Optical techniques for the measurement of liquid solid-contact in film and transition boiling regimes.

Timothy Butrie
OPTICAL TECHNIQUES FOR THE MEASUREMENT OF LIQUID SOLID-CONTACT IN FILM AND TRANSITION BOILING REGIMES

by

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<tr>
<td>c</td>
<td>speed of light</td>
</tr>
<tr>
<td>CHF</td>
<td>critical heat flux</td>
</tr>
<tr>
<td>D</td>
<td>diameter</td>
</tr>
<tr>
<td>f</td>
<td>focal length</td>
</tr>
<tr>
<td>F</td>
<td>fraction</td>
</tr>
<tr>
<td>i</td>
<td>angle of incidence</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>l</td>
<td>length</td>
</tr>
<tr>
<td>n</td>
<td>index of refraction</td>
</tr>
<tr>
<td>N.A.</td>
<td>numerical aperture</td>
</tr>
<tr>
<td>OD</td>
<td>outside diameter</td>
</tr>
<tr>
<td>PMT</td>
<td>photomultiplier tube</td>
</tr>
<tr>
<td>q</td>
<td>heat flux</td>
</tr>
<tr>
<td>Q</td>
<td>heat transfer per unit area</td>
</tr>
<tr>
<td>r</td>
<td>angle of refraction</td>
</tr>
<tr>
<td>r</td>
<td>radius</td>
</tr>
<tr>
<td>R</td>
<td>ratio of reflected light to incident light</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>TC</td>
<td>thermocouple</td>
</tr>
<tr>
<td>X</td>
<td>distance</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>thermal diffusivity</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>wave length</td>
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\(\phi\) angle of incidence or refraction
\(\tau\) time period
\(\Delta\) change in

**Subscripts**
- a area
- c contact
- e,i interface
- f focal length
- FB film boiling
- i initial
- k fraction of wetted area
- L liquid
- m maximum
- NB nucleate boiling
- o ambient
- S solid
- t time
- t,T total
- TB transition boiling
OPTICAL TECHNIQUES FOR THE MEASUREMENT OF LIQUID-SOLID CONTACT IN FILM AND TRANSITION BOILING REGIMES

by

Timothy Butrie

ABSTRACT

Two optical systems were developed to detect and measure liquid contacts on a heated surface in pool boiling experiments. The first method was a proof of principle experiment on a glass boiling surface intended to demonstrate the applicability of optical systems for this type of measurement. Data from pool boiling experiments on the high temperature quartz surface showed that liquid contact fraction increased monotonically with decreasing surface superheat. The second technique involved a small fiber optic probe mounted flush on the surface of a copper block. The probe was durable and fast responding and provided quantitative measurements of liquid contact behavior in film and transition pool boiling. No liquid contacts were observed over 230°C surface superheat. The liquid contact fraction increased steadily to a value of 0.5 as superheat decreased to 60°C. Eventually, the contact fraction approached unity as the surface superheat was lowered to zero. The functional dependence of contact
frequency and durations was determined for the glass boiling surface and copper boiling surface experiments. The effects of surface oxidation on the copper surface were studied and revealed a decrease of the liquid contact fraction as the surface became oxidized.
I. INTRODUCTION

1.1 General

During a loss-of-coolant accident and subsequent reflooding in water cooled nuclear reactors, the associated heat transfer in film and transition boiling regimes is of great importance in thermal analysis. It is necessary to have a greater understanding of the liquid-solid contact phenomena in these boiling regimes to better predict the heat transfer. However, there is a scarcity of data where actual measurements of liquid contacts on a high temperature boiling surface were taken. The objective of this investigation was to develop optical techniques for detecting and measuring liquid-solid contacts in high temperature pool boiling experiments.

1.2 Boiling Heat Transfer

Boiling usually occurs when a liquid is exposed to a surface whose temperature is above that of the saturation temperature of the liquid. Nukiyama (1) first observed different regimes of boiling in 1934 using an electrically heated wire submerged in water. Figure 1.1 illustrates the several regimes of boiling where heat flux data is plotted against the temperature difference between the saturation temperature of the liquid and wall (or surface) temperature.

-3-
Fig. 1: Typical Boiling Curve
As liquid near the heated surface becomes superheated, bubbles begin to form on the boiling surface and are dissipated in the nearby liquid. This represents the beginning of the nucleate boiling regime. As the superheat increases, bubbles are generated more rapidly and rise to the surface of the liquid. This results in a very efficient regime to remove heat from the boiling surface.

Eventually, as the superheat becomes very high, the bubbles coalesce to form a vapor film surrounding the heated surface. This point on the boiling curve corresponds to critical heat flux (CHF), and marks the beginning of the film boiling regime. Due to the low thermal conductivity of the vapor, the heat transferred from the surface is greatly reduced. The vapor film is subject to liquid turbulence and may break down allowing liquid droplets to briefly contact the surface. Since the liquid has a much greater thermal conductivity than the vapor, a significant increase in the heat transfer rate can be observed.

As the surface superheat is lowered to a minimum film boiling point, a continuous vapor film can no longer be maintained. For surface superheats less than this minimum superheat, the transition boiling regime is observed. In transition boiling, the heated surface is contacted alternately by liquid and vapor. Rapid
heat transfer to the contacting liquid causes the wall superheat to decrease further resulting in an increased duration and frequency of liquid contacts. Eventually, the liquid contact fraction approaches unity as the surface is completely covered by the liquid.

The heat transfer caused by the liquid contacts is of great importance in film and transition boiling but is not fully understood. Therefore, it is important to quantitatively measure liquid contact fraction and frequency in order to accurately predict the heat transfer. However, measurements of this type are very difficult due to the short time durations of the liquid contacts and the hostile boiling environment to which measurement devices are exposed. The objective of this investigation was to develop instrumentation for the detection and measurement of transient liquid contact in film and transition pool boiling.
II. SURVEY OF LITERATURE

2.1 Film and Transition Boiling

In 1960, Bradfield, Barkdoll and Byrne (2) reported possible liquid-solid contact at film boiling temperatures involving quenching experiments with various degrees of subcooling.

