presented at the
Seventh International Heat
Transfer Conference
Munich, West Germany
1982

LIQUID-SOLID CONTACT AND ITS RELATIONSHIP TO IMPROVED FILM BOILING HEAT TRANSFER RATES

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ABSTRACT

The possible improvement of film boiling heat transfer through the use of surface macro-roughness elements is the subject of the present study. A macro-roughened heating surface was fabricated with a flush-mounted micro-thermocouple in the protruding end of one of the macro-roughness elements. The temperature measurements obtained from this micro-thermocouple indicated that intermittent, direct liquid-solid contact occurred between the boiling liquid and the instrumented macro-roughness element at bulk surface temperatures significantly above the smooth surface minimum film boiling temperature. The boiling heat transfer on the macro-roughened surface was found to be as much as 500% greater than that measured for the same liquid on a smooth surface at the same bulk surface temperature.

1. INTRODUCTION

The most fundamental characteristic of film boiling is the presence of a vapor layer that essentially maintains a separation between the heating surface and the liquid. This separating vapor layer constitutes a restriction to heat transfer. This restriction to heat transfer due to the vapor layer is the logical focal point on which to concentrate research efforts to improve the thermal effectiveness of film boiling heat transfer (i.e. to re-establish and/or increase direct contact between the heating surface and the boiling liquid). Direct contact between the liquid and the heating surface in film boiling has been reported by a number of investigators (e.g. [1-6]). One method of improving the thermal effectiveness of film boiling heat transfer which has been shown to be successful [4,5] is that of introducing macro-roughness to the heating surface. Bradfield [1] alluded to this method of improving the thermal effectiveness of film boiling heat transfer in his statement: "Liquid-solid contact can be achieved at stable film boiling temperatures by any means which will induce surface roughness elements to tickle the liquid-vapor interface ... It may become desirable to control heat flow by controlling liquid-solid contact in the stable film boiling regime."

The relationship between liquid-solid contact and improved film boiling heat transfer rates on macro-roughened surfaces has not been thoroughly investigated and specific data is scarce. The objectives of the present study have been (1) to obtain quantitative measurements of liquid-solid contact in film boiling on a macro-roughened surface, (2) to obtain overall heat transfer coefficients for film boiling on a macro-roughened surface, and (3) to obtain a fundamental understanding of the physical mechanisms operative in producing the observed changes in heat transfer on a macro-roughened surface.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A macro-roughened heating surface was fabricated by press-fitting 492 0.162 cm diameter cylindrical pins into an otherwise smooth surface, each pin having a height of 0.127 cm and arranged in a square array having an in-line center-to-center spacing of 0.305 cm (see Figure 1). The surface and pins were fabricated from mild steel. One of the pins was fitted with a flush-mounted micro-thermocouple junction at the protruding tip (see Figure 2). This thermocouple/pin was fabricated by drilling a hole in one of the cylindrical pins and inserting a 0.0254 cm diameter constantan wire and a ceramic insulator from the bottom, brazing the exposed junction with 24K gold, milling the brazed junction until flush with the top of the pin, press-fitting the assembly into the heating surface, and plating the entire surface and pins with approximately 0.005 cm of nickel to inhibit corrosion. The output of the thermocouple junction was calibrated against a chromel-alumel thermocouple. The signal from the thermocouple/pin was amplified by a Honeywell Accudata Model 122 differential amplifier. The measured response rate of the thermocouple/pin assembly was determined to be at least 12,000°C/sec. The bulk temperature of the heating surface was determined from a chromel-alumel thermocouple inserted in the 0.178 cm diameter hole detailed in Figure 1. The bulk surface temperature and the temperature of the junction in the tip of the thermocouple/pin were displayed on an oscilloscope and recorded on a strip chart. The surface was heated from beneath by a gas burner or an electric hot plate. All experiments were conducted at atmospheric conditions.

