samples used in this study. The dramatic enhancement also indicates that the coatings effect may be a strong function of the initial surface condition.

The results of Vachon *et al.* [10] qualitatively agree with those found in this study. The thinnest coating enhanced the boiling, while the thickest acted as an insulator. However, although the thinnest coating used by Vachon was more than fifty times thicker than the 150 nm TFE coating used in this study, enhanced boiling was still observed. Since they used a Teflon enamel to apply the coatings, it is possible that a substantial amount of the polymer eroded away during the boiling process, since conventional coating methods often produce poor adhesion of Teflon to metal. It is only possible to speculate, however, since no mention of coating durability was made in their paper.

The results of this study show that it is possible to use a material that is an inherent insulator to enhance the nucleate boiling characteristics of a heat transfer surface. It is also worth noting that the coatings were quite durable. For instance, the position of the boiling curve for the 150 nm coated surfaces was consistently to the right of the uncoated surfaces. If the coating had peeled off, the boiling curve would have shifted with successive runs toward that of the uncoated surfaces. Coating durability of this type is required if this method of heat transfer enhancement is to be considered for an industrial application.

In practical applications that utilize boiling heat transfer, the liquid many times contains impurities that corrode the heat transfer surface. The possibility of employing a thin plasma polymer coating as a protective barrier on a heat transfer surface is certainly worth investigating in future study. Ideally, it may be possible to obtain a coating that will enhance the nucleate boiling and act as a protective barrier at the same time.

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APPENDIX 1. ERROR ANALYSIS

Heat flux measurement

It was assumed in this study that all the heat produced in the core was transferred through the copper heat transfer surface. This is justified since any small loss that did occur would have affected the position of the boiling curve for each surface similarly, thereby still allowing a comparison of one surface with another. A calculation by Messina for a similar apparatus showed that the heat loss was less than 5% of the total.

The heat flux calculation is a function of the voltage, current, and the area of the heat transfer surface. The error in

the voltage and current readings were $\pm 0.07\%$ and $\pm 4\%$, respectively. The error in the surface area determination was estimated to be $\pm 1.5\%$. The error in the heat flux calculation is therefore calculated to be $\pm 5.5\%$.

Temperature measurement

Two liquid and three surface thermocouples were used to obtain an average temperature difference between the heat transfer surface and the boiling liquid. The largest source of error in this value was in the determination of the average surface temperature. One reason for this was that the surface thermocouple millivolt values were observed to fluctuate by up to ± 0.01 mV, which corresponds to ± 0.25 K. This error was decreased to approximately ± 0.005 mV by taking a mental average for each thermocouple reading. In addition, up to a 1.5 K temperature gradient was observed on the heat transfer surface at high fluxes. Therefore when averaging the three surface temperatures, a representative value of the true average was assumed.

The digital millivolt meter used had an accuracy of ± 0.008 mV, or ± 0.2 K.

Using the above uncertainty limits, the error in the final ΔT value is calculated to be ± 0.3 K.

Pressure control system

In order to achieve good control of the system pressure, it was necessary to decrease the immersion heater voltage slightly as the flux values were increased. By doing this the system pressure was controlled to within ± 1000 Pa (± 0.01 atm).

APPENDIX 2. SAMPLE CALCULATIONS

The sample calculations illustrated below are for the first run of surface 2 (untreated copper surface). The readings were taken at steady state.

The voltage and current values are needed to calculate the heat flux, as shown below

$$V = 39.7 \text{ V}$$

$$i = 4.00 \text{ A}$$

$$\text{surface area} = \pi(0.0310/2)^2$$

$$= 7.55 \times 10^{-4} \text{ m}^2$$

$$\text{heat flux} = \frac{(39.7)(4.00)}{7.55 \times 10^{-4}}$$

$$= 210\,000 \text{ W m}^{-2}.$$

The pool thermocouple millivolt values were 4.275 mV (99.9°C) and 4.277 mV (100.0°C), and the surface thermocouple values were 4.780 mV (110.7°C), 4.755 mV (110.1°C) and 4.788 mV (110.8°C). The temperature difference between the liquid and surface is estimated to be

$$\Delta T = \frac{110.8 + 110.1 + 110.7}{3} - \frac{100.0 + 99.9}{2}$$

$$= 10.6°C.$$

EFFET DU DEPOT DE POLYMERE PAR PLASMA DANS LE COMPORTEMENT DE L'EBULLITION NUCLEEE SUR DES SURFACES EN CUIVRE,

Résumé—On étudie l'effet des polymère déposés par plasma sur le comportement de l'ébullition nucléée avec des surfaces de cuivre en utilisant l'eau comme liquide bouillant. Les monomères utilisés sont le tetrafluoroethylène (TFE) et le méthane. On trouve qu'un revêtement de $1,8 \times 10^{-8}$ m (180 Å) de TFE augmente l'ébullition nucléée tandis qu'une couche de $1,5 \times 10^{-7}$ m (1500 Å) d'épaisseur diminue l'ébullition nucléée. Les deux revêtements de $1,5 \times 10^{-8}$ et $1,5 \times 10^{-7}$ m de méthane réduisent l'ébullition nucléée, avec un effet plus prononcé pour le revêtement le plus épais. Un effet d'énergie de surface est avancé pour expliquer la modification de l'ébullition.

DER EINFLUSS PLASMA-GESPRITZTER POLYMERE AUF DAS BLASENSIEDEN AN KUPFER-HEIZFLÄCHEN

Zusammenfassung—Der Einfluß plasma-gespritzter Polymere auf das Blasensieden von Wasser an Kupfer-Heizflächen wurde bestimmt. Die verwendeten Monomere waren Tetrafluoräthylen (TFE) und Methan. Es zeigte sich, daß eine $1,8 \cdot 10^{-8}$ m (18 nm) dicke TFE-Beschichtung das Blasensieden verstärkt, eine solche von $1,5 \cdot 10^{-7}$ (150 nm) Dicke es jedoch vermindert. Beide Methan-Beschichtungen (15 und 150 nm dick) verminderten das Blassensieden wobei, der Einfluß bei der dickeren Beschichtung stärker ausgeprägt war.
Zur Erklärung des beobachteten verstärkten Siedens wird ein Oberflächenenergie-Effekt herangezogen.

ВЛИЯНИЕ ПОЛИМЕРОВ, НАНЕСЕННЫХ ПЛАЗМЕННЫМ СПОСОБОМ, НА ПОВЕДЕНИЕ МЕДНЫХ ТЕПЛОПЕРЕДАЮЩИХ ПОВЕРХНОСТЕЙ ПРИ ПУЗЫРЬКОВОМ КИПЕНИИ

Аннотация — Определялось влияние нанесенных плазменным способом полимеров на поведение медных теплопередающих поверхностей при пузырьковом кипении. В качестве кипящей жидкости использовалась вода, а в качестве покрытий — тетрафторэтилен (ТФЭ) и метан.

Найдено, что при толщине слоя ТФЭ $1,8 \cdot 10^{-8}$ м (18 nm) интенсивность пузырькового кипения усиливалась, а при толщине $1,5 \cdot 10^{-7}$ м (150 nm) — снижалась. На покрытиях из метана толщиной $1,5 \cdot 10^{-8}$ м (15 nm) и $1,5 \cdot 10^{-7}$ м (150 nm) интенсивность пузырькового кипения снижалась, причем тем сильнее, чем больше толщина покрытия. Высказано предположение о влиянии поверхностной энергии на интенсификацию кипения.