In 1961, Berenson (3) reported the effect on surface roughness on the transition boiling regime, suggesting possible liquid-solid contact. Later Bradfield (4) suggested the possibility of liquid contacts in stable film boiling in transient and steady-state experiments. He investigated the effects of surface roughness, subcooling and the thermal conductivity of the heated surface and concluded that periodic liquid contact was possible in the film boiling regime.

Bankoff and Mehra (5) developed a quenching theory for transition boiling suggesting a method to determine the total heat transferred to the liquid per contact. The temperature of the liquid brought into contact with a large slab of metal, initially at temperature $T_{s,i}$ is predicted by Carslaw and Jaeger (6) to be:

$$
T_s = T_{L,i} + (T_e - T_{L,i}) \text{erfc} \frac{x}{2\sqrt{\alpha L t}}
$$

(2.1)

where $T_e$ is the interfacial temperature, $x$ is the distance from the interface, $t$ is the time, and $\alpha$ is the thermal diffusivity of the liquid. The temperature of the interface will be:  

-7-
where \( k \) is the thermal conductivity. The heat transfer to the liquid contact is obtained by integrating equation (2.1) yielding:

\[
Q = 2k_L (T_e - T_{L,i}) \left[ \frac{t_c}{\pi \sqrt{\alpha_L}} \right]^2
\]

(2.3)

where \( t_c \) represents the average contact duration.

More recently in 1974, Henry (7) postulated that liquid contacts produce significant thermal transients on the heated surface which in turn could lead to the increasing breakdown of the vapor film. Swanson (8), in film boiling experiments, measured the heated surface temperature transients which confirmed the theory that intimate liquid-solid contact produced significant heat transfer. However, these experiments indirectly measured liquid contact through temperature transients and they were unable to quantitatively measure individual liquid-solid contacts.

2.2 Previous Investigations

Several attempts have been made to measure liquid contact phenomena in film and transition boiling
regimes with electrical probes and temperature measurement probes. Each type of probe has had some limited success in obtaining experimental data in transient and steady state experiments.

2.2.1 Electrical Probes

The most common electrical probe is a conductance probe which detects the variation in the resistance for the different phases. By using an electrical conductance probe, Griffith et al. (9,10) investigated the transition between slug flow and annular flow. The probe measured resistance between the probe tip and the wall indicating whether or not vapor filled the channel core signifying annular flow. Hewitt et al. (11) used a similar technique to measure the liquid film thickness in annular flow.

Yao and Henry (12,13) developed electrical conductance probes to investigate liquid-solid contact behavior in film boiling. They measured the liquid contact area fraction, the duration and frequency of contacts as a function of system pressure. A grid of probes was inserted into the liquid within 1.5mm of the solid surface. The liquid contacts on the boiling surface were detected by measuring the electrical conductance between the boiling liquid mass and the heated surface. Their results (Figures 2.1 and 2.2) indicate that the contact area fraction and the
Fig 2.1: Measured contact areas as a function of Interface temperature for ethanol on a gold-plated copper surface

From Yao & Henry (13)

Fig. 2.2 Measured contact areas as a function of Interface temperature for water on a gold-plated copper surface
Fig. 2.1: Measured contact areas as a function of interface temperature for ethanol on a gold-plated copper surface.

From Yao & Henry (13)

Fig. 2.2: Measured contact areas as a function of interface temperature for water on a gold-plated copper surface.
duration of contacts is dependent upon interfacial temperature. The general trend is for contact area fraction and duration of contacts to increase as the interface temperature is lowered. However, the calibration of their probes was very difficult and there is typically a factor of two uncertainty in the contact area fraction data.

Ragheb and Cheng (14,15) developed a probe made of zirconium wire coated with a platinum tip to detect phase changes at a heated surface. The probe detected the phase present on the surface by measuring the voltage drop between the platinum tip and the heated surface. The probe configuration and test section are shown in Figure 2.3. A sample trace from the probe is shown in Figure 2.4. The probe trace clearly indicates some intermittent liquid contacts in the film boiling and transition boiling regimes (regions AB and BC respectively). However, the response time of their system was not sufficient enough to permit quantitative measurements of actual liquid contact and they obtained only filtered signal responses indicating liquid contact increased as the heated surface cooled.

2.2.2 Temperature Measurement Probes

By using thermocouple probes to measure surface temperature fluctuations, it is possible to detect
From Ragheb & Cheng (15)

Fig. 2.3: Zirconium probe schematic
From Ragheb & Cheng (15)

Fig. 2.3: Zirconium probe schematic
From Ragheb & Cheng (15)

**Fig. 2.4:** Sample Probe trace

RUN P301

\[ G = 68 \text{ kg/m}^2, \Delta T_{\text{sub}} = 27.8 \, ^\circ\text{C} \]
Fig. 2.4: Sample Probe trace from Ragheb & Cheng (15)

RUN P301
G = 68 kg/m²s
ΔT_{\text{sub}} = 27.8 °C

THERMOCOUPLE TRACE

VAPOR SLUGS

TIME

10 SEC

PROBE TRACE

A

B

C

D
phase changes. In measuring liquid contact behavior, it is imperative to have a fast responding system since liquid contacts can be of short duration (typically milliseconds).

Hsu and Schmidt (16) designed a specially fabricated thermocouple placed in contact with a heated surface in nucleate boiling experiments. They used an average variation method to construct boiling curves (Fig. 2.6) from the thermocouple traces (Fig. 2.5) to show the effect of surface roughness and temperature in nucleate boiling.

Yu and Messler (17) also studied nucleate boiling near critical heat flux through measurement of the transient surface temperature. By using high speed cinephotography and simultaneous measurement of the transient surface temperature during nucleate boiling (Fig. 2.7), they observed the presence of a liquid film, or macrolayer, beneath vapor bubbles at the surface.