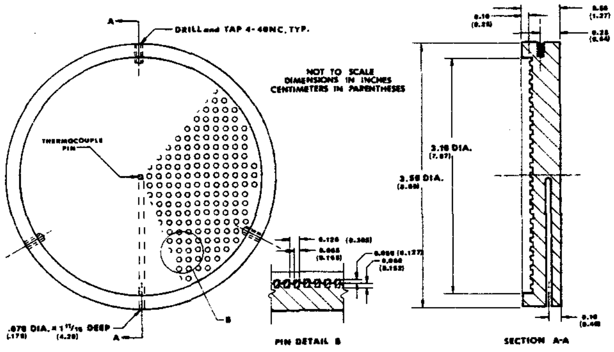

Figure 1. Detail of Heating Surface CP54

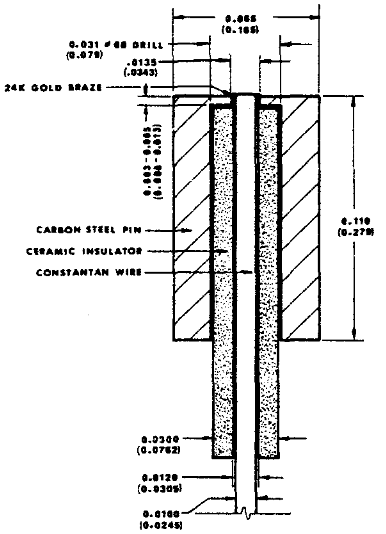

Figure 2. Detail of Micro-Thermocouple/Pin

Stationary discrete (Leidenfrost) drops were introduced by gently pouring saturated liquid onto the heating surface. The vertically projected area of the drops was photographed at 2 second intervals throughout the vaporization process with a Bolex Model H16RX5 16 mm single-frame/movie camera which was positioned directly above the heating surface (lense facing downward). Instantaneous heat transfer coefficients were calculated from the vaporization rate of the drops as determined from the photographs. The heat transfer coefficient for a film boiling drop as defined in the present study is given by Equation 1.

$$h_D = -\frac{\rho_f \, \Delta h_v \, \frac{dV_D}{dt}}{A_p(T_w - T_L)} \tag{1}$$

In Equation 1 it is assumed that all of the heat transferred to the drop results in vaporization. The vertically projected drop area, A_p, was obtained from the photographs by projecting these onto a drafting table and measuring the area with a polar planimeter. The drop volume, V_D, was determined from the vertically projected drop area through a numerical solution to the Laplace Capillary Equation for sessile drops (a detailed description of this solution may be found in Reference 7).

Four liquids were investigated: water, denatured ethanol, iso-propanol, and ethylene-chloride. A total of 674 heat transfer coefficients were obtained for the four liquids with bulk surface temperatures ranging from 220°C to 620°C and drop sizes ranging from 0.01 to 10.0 cc. The transient temperature of the protruding tip of the instrumented thermocouple/pin throughout 45 drop lifetimes was recorded. The contact period and duration were determined from the temperature of the junction at the tip of the thermocouple/pin. The liquid-solid contact duration was taken to be the time during which the temperature of the junction was falling and the contact period was taken as the time between successive maxima in the temperature of the junction. The pin tip temperature (characterized by the temperature of the junction in the top/center of the pin) experienced a maximum and a minimum during each contact period. The maximum is referred to as the recovery temperature and the minimum is referred to as the quench temperature. The difference between the temperature of the pin tip and the bulk surface temperature is referred to as the temperature depression across the pin.

3. RESULTS

The 674 heat transfer data points are presented in the following form: percent increase in the heat flux on the macro-roughened surface as compared to that which would occur on a smooth surface for the same liquid, drop volume, and bulk surface temperature. The corresponding smooth surface heat flux was determined from the correlation given in Reference 8. Thus, the heat flux as measured in the present study may be computed from the percent increase given in Figures 3 through 6 and the corresponding smooth surface heat flux determined from the correlation given in Reference 8.