Lee (18) and Lee, Chen, and Nelson (19) developed a microthermocouple probe (Figures 2.8 and 2.9) to detect liquid contacts on a high-temperature surface in film and transition boiling. The probe consisted of a microthermocouple with a sensing active junction created by a $5 \times 10^{-6}$ meter layer of electroplated nickel. The operational basis for the probe is shown
Fig. 2.5: TC trace in nucleate boiling

From Hsu & Schmidt (16)

Fig. 2.6: Boiling curves obtained
Fig. 2.5: TC trace in nucleate boiling

From Hsu & Schmidt (16)

Fig. 2.6: Boiling curves obtained
Fig. 2(a). The boiling vessel.

Dimensions of the boiling surface.

From Yu & Messler (17)

Transient surface temperature at 1.3 MW, m².

Fig. 2.7: Nucleate boiling experiment
Fig. 2(a). The boiling vessel.

Dimensions of the boiling surface.

From Yu & Messler (17)

Transient surface temperature at 1.3 MW/m².

Fig. 2.7: Nucleate boiling experiment
Fig. 2.8: Top view of surface temperature probe (junction open)

Fig. 2.9: Side view of surface temperature probe (with closed junction)

From Lee, et al. (18)
Fig. 2.10 Operational basis for surface temperature measurement probe.

Fig. 2.11: Typical probe response during film boiling.

From Lee, et al. (18)
Fig. 2.10: Operational basis for surface temperature measurement probe.

Fig. 2.11: Typical probe response during film boiling.

From Lee, et al. (18)
Sample traces of the probe in film and transition boiling are shown in Figures 2.11 and 2.12. Pool boiling experiments indicated the ability of the probe to detect liquid contact time fraction as a function of surface temperature (Figure 2.13). However, the durability of such a probe may be adversely affected by the hostile boiling environment to which it is exposed in high temperature pool boiling experiments. Also, the response time of the thermocouple is a limiting factor and can result in the omission of very short liquid-solid contacts.
Fig. 2.11: Typical probe response during transition boiling.

Fig. 2.12: Typical average liquid contact time and maximum surface temperature during a complete quench of the test block.

From Lee, et al. (18)
Fig. 2.11: Typical probe response during transition boiling.

Fig. 2.12: Typical average liquid contact time and maximum surface temperature during a complete quench of the test block.

From Lee, et al. (18)
III. VYCOR GLASS POOL BOILING EXPERIMENT

3.1 Objective

The objective of this experiment was to quantitatively measure liquid-solid contact on a high temperature VYCOR glass surface in pool boiling. This proof of principal experiment was intended to demonstrate the applicability of optical techniques for detecting intimate liquid contacts on a heated surface. The relationship between initial surface superheat and liquid contact time fraction, frequency, and average time duration will be determined.

3.2 System Overview

The optical system developed for this experiment is shown schematically in Figure 3.1. A Helium Neon laser beam is focused to a very small point on the glass boiling surface. The amount of light reflected from the upper glass surface is dependent on the angles of incidence and refraction of the laser light (Fig. 3.2). The ratio of reflected light to incident light at an interface can be determined from:

\[ R = \frac{1}{2} \left[ \frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)} \right] \]  

where \( i \) = angle of incident light

\( r \) = angle of refracted light
Fig. 3.1: Schematic of glass boiling surface experiment
Fig. 3.2: Reflection and refraction at an interface

\[ \phi_1 = \text{angle of incidence} \]

\[ \phi_2 = \text{angle of refraction} \]
The incident angle is fixed by the geometry of the system and the angle of refraction is a function of the refractive index of the medium in contact with the glass boiling surface. Therefore, by monitoring the light reflected from the upper glass surface, it is possible to detect liquid contact in film and transition boiling regimes.

In the present system, a Spectra-Physics Model 146, 4mW Helium-Neon laser is used. This light has a wavelength of 632.8 nanometers. The original beam diameter of 0.922 mm is focused to a very small sensing point on the upper glass surface to achieve a local measurement of liquid-solid contact. The actual size of the sensing area can be determined from:

\[ D_f = \frac{5 \lambda f}{\pi D_{1/e}} \]

where
- \( D_f \) = diameter of beam at focal length
- \( \lambda \) = wavelength of incident light
- \( f \) = focal length of beam focusing lens
- \( D_{1/e} \) = original beam diameter

Using a 100 mm focal length lens, the beam diameter at the measurement point is found to be 0.109 mm.
The light reflected from the interface II is a function of the angle of incident light. The incident angle $\phi_1$ (Figure 3.3) to interface I remains constant and is fixed by the position of the first plane mirror (Figure 3.4). By measuring the vertical and horizontal distances from the plane mirror to the sensing area on the glass surface, $\phi_1$ was calculated to be $34.0^\circ$. $\phi_2$ the angle of refraction at interface I (Figure 3.3), can be found using Snell's law:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \quad (3.3)$$

where $n_1$ = index of refraction for medium 1
$n_2$ = index of refraction for medium 2
$\phi_1$ = angle of incident light
$\phi_2$ = angle of refracted light

Using $n_1 = 1$ for air and $n_2 = 1.54$ for the Vycor glass, $\phi_2$ is found to be $21.3^\circ$. $\phi_2$ remains constant for this experiment and is fixed by the position of the plane mirror. The angle $\phi_3$ can also be determined by applying Snell's law. Here, angle $\phi_2$ is now the angle of incidence to interface II and $\phi_3$ is the angle of refraction (Figure 3.3). The index of refraction $n_3$, will either be close to unity for vapor or about 1.33 for water, depending on the medium that is in contact with the glass surface.
Fig. 3.3: Reflection and refraction on glass specimen
If the vapor phase is present at interface II, $n_3 = 1.0$ and $\phi_{3V}$ is calculated to be $34.0^\circ$. For liquid in contact with the solid surface, the angle of refraction $\phi_{3L}$ is found to be $24.9^\circ$. From the above it is apparent that the amount of light reflected from the interface toward the photodetector is a function of the index of refraction of the medium in contact.

The ratio of incident light to reflected light for vapor present on the glass surface is determined using equation 3.1 to be 0.048. When water is the medium in contact with the boiling surface, the ratio of reflected light to incident light is calculated to be 0.0056. Thus, there is an order of magnitude difference in the amount of light reflected from interface II, making it relatively easy to distinguish the phase present at the local sensing spot in high temperature pool boiling experiments.

3.3 Data Collection

The reflected light from the boiling surface is detected by a RCA Model IP28 photomultiplier. A collection mirror is positioned such that only the reflection from interface II will be directed to the PMT (Figure 3.4). The light is focused into the PMT using a 50 mm focal length lens. A 633 nm wavelength interference filter and a 7.5 cm long light shield were attached to the PMT to prevent ambient light from entering the detector.  -27-
Fig. 3.4: Schematic of mirror placement
With about 500 volts applied to the PMT, the PMT current produced a 3 volt drop across a 300 kΩ load resistor when vapor was in contact with the glass surface and roughly 0.5 volts for the liquid phase (Figure 3.5). Increasing the voltage applied to the PMT within limits will increase the output of the PMT but will also increase unwanted noise to the output signal. The 3.0 volt output from the PMT for vapor on the glass surface was found to be the optimum output level with minimum noise.

The response time of the PMT with the load and gain resistors used here was measured by observing the output of the PMT and a pulsing LED simultaneously. In Figure 3.6, the upper trace is the voltage applied to the LED as a function of time and the lower trace is the output signal of the PMT. The LED has a threshold voltage of 2.0 volts. The response time of the PMT is seen to be approximately 250 nanoseconds (250 E-09 sec.). This response time is more than adequate for the present application since the phenomena to be observed is of the order of milliseconds.

The output signal of the PMT was monitored and recorded using a Nicolet Model 1091A Explorer digital oscilloscope. Using full memory, it is possible to record and store 4096 data points. This allows for a
Fig. 3.5: Oscilloscope trace of PMT output

Fig. 3.6: Response time of photomultiplier tube
0.82 second time interval to be captured when using a 0.2 millisecond per point sweep rate (5000 samples/second). The stored signal is recorded onto a Techtran 817 data cassette through a Nicolet 194A buffer unit. The data is stored in standard ASCII format on the cassette tape and can then be interfaced with Lehigh University's Cyber 720 mainframe computer for analysis. Only one 0.82 second time interval could be recorded for each quenching run with the above arrangement because of very slow transfer rate from the oscilloscope to the cassette tape. The time interval can be increased if a slower sweep is used but this results in a sacrifice of temporal resolution and might in turn result in the omission of very short duration liquid contacts.

3.4 Experimental Procedures

The Vycor glass specimen was fitted with a 3.2 mm type K thermocouple which was held in place by a sheet metal skirt. The thermocouple recorded the initial surface temperature before the quenching water was released. The assembly was sealed with high temperature cement to prevent the quenching water from leaking. The glass specimen was heated to the desired temperature in a resistance heating oven. A 1 kW heater was used to heat distilled, deionized water to saturation temperature (100°C), which was then released onto the
glass specimen by means of a solenoid operated
valve (Figure 3.7). The oscilloscope could be
triggered manually or by using the mid-signal
triggering mode. The latter method triggered
automatically when the output signal dropped below
the vapor voltage level permitting observation of
the first liquid contact. A typical quench on the
quartz plate lasted less than 10 seconds making mid­
signal triggering particularly useful in such a short
duration experiment.

3.5 Experimental Runs and Data Reduction

Figure 3.8 shows a typical signal from one
quenching run. The vapor voltage level is approximately
3.0 volts. Data points which lie under a certain contact
limit voltage, 0.5 volts in this case, are considered
to be liquid contacts on the glass surface. Figure 3.9
is an exploded version of the same trace expanded in
time. The individual liquid contacts are of varying
durations and can be readily distinguished. Typically,
only 0.2 to 0.4 msec is required for the signal to fall
from the vapor voltage level to the liquid voltage level.
However, 0.8 to 1.6 msec may be necessary for the signal
to return to the vapor voltage level. This may be
caused by the low thermal conductivity of the glass
plate. During cooling the enthalpy is available to be
given to the liquid while in heating the enthalpy to
Fig. 3.7: Schematic of quenching water release setup
Fig. 3.8: Typical trace in glass boiling surface experiment
Fig. 3.9: Trace expanded in time
the test location depends on the conduction through the quartz specimen.

No liquid contacts were observed above 750°C superheat. The vapor film gradually began to break down as the wall superheat decreased from 750°C to roughly 640°C. Figure 3.10 is a typical trace recorded in this film boiling regime. As the initial wall superheat was lowered from 640°C to 530°C, the heated surface was no longer able to support a continuous vapor film and liquid contacts were increasing in duration and frequency. Eventually, quenching occurs at approximately 525°C. Figure 3.11 is representative of deep transition boiling with final quenching of the glass plate.

The results of the quenching runs have been plotted as initial surface superheat versus liquid contact time fraction, frequency, and average duration of contact. The liquid contact time fraction $F_{L,t}$ is defined as the ratio of the time of all liquid contacts on the heated surface to total time elapsed in a given sample time period. The surface superheat was taken to be the initial thermocouple reading minus the saturation temperature of water. All tests were taken at atmospheric pressure.

Figure 3.12 is a plot of liquid contact time fraction versus initial surface superheat. At very high
Fig. 3.10: Typical trace in film boiling regime
Fig. 3.11: Typical trace in deep transition boiling regime
Fig. 3.12: Liquid contact time fraction vs. surface superheat
temperatures, (superheat greater than 700°C), liquid contacts were very few and of short duration, with $F_{L,t}$ in the range of 0.001 to 0.0015. As the superheat decreases to roughly 650°C, the contact fraction approached a value of 0.01. $F_{L,t}$ increases more rapidly as the surface superheat is lowered from 650°C to 610°C. For the 40°C drop in temperature, the liquid contact time fraction increases roughly an order of magnitude from 0.01 to 0.1. Eventually, $F_{L,t}$ approached a value near unity as the superheat reached 530°C. Below this temperature, only nucleate boiling was observed.