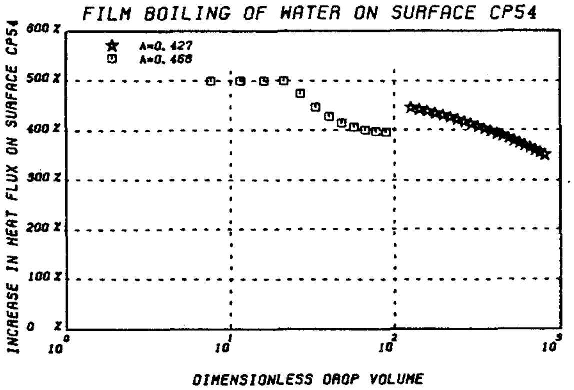

Figure 3. Increase in Heat Flux for Water on Surface CP54

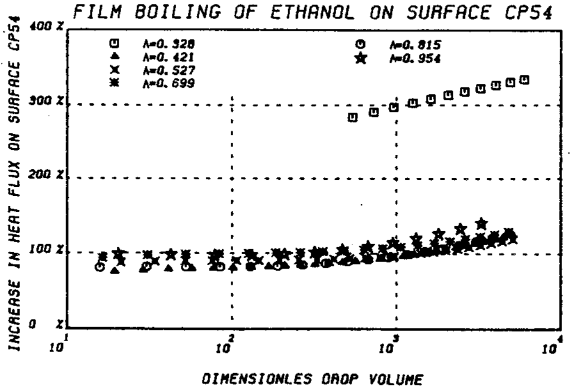

Figure 4. Increase in Heat Flux for Ethanol on Surface CP54

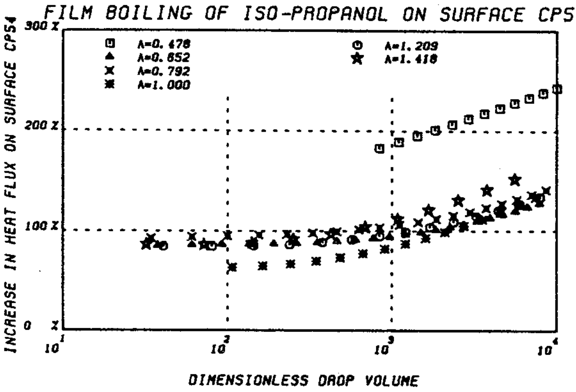

Figure 5. Increase in Heat Flux for Iso-Propanol on Surface CP54

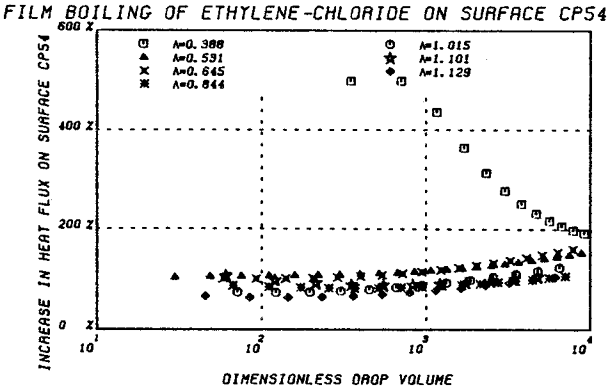

Figure 6. Increase in Heat Flux for Ethylene-Chloride on Surface CP54

This particular smooth surface discrete drop film boiling correlation was used to reduce the data as it was in good agreement with 714 additional data points obtained in the present study on a smooth nickel plated carbon steel surface using the same four liquids. In the figures, the percent increase in heat flux is shown rather than the actual measured heat flux so that the effect of the macro-roughness elements will be readily discernible. The increase in heat flux can be seen to vary significantly for the four different liquids investigated as well as the bulk surface temperature (represented by dimensionless superheat, Λ) and the size of the drop (represented by dimensionless drop volume, V^*). Some typical temperature traces from the micro-thermocouple are shown in Figures 7 through 9 (actual strip chart records).