Figure 3.13 illustrates the frequency of liquid contacts as a function of surface superheat. Typically, at high superheats, from 750°C down to 650°C, the frequency was generally low ranging from 5 to 15 Hz. The frequency increased to a maximum value of 70 Hz as the superheat dropped to 580°C. The frequency dropped slightly as superheats were lowered further to 530°C.

The average time duration of liquid contact is shown plotted versus superheat in Figure 3.14. At high superheats, the liquid contacts were generally very short in duration averaging 0.5 msec. At superheats of 540°C to 530°C, average time duration reached at a maximum value of 15 msec. At superheats of 600 to 675°C, the average duration was generally 1 msec.
Fig. 3.13: Frequency of contacts vs. surface superheat
Fig. 3.14: Average duration of contacts vs. superheat
In summary, at high superheats in pool boiling experiments, liquid contacts on the glass surface are few and are of short duration. As the initial surface temperature dropped, the frequency of contacts generally increases until reaching its maximum value at 580°C. Average time duration also increased as surface temperature decreased, reaching a maximum immediately preceding the quenching of the glass surface. Due to the increased durations and number of liquid contacts, the contact time fraction increased as the superheat decreased.
IV. POOL BOILING EXPERIMENTS ON COPPER BLOCK

4.1 Objective

The objective of this experiment was to develop a fiber optic probe for detection and measurement of liquid-solid contact on a heated surface in a high temperature pool boiling experiment. The probe should be small, fast-responding and durable to provide accurate local measurements of liquid contact. The relationship between surface superheat and liquid contact time fraction, frequency and average time duration were to be determined in these experiments. Surface aging and its effect on liquid-contact phenomena were also to be determined.

4.2 Fiber Optics

In the past fifteen years, astounding progress has taken place in the development and fabrication of very low-loss optical fibers. Attenuations in fibers have been lowered from decibels per meter to decibels per kilometer (20). Fibers can now be manufactured in lengths of several kilometers with strengths comparable to fine steel (21).

The first low-loss optical fibers were manufactured in 1958 and were made of what is usually called glass (22). The basic light propagation mechanism is total internal reflection. This "step-index" fiber consists of a core
region and a cladding region as shown in Figure 4.1. The index of refraction of the cladding material is slightly less than the refractive index for the core material. The core has typically a 50 to 100 \( \mu \text{m} \) diameter surrounded by a cladding of diameter 100 to 200 \( \mu \text{m} \).

A decade later, the "graded-index" fiber was developed (23). Light waves in a graded index fiber do not propagate by total internal reflection but instead travel in helical or sinusoidal paths as shown in Figure 4.2. The light rays travel in "smooth" paths bending toward the core center because of a varying index of refraction. The refractive index tapers off slowly from a maximum value at the core center to the core-cladding interface. Light propagation in step-index and graded-index fibers will be discussed briefly in the following sections.

4.2.1 **Step-Index Optical Fibers**

Light propagation in a step-index fiber can be studied using geometrical optics rather than using more rigorous wave optics. This is possible because the standard diameter of the core material is up to a hundred times larger than the wavelength of the propagating light rays. The core diameter typically ranges from 50 to 100 \( \mu \text{m} \) (24). This permits the use of simple ray theory and Snell's law of refraction in studying the propagation phenomena.
Fig. 4.1: Light ray in a step-index fiber

Fig. 4.2: Light ray in a graded-index fiber
Snell's law states that if $\phi_1$ is the angle of incidence and $\phi_2$ is the angle of refraction, they are related by:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

where $n_1$ and $n_2$ are the refractive indices for medium 1 and medium 2. Consider Figure 4.3 which depicts the core-cladding interface in a step-index fiber. The core refractive index, $n_{core}$ is slightly less than $n_{clad}$, the index of refraction for the cladding. The optical fiber is surrounded by a medium with a refractive index of $n_0$. Rays which enter the fiber core and strike the cladding at a sufficiently large angle are refracted through the cladding (Figure 4.3). As $\phi_1$, the incidence angle, becomes greater, the angle of refraction increases until the refracted light ray travels parallel to the interface (Figures 4.4). The angle of incidence at which this occurs is known as the critical angle, $\phi_c$. The critical angle can be obtained using Snell's law. For the limiting case of a transmitted ray striking the core-cladding interface and emerging parallel to the interface, Snell's law shows:

$$n_{core} \cos^2 \phi_{\text{incident}} = n_{clad} \cos^2 \phi_{\text{refracted}} = 1 \quad (4.1)$$

The refracted angle is equal to $90^\circ$ (or $\cos \phi_{\text{refracted}}$).
Fig. 4.3: Light ray refracted through interface

Fig. 4.4: Light ray refracted parallel to interface
for the limiting case and equation 4.1 reduces to:

\begin{equation}
    n_{\text{core}} \cos^2 \phi_{\text{max}} = n_{\text{clad}}
\end{equation}

or

\begin{equation}
    \sin \phi_{\text{max}} = \left[ 1 - \left( \frac{n_{\text{clad}}}{n_{\text{core}}} \right)^2 \right]^{1/2}
\end{equation}

where \( \phi_{\text{max}} \) is the critical angle. Rays which strike the interface at an angle greater than the critical angle will be totally internally reflected (Figure 4.1). Equation 4.3 gives the maximum angle for a ray inside the fiber. By using Snells' law again, it is possible to find the maximum angle an incident light ray can have for the fiber surrounded by a medium with refractive index \( n_0 \). The critical angle is found to be:

\begin{equation}
    \sin \phi_{\text{max}} = \frac{1}{n_0} \left[ n_{\text{core}}^2 - n_{\text{clad}}^2 \right]^{1/2}
\end{equation}

Any incident light upon the fiber end will be totally internally reflected only if the incident angle is less than the critical angle defined in equation 4.4. A "numerical aperture," or acceptance cone half-angle (Figure 4.5) can be defined as:
N.A. = \( n_0 \sin \phi_{\text{max}} = \left[ n_{\text{core}}^2 - n_{\text{clad}}^2 \right]^{1/2} \) (4.5)

Consider the two light rays entering the fiber illustrated in Figure 4.6. It is apparent that the high-angle light ray travels a longer path per unit axial length as compared to a low-angle light ray. The "slowest" possible ray is one traveling at the critical angle and the "fastest" ray is an axial ray traveling parallel to the core axis. If both an axial ray and a ray traveling at the critical angle entered the fiber at the same instant, the axial ray would exit the fiber first since its path is shorter. This time delay difference results in a modulated light pulse which broadens as the light travels thru the fiber. The time necessary for an axial ray to travel a unit length of the fiber can be expressed by:

\[ \tau_{\text{axial}} = \frac{n_{\text{core}}}{C} \] (4.6)

For a ray traveling at the maximum angle, the time required to travel a unit length is:

\[ \tau_{\text{max}} = \frac{n_{\text{core}}}{C} \cdot \frac{1}{\cos \phi_{\text{max}}} = \frac{n_{\text{core}}}{C} \left( \frac{n_{\text{core}}}{n_{\text{clad}}} \right) \] (4.7)

The temporal time delay can be found by subtracting equation 4.6 from equation 4.7:
Fig. 4.5: Acceptance cone of optical fiber

Fig. 4.6: Time delay in step-index optical fiber
\[ \Delta \tau = \tau_{\text{max}} - \tau_{\text{axial}} = \frac{n_{\text{core}}}{C} \left[ \frac{n_{\text{core}}}{n_{\text{clad}}} - 1 \right] \] (4.8)

and has units of nanoseconds per kilometer (\(\frac{\text{ns}}{\text{km}}\)).

This pulse-broadening effect is undesirable in many cases, particularly digital transmission. One of the best ways to reduce this modal dispersion is through the use of a graded-index fiber.

4.2.2 Graded-Index Optical Fibers

The graded-index fiber allows light rays to travel in helical or sinusoidal paths unlike the straight line paths experienced in step-index fibers (Figure 4.7). The core of a graded-index fiber consists of material in which the refractive index is a function of radial distance from the core axis. The index of refraction is highest at the core center and is lowest at the core-cladding interface (Figure 4.8).

It is possible to describe the path of a light ray by applying Snell's law at radii \(r_1\) and \(r_2\):

\[ n(r_1) \cos \phi_1 = n(r_2) \cos \phi_2 \] (4.9)

where \(\phi_i\) = angle of ray relative to axis

\[ n(r_i) = \text{index of refraction at radius } r_i \]

\[ r_2 > r_1 \]

As a light ray travels further away from the center of the core, the angle \(\phi\) becomes smaller due to the
Fig. 4.7: Sinusoidal paths in a graded-index fiber

Fig. 4.8: Refractive index profile in graded-index fiber
lower refractive index material (Figure 4.9). The light ray eventually will be bent back towards the axis and will periodically oscillate about the core axis.

Using the same approach as with the step-index fiber, the maximum allowable angle for light to enter the fiber is found by:

\[
\sin \phi_{\text{max}} = \frac{1}{n_o} \left[ n_{\text{core}}^2 - n_{\text{min}}^2 \right]^{1/2}
\]  (4.10)

where \( n_{\text{min}} \) is the refractive index of the material at the maximum radial excursion of the light ray.

The numerical aperture for a graded index fiber can now be expressed as:

\[
\text{N.A.} = n_o \sin \phi_{\text{max}} = \left[ n_{\text{core}}^2 - n_{\text{min}}^2 \right]^{1/2}
\]  (4.11)

which is very similar to eq. 4.5 to step-index fibers.

From a geometrical viewpoint, the helical or sinusoidal paths in the graded-index fiber are actually longer than the straight paths experienced in the step-index fiber. However, light rays in a graded-index fiber travel the greatest amount of time in the portions of the core material having a lower index of refraction (nearer the core-cladding interface).
Fig. 4.9: Light ray bending in graded-index fiber
From equations 4.6 and 4.7, it is apparent that the velocity of a light ray is higher when traveling in the lower index medium. This results in the light rays which travel away from the axis making up in speed through the fiber for what they lose in geometrical distance. With careful control of the refractive index profile, it is possible to reduce modal dispersion by two orders of magnitude relative to a similar step-index fiber (24).

4.3 Experimental Apparatus

4.3.1 System Overview

The fiber optic probe system developed is shown schematically in Figure 4.10. The Helium-Neon laser beam is focused into a Corning graded-index optical fiber, one end which is mounted flush with a copper boiling surface. The amount of light returning back through the fiber is directly related to the index of refraction of the medium present at the fiber end. The light scattered back is monitored and recorded using a photomultiplier tube (PMT) and a digital storage oscilloscope permitting quantitative measurements of liquid contact phenomena. The probe system and its components will now be discussed in detail.

4.3.2 Fiber Optic Probe

The Corning graded-index fiber has the following characteristics:
Fig. 4.10: Schematic of fiber optic probe system
core diameter = 63 μm
coated diameter = 138 μm
numerical aperature = 0.21
attenuation = 12 db/km @ 600 nm
minimum bend radius = 25 mm

The fiber is coated with a lacquer finish which provides protection and increases flexibility. The fiber was tested for durability in a high-temperature furnace. The tests indicated that the fiber could withstand temperatures as great as 850°C, with only a slight loss in flexibility due to the burning off of the protective lacquer coating. In order to compensate for this loss, the fiber was shielded from damage by a 3.2mm O.D. copper tube sleeve which was attached to the copper test block.