The thermal response of the instrumented macro-roughness element to the liquid-solid contact observed could be classified into three distinct categories:

1. Intermittent liquid-solid contact resulting in a staircase-like reduction in temperature to an asymptotic value where stable film boiling is maintained (see Figure 7).
2. Intermittent liquid-solid contact resulting in a staircase-like reduction in temperature until a certain value of temperature is reached, at which time the liquid-solid contact becomes essentially continuous and the film boiling process evolves into quasi-nucleate-type boiling (see Figure 8). (In the present paper, film boiling and quasi-nucleate boiling are distinguished by whether the liquid solid contact is intermittent or continuous, respectively.)
3. The first contact is essentially sustained throughout the lifetime of the drop and quasi-nucleate-type boiling begins almost immediately upon introduction of the drop to the surface (see Figure 9).

This variation in boiling behavior on a macro-roughened surface necessitates clarification of the definition of film boiling and the minimum film boiling temperature.

Nishio and Hirata [2] (who dealt with impinging, rather than stationary, drops) obtained photographic evidence showing that under certain circumstances, when the liquid comes into direct contact with the heating surface and the temperature of the surface at the point of contact is above some minimum value, rapid local vaporization will occur causing the liquid to be forced away from the surface at the point of contact, thus re-establishing the vapor layer separating the heating surface from the boiling liquid. This local minimum temperature that must be maintained in order to subsequently maintain the vapor layer characteristic of film boiling is herein termed the "local minimum film boiling temperature", abbreviated LMFBT. The bulk surface temperature required to maintain the LMFBT at every point on the heating surface where liquid-solid contact occurs is herein termed the "bulk minimum film boiling temperature" abbreviated BMFBT.

This definition of the LMFBT inherently associates a locally intermittent character with liquid-solid contact in film boiling. Bradfield [1] stated that the liquid-solid contact in what he termed "stable film boiling" could be "periodic" (intermittent) or "quasi-steady" (presumably not intermittent).

Photographs taken in the present study indicate that liquid-solid contact on the macro-

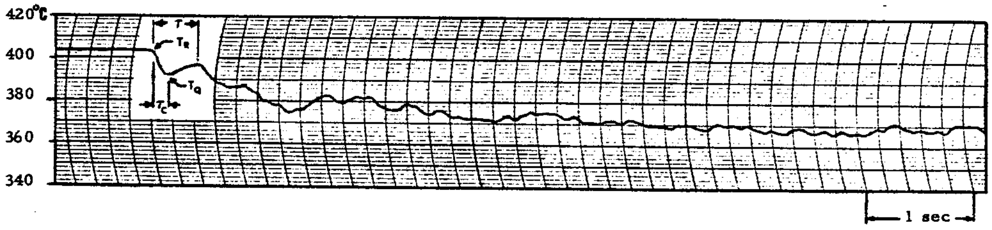

Figure 7. Temperature Response of Thermocouple/Pin to Intermittant Liquid-Solid Contact with Iso-Propanol

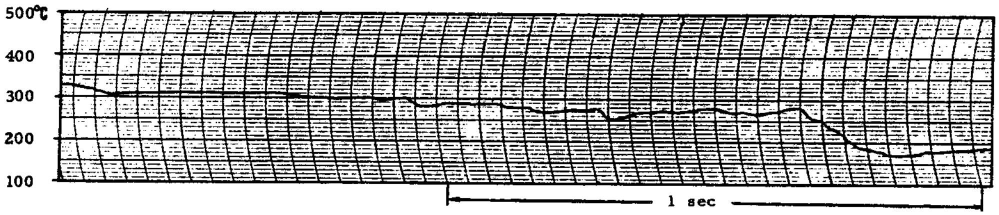

Figure 8. Temperature Response of Thermocouple/Pin to Intermittent Liquid-Solid Contact with Water

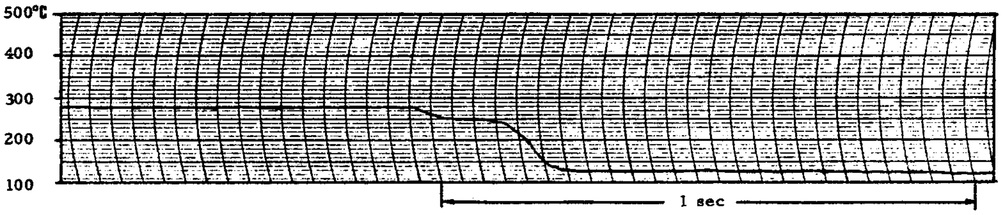

Figure 9. Temperature Response of Thermocouple/Pin to Intermittent Liquid-Solid Contact with Water

roughened surface investigation primarily occurs at the top of the cylindrical pins. It is for this reason that the temperature of the thermocouple junction in the top/center of the instrumented pin is thought to be characteristic of the liquid-solid contact process in the immediate vicinity of contact. The liquid-solid contact period, duration, and temperature depression data taken in the present study is the only data of this type for film boiling on a macro-roughened surface known to the authors at the present time.

The BMFBT in the present study was determined from the thermocouple/pin temperature fluctuations. When the contact duration became essentially equal to the contact period (thus the liquid-solid contact became continuous) the bulk surface temperature was said to be equal to the BMFBT. The BMFBT for water, ethanol, iso-propanol, and ethylene-chloride on the macro-roughened surface investigated in the present study were determined to be approximately 600°C, 240°C, 240°C, and 235°C respectively. The smooth surface BMFBT for the same fluids are 235°C, 155°C, 150°C, and 150°C [9]. The temperature of the thermocouple/pin tip just prior to the time when the liquid-solid contacts became continuous was said to be equal to the LMFBT. The LMFBT for water, ethanol, iso-propanol, and ethylene-chloride on the macro-roughened surface was determined to be approximately 275°C, 230°C, 230°C, and 225°C respectively.

The thermal response of the instrumented macro-roughness element to intermittent liquid-solid contact in film boiling is summarized in Table 1. Each series represents one complete drop lifetime (from introduction to the surface to complete vaporization). The letters following the series numbers indicate selected segments of the drop lifetime. The number of contacts in each segment of each series is indicated in the table. The contact period, duration, and characteristic temperatures were averaged over the number of contacts in the segment. Average values, as well as the standard deviation (where applicable), are given for each quantity.

Temperature depressions across the instrumented thermocouple/pin of up to 147°C were recorded with water (series 17d), resulting from intermittent liquid-solid contacts having an average period of 0.069 sec. and an average duration of 0.032 sec. If this temperature of the thermocouple/pin tip and the contact duration and