The light source used in this experiment was a Spectra-Physics Model 146, 4mW helium eon laser. The nominal beam diameter is 0.922mm and the light has a wavelength of 632.8 nanometers. In order to transmit the maximum amount of light through the fiber, two requirements must be met. First, the beam diameter should be focused to a diameter less than or equal to the optical fiber core diameter. Second, the numerical aperature or acceptance cone half-angle of the focused beam should be less than or equal to the fiber numerical aperature.
The diameter of the focused beam can be determined from:

\[ D_f = \frac{5 \lambda f}{\pi D_{1/e}} \]

where \( D_f \) = diameter of beam at focal length
\( \lambda \) = wavelength of incident light
\( f \) = focal length of beam focusing lens
\( D_{1/e} \) = original beam diameter

In this system, a lens with a focal length of 27nm. was used which focused the beam diameter to \( 29 \times 10^{-3} \) mm. This is about half the core diameter of the Corning fiber.

The numerical aperature of the focusing lens can be found from:

\[ \text{N.A.}_f = \sin \left( \tan^{-1} \frac{D_{1/e}}{f} \right) \]

(4.21)

where \( \text{N.A.}_f \) = numerical aperature of focusing lens
\( D_{1/e} \) = original beam diameter
\( f \) = focal length of focusing lens

The 27 mm focal length lens has a numerical aperature of 0.034 which is significantly less than the 0.21 numerical aperature of the Corning fiber. Therefore, the 27 mm focal length lens meets both requirements to insure the maximum amount of light to be transmitted
A portion of the light transmitted through the fiber is scattered back from the fiber end that is mounted in the copper block. The amount of light returning back through the fiber is a function of the refractive indices of the fiber and the medium in contact at the fiber end. Previously in Chapter III, the ratio of reflected light to incident light at an interface was shown to be:

\[
R = \frac{1}{2} \left[ \frac{\sin^2(i-r)}{\sin^2(i+r)} + \frac{\tan^2(i-r)}{\tan^2(i+r)} \right]
\]

where \( i \) = angle of incident light
\( r \) = angle of refracted light

In the case of normal incidence (\( i=0 \)) at the interface (Figure 4.11), equation 3.1 reduces to:

\[
R = \left[ \frac{n_1-n_2}{n_1+n_2} \right]^2
\]

where \( n_1 \) = index of refraction of medium 1
\( n_2 \) = index of refraction of medium 2

In the present system, medium 1 is the fiber optic core with an index of refraction of roughly that of quartz (\( n_1 = 1.54 \)). Medium 2 can either have an index of refraction of approximately unity for vapor or 1.33 for water. The ratio of reflected light to incident
Fig. 4.11: Zero (normal) incidence
is \( R = 0.045 \) when liquid is in contact with the fiber end. The ratio for vapor present at the fiber end is \( R = 0.0054 \). This large difference in the amount of light returning back through the fiber makes it relatively easy to distinguish the phase is present at the fiber end.

The focused laser beam was vertically polarized and passed through a 50-50 beam splitter before entering the fiber. The beam splitter allows 50\% of the polarized light to reach the fiber end. The fiber optic end was properly positioned by first placing the fiber in a small hypodermic needle and then inserting the needle into an X-Y positioner (Fig. 4.12). The fiber and associated optical equipment were mounted on an optical bench as shown in Figure 4.13.

A large portion of the light focused into the fiber, between 95 to 99\%, will exit at the fiber end mounted in the copper block. The remaining light is transmitted back through the fiber and 50\% of this light is directed toward the collection optics by the 50-50 beam splitter (Figure 4.14). Less than 2.25 \% of the original beam strength reaches the photodetector if vapor is present at the fiber end and 0.25 \% if water is present.
Fig. 4.12: Schematic of fiber optic holder
Fig. 4.13: Optical bench setup for laser fiber interface
Fig. 4.14: Light transmitted back through fiber toward PMT
A portion of the focused light destined to enter the fiber is reflected off of the front fiber face. The amount of this reflected light is unacceptably large when compared to the intensity of the light transmitted back through the fiber. The solution to this problem was to vertically polarize the light before it enters the fiber and place a horizontal polarizer immediately before the photomultiplier tube. The second polarizer prevents most of the unwanted light reflected off the front fiber face from entering the photodetector. The vertically polarized light which enters the fiber and is scattered back through becomes randomly polarized by the time it reaches the collection optics. A sufficient portion of this random polarized light can pass through the horizontal polarizer into the photomultiplier tube.

The collection optics consisted of a focusing lens with a focal length of 50 mm placed between the beam splitter and the photomultiplier tube. This lens focused the light to be measured to its original diameter as it exited the fiber. In addition, a 100 μm diameter pinhole and a 632.8 nm wavelength interference filter were placed in front of the photosensor. The filter and pinhole performed satisfactorily in preventing unwanted ambient light from flooding the probe signal.
4.3.3  Test Section

The fiber probe was mounted into a test block assembly consisting of 100% oxygen free copper. The copper specimen measured 100 mm in diameter and was 70 mm long. Figure 4.15 is a cross section of the test section. The 1.6 mm type K thermocouple was brazed flush with the boiling surface to provide a temperature history of the quenching process. Because of the great difficulty involved in drilling a hole as small as the outside diameter of the fiber, a hypodermic needle sleeve was inserted into a 0.44mm hole drilled in the block. The fiber was then sealed into the sleeve using high-temperature furnace cement. The exiting fiber was protected from damage by a 3.2mm diameter copper tube mounted on the bottom of the test block.

4.3.4  Fiber Preparation

The fiber ends must be properly prepared for optimum light transmission. It is important to have a smooth, flat fiber end at the laser interface to minimize the entrance and exit losses. Also, the fiber end mounted in the test block must have a smooth, level surface to permit proper scattering of the light at the heated surface. A ill-finished end can decrease the signal to noise ratio resulting in difficulty distinguishing the phase present.
Fig. 4.15: Cross section of test block assembly
The fiber ends were soaked in acetone in order to dissolve the protective lacquer coating. The stripped fiber was placed under slight tension and scored with a sapphire-edged cutting tool. By applying greater tension, the fiber broke at the nick. This scribe and break technique produced very smooth, flat faces which were adequate for the present application.