Table 1. Summary of thermocouple/pin data for surface CP54

S#	FL	#C	$\overline{\text{TAU}}$	$\overline{\text{THETA}}$	TW	$\overline{\text{TR}}$	$\overline{\text{TQ}}$	$\overline{\text{TP}}$	$\overline{\text{DTP}}$	$\overline{\text{DTC}}$
1A	WA	16	.15 (.054)	.44(.22)	495	430(23)	420(15)	425(20)	70	10
1B	WA	11	.12 (.054)	.36(.20)	485	395(7)	389(7)	392(7)	93	6
1C	WA	7	.096(.072)	.31(.13)	475	381(2)	376(3)	378(4)	97	5
1D	WA	8	.10 (.033)	.42(.13)	465	362(6)	357(7)	359(7)	106	5
1E	WA	11	.087(.036)	.41(.15)	450	337(8)	330(12)	333(11)	117	7
1F	WA	13	.086(.028)	.36(.17)	425	290(15)	281(17)	286(16)	139	9
17A	WA	7	.24 (.096)	.43(.30)	430	362(37)	341(29)	358(33)	72	21
17B	WA	6	.083(.026)	.59(.21)	420	315(9)	306(9)	310(10)	110	9
17C	WA	5	.16 (.12)	.38(.21)	410	284(16)	269(13)	277(16)	133	15
17D	WA	3	.080(.012)	.40(.32)	400	258(8)	248(8)	253(8)	147	10
11A	EA	17	.25 (.12)	.55(.23)	520	474(12)	469(7)	472(7)	48	5
11B	EA	17	.16 (.052)	.58(.22)	515	459(7)	457(6)	458(7)	57	2
11C	EA	19	.20 (.12)	.55(.20)	510	451(3)	449(3)	450(3)	60	2
24A	EA	11	.21 (.10)	.84(.21)	405	381(7)	378(3)	380(5)	25	3
24B	EA	11	.17 (.045)	.50(.19)	405	374(1)	373(1)	374(1)	31	1
24C	EA	11	.21 (.13)	.52(.12)	405	375(1)	373(2)	374(2)	31	2
24D	EA	11	.22 (.087)	.56(.21)	400	372(3)	370(2)	371(2)	29	2
28A	EA	21	.21 (.10)	.54(.22)	385	358(7)	355(5)	357(6)	28	3
28B	EA	20	.16 (.060)	.58(.15)	380	348(2)	347(3)	348(2)	32	1
28C	EA	14	.22 (.082)	.56(.22)	375	340(4)	338(4)	339(4)	36	2
28D	EA	11	.21 (.054)	.53(.093)	370	339(1)	337(1)	338(1)	32	2
36A	EA	10	.24 (.19)	.60(.27)	325	304(10)	296(16)	392(10)	23	5
36B	EA	10	.30 (.20)	.45(.22)	320	296(2)	294(3)	295(2)	25	2
12A	IP	24	.22 (.10)	.52(.26)	515	461(10)	456(3)	459(8)	56	5
12B	IP	15	.21 (.11)	.53(.21)	510	451(4)	447(3)	494(4)	61	4
12C	IP	8	.21(.091)	.42(.21)	505	444(3)	442(2)	443(3)	62	2
12D	IP	6	.30 (.21)	.46(.17)	500	439(2)	436(2)	438(3)	62	3
12E	IP	8	.25 (.10)	.46(.20)	495	438(2)	435(2)	436(3)	59	3
25A	IP	26	.16 (.12)	.44(.25)	405	380(8)	377(6)	378(7)	27	2
25B	IP	26	.17 (.060)	.50(.19)	400	369(2)	368(2)	368(3)	32	2
25C	IP	11	.22 (.12)	.44(.23)	395	365(3)	363(2)	364(3)	31	2
25D	IP	15	.18 (.095)	.34(.24)	390	363(2)	361(1)	362(7)	38	2
25E	IP	5	.16 (.025)	.51(.45)	385	361(2)	359(2)	360(3)	25	2
29A	IP	26	.19 (.071)	.49(.32)	380	348(7)	346(5)	347(6)	33	2
29B	IP	26	.15 (.071)	.50(.21)	370	339(3)	338(3)	339(3)	31	1
29C	IP	26	.18 (.10)	.47(.25)	360	332(4)	331(4)	332(4)	28	2
37	IP	15	.29 (.14)	.52(.25)	325	300(6)	297(3)	299(5)	26	4
14A	EC	13	.17 (.12)	.55(.27)	505	486(11)	483(11)	485(11)	20	3
14B	EC	4	.11 (.035)	.26(.16)	505	470(2)	469(2)	469(2)	36	1
14C	EC	15	.16 (.059)	.53(.29)	500	463(2)	462(2)	463(2)	37	2
14D	EC	17	.11 (.052)	.44(.20)	495	463(1)	462(1)	462(1)	33	1
27A	EC	11	.22 (.22)	.53(.19)	405	392(6)	389(6)	391(6)	14	3
27B	EC	14	.13 (.045)	.54(.26)	405	379(3)	378(3)	378(3)	27	1
27C	EC	10	.14 (.094)	.52(.22)	405	374(1)	373(1)	373(1)	32	1
27D	EC	12	.12 (.062)	.47(.17)	400	377(3)	375(1)	376(2)	24	2
27E	EC	6	.17 (.042)	.50(.27)	400	375(2)	373(1)	374(2)	26	2
30A	EC	22	.20 (.11)	.54(.26)	385	365(8)	364(7)	365(8)	20	2
30B	EC	16	.25 (.086)	.49(.21)	380	352(4)	351(3)	352(4)	28	2
30C	EC	14	.16 (.035)	.44(.19)	380	353(1)	352(1)	352(1)	28	1
30D	EC	11	.17 (.055)	.39(.19)	375	350(2)	349(1)	349(2)	26	1
38A	EC	4	.43 (.18)	.62(.18)	335	314(10)	305(7)	309(9)	26	9
38B	EC	11	.23 (.091)	.50(.20)	330	303(3)	301(1)	302(2)	28	2
38C	EC	16	.16 (.062)	.59(.24)	330	302(1)	300(1)	301(1)	29	1
38D	EC	6	.19 (.092)	.44(.23)	325	303(3)	300(2)	301(3)	24	3
39A	EC	11	.16 (.045)	.65(.35)	320	294(7)	297(4)	298(5)	22	3
39B	EC	26	.17 (.052)	.43(.24)	310	291(2)	290(2)	290(2)	20	1

TEMPERATURES ARE IN DEGREES CELSIUS (STANDARD DEVIATIONS IN PARENTHESES)
S#=SERIES NUMBER FL=FLUID #C=THE NUMBER OF CONTACTS IN THE SAMPLE
TAU=THE CONTACT PERIOD IN SECONDS THETA=CONTACT DURATION/PERIOD RATIO
TW=BULK SURFACE TEMPERATURE TR=RECOVERY TEMPERATURE TQ=QUENCH TEMPERATURE
DTP=TEMPERATURE DEPRESSION ACROSS PIN DTC=TEMPERATURE CHANGE DURING CONTACT
WA=WATER EC=ETHANOL IP=ISO-PROPANOL EC=ETHYLENE-CHLORIDE

period are used with the equation for contact heat flux employed by Yao and Henry [6] (which is the standard error function solution for the contact of two semi-infinite static media), the local heat flux during liquid-solid contact is calculated to be 1.6 MW/m^2, which is slightly above the critical heat flux for water of 1.4 MW/m^2. Both the contact duration and the calculated heat flux are of the same order of magnitude as that predicted by the analysis of Yao and Henry. The applicability of the error function solution for liquid-solid contact in the present case was investigated by noting the initial temperature depression of the pin tip as the liquid was first introduced to the heating surface. The initial temperature depressions measured in the present study were in good agreement with those predicted by the error function solution for the contact of two semi-infinite static media, indicating that this formulation may be applicable to the liquid-solid contact phenomenon on macro-roughened surfaces, provided the temperature within the macro-roughness elements is initially uniform and the heat transfer is essentially one dimensional. Although this relatively large heat flux resulting from intermittent liquid-solid contact occurs only over a relatively small fraction of the heating surface (the surface area of the pin tip accounts for only about 20% of the total area of the heating surface) a substantial increase in film boiling heat flux can be realized (see Figures 3 through 6). The BMFBT which marks the transition between quasi-nucleate and film boiling is clearly distinguishable from both the temperature traces of the flush-mounted micro-thermocouple in the protruding tip of the instrumented macro-roughness element and the overall heat flux. The distinction between quasi-nucleate and film boiling can be clearly seen by comparing the first data sequence to the subsequent data sequences in Figures 4 through 6.

4. CONCLUSIONS

Direct liquid-solid contact may occur in film boiling. Furthermore, this occurrence may be significantly increased by the introduction of macro-roughness elements to the heating surface. If the macro-roughness elements protrude above the heating surface enough to bridge the vapor layer that characteristically separates the heating surface from the liquid in film boiling, an enhancement in heat transfer will result. The magnitude of the effect of introducing macro-roughness elements to the heating surface was found to depend on the liquid, the drop size, and the bulk surface temperature (as can be seen from Figures 3 through 6). The BMFBT as well as the LMFBT can be determined when liquid-solid contact is present through the use of a micro-thermocouple. The increase in BMFBT on a macro-roughened surface as compared to a smooth surface is greater than the corresponding increase in LMFBT. This is thought to be evidence of the large localized heat flux in the vicinity of liquid-solid contact.

5. NOMENCLATURE

A_p	vertically projected drop area
C_{pg}	constant pressure specific heat of saturated vapor
h_D	drop heat transfer coefficient (Eqn. 1)
T_L	liquid (saturation) temperature
T_p	instantaneous temperature at the tip of the instrumented pin
T_Q	quench temperature (the minimum value of T_p during a contact)
T_R	recovery temperature (the value of T_p just prior to contact)
T_W	bulk surface temperature
V_D	drop volume
$V^* = V_D\left[\frac{\sigma g_c}{g(\rho_F-\rho_g)}\right]^{-3/2}$	dimensionless drop volume
$\Delta T_c = T_R - T_Q$	the excursion of T_p during a contact
$\Delta T_p = T_W - T_p$	the instantaneous pin tip temperature depression
$\theta = \frac{\tau_c}{\tau}$	the contact duration/period ratio

$\Lambda = \frac{C_{pg}(T_W - T_L)}{\Delta h_v}$	dimensionless superheat
ρ_F	density of saturated liquid
ρ_g	density of saturated vapor
τ	contact period (the time between contacts)
τ_c	contact duration

Superscripts

——	indicates average quantity

REFERENCES

1. Bradfield, W. S., "Liquid-Solid Contact in Stable Film Boiling," Industrial and Engineering Chemistry: Fundamentals, vol. 5, No. 2, pp. 200-204, May 1966.
2. Nishio, S. and Hirata, M., "Direct Contact Phenomenon Between a Liquid Droplet and High Temperature Solid Surface," Proceedings of the Sixth International Heat Transfer Conference, Toronto, Canada, pp. 245-250, August 1978.
3. Seki, M., Kawamura, H., and Sanokawa, K., "Transient Temperature Profile of a Hot Wall Due to an Impinging Liquid Droplet," ASME Journal of Heat Transfer, vol. 100, pp. 167-169, February 1978.
4. Knobel, D. H. and Yeh, Y. C., "The Effect of Artificial Surface Projections on Film-Boiling Heat Transfer," Proceedings of the AIChE-ASME National Heat Transfer Conference, Salt Lake City, Utah, August 1977.
5. Tevepaugh, J. A. and Keshock, E. G., "Influence of Artificial Surface Projections on Film Boiling Heat Transfer," Proceedings of the Eighteenth National Heat Transfer Conference: Advances in Enhanced Heat Transfer, San Diego, California, pp. 133-140, August 1979.
6. Yao, S. C. and Henry, R. E., "Experiments of Quenching Under Pressure," Proceedings of the Sixth International Heat Transfer Conference, Toronto, Canada, pp. 263-267, August 1978.
7. Hartland, S. and Hartley, R. W., Axisymmetric Fluid-Liquid Interfaces, Elsevier Scientific, Amsterdam, 1976.
8. Baumeister, K. J., Keshock, E. G., and Pucci, D. A., "Anomalous Behavior of Liquid Nitrogen Drops in Film Boiling," NASA TM X-52800, June, 1970.
9. Baumeister, K. J. and Simon, F. F., "Lendenfrost Temperature - Its Correlation for Liquid Metals, Cryogens, Hydrocarbons, and Water," ASME Journal of Heat Transfer, pp. 166-173, May 1973.