4.3.5 Data Collection

The light reflected back through the fiber was monitored using a RCA Model IP28 photomultiplier tube. This is the same PMT previously described in the glass boiling surface experiment. The response time of the detector was shown to be approximately 250 nanoseconds which is sufficient for the present application of observing liquid contact phenomena.

The incident light upon the PMT was relatively small and required a substantial voltage to be applied across the tube. The PMT was operated at 1100 V potential using a Bertram Model 215 Power Supply, which is near the recommended maximum allowable voltage of 1200 volts for this PMT. This resulted in minimal and tolerable amount of background noise (light) in the output signal of the PMT. Figure 4.16 is a photograph of the oscilloscope trace for the fiber probe in air (top trace) and in water (lower trace). For air present
Fig. 4.16: Oscilloscope trace of probe in air and water
at the fiber end, the output voltage of the PMT was roughly 20 volts. The output voltage dropped to approximately 7 volts when the probe tip was immersed in water. The voltage difference between the two cases proved to be sufficient in determining the phase was present at the fiber end.

The output signal of the photomultiplier tube was monitored and recorded using a Nicolet Model 1091 Explorer digital oscilloscope. Using full memory, it was possible to record 4096 data points per sweep. This allowed for a 0.82 second time interval to be captured when using a 0.2 millisecond per point sweep rate. The stored signal was recorded onto a Techtran 817 data cassette via a Nicolet 194 buffer unit. The data was stored in standard ASCII format which allowed the data to be transferred to a Cyber 720 mainframe computer for analysis.
4.4 Experimental Runs and Data Reduction

4.4.1 Experimental Procedures

In the present experiment, a transient method was used to determine liquid contacts in high temperature, atmospheric pressure pool boiling experiments. The copper block test assembly was initially heated to a uniform temperature of 450°C in an electrical resistance heating oven. Distilled, deionized water, heated to the saturation temperature (100°C) was released onto the copper block. A sheet metal skirt sealed with high-temperature cement contained the quenching fluid on the copper surface.

Immediately after the water was introduced, the formation of a vapor film was observed. As the block gradually lost its sensible heat, the vapor film began to collapse resulting in short duration contacts. The liquid contacts cooled the surface until the surface could no longer support the vapor film and transition boiling was observed. Finally quenching occurred and the surface was entirely covered by liquid. The high thermal capacity of the copper block permitted longer film and transition boiling and allowed the block to act under quasi-steady state conditions. A typical quench process lasted about three minutes for an initial temperature of 450°C depending on surface conditions.
The experimental runs were broken into two categories:

1) Quenching Runs Series I were performed when the boiling surface possessed little or no oxide. The copper surface was cleaned with fine emery cloth after every three quenches.

2) Quenching Runs Series II were performed after the surface was fully oxidized. The surface condition essentially remained in an equilibrium state throughout all the Series II tests.

4.4.2 Experimental Results

Figure 4.17 shows a typical probe signal from one quenching run. The vapor voltage is approximately 20 volts and during liquid contacts the output voltage dropped considerably to 7 volts. Figure 4.18 is the same trace expanded in time. Individual contacts can be readily distinguished and observed to have varying durations. Any data points which fell under a specified contact limit (roughly 7.5 volts) were considered to be liquid contact on the heated surface.

The first contacts occurred at roughly 230°C surface superheat. These contacts were infrequent and of short duration. Figure 4.19 is typical of the probe
Fig. 4.17: Typical probe trace in pool boiling experiment
Figure 4.18: Probe signal expanded in time
Fig. 4.19: Probe signal in film boiling regime
Fig. 4.20: Probe signal in transition boiling regime
signal during this film boiling regime. As the block began to cool, more contacts occurred and were longer in duration. At deep transition boiling preceding quenching, the probe signal revealed very long duration contacts as shown in Figure 4.20.

The overall quenching history was recorded from the thermocouple for the Series I and Series II tests. The temperature curve became steeper after the surface became fully oxidized (Figure 4.21 & 4.22). This resulted in a faster quench for the Series II runs as compared to the Series I tests for identical initial temperatures.

The liquid contact time fraction, frequency, and duration have been plotted versus superheat temperature. The superheat temperature was observed and recorded from a digital thermometer simultaneously with the probe signal being recorded and stored in oscilloscope. The liquid contact time fraction $F_{L,t}$ is defined as the ratio of the time of all liquid contacts on the heated surface to total time elapsed in a given sample time interval. All pool boiling tests were taken at atmospheric pressure.

Figure 4.23 is a plot of liquid contact time fraction versus wall superheat for the Series I and
Fig. 4.21: Thermocouple trace of complete quenching (smooth surface)
Fig. 4.22: Thermocouple trace of complete quenching (oxidized surface)
Series II quenching tests. At very high superheats ranging from 190°C to 230°C, \( F_{Lt} \) is only 0.001 to 0.003 because of infrequency and short duration liquid contact. The contact fraction jumped to 0.01-0.05 as the wall temperature decreased only 15°C. Contacts on the boiling surface become longer in duration as the superheat decreased further. Frequency also gradually increased resulting in a higher contact time fraction for the lowered superheats. As the superheat approached 60°C, the wall was covered roughly half the time by liquid. Eventually, \( F_{Lt} \) approached a value of unity as the surface superheat neared zero. Comparison of Series I and II runs, reveals a slight shift in \( F_{Lt} \) data. In Series I, the smooth surface allowed a greater contact fraction when compared to the oxidized surface for roughly the same superheat. This shift was more evident at the lower superheats (60°C to 120°C).

The average duration of liquid contacts as a function of surface superheat is shown in Figure 4.24. At the lower superheats, the average duration was the greatest reaching a maximum value of approximately 20 ms. The general trend exhibited was for the average duration to decrease steadily as higher wall temperatures are encountered. There is no substantial difference between the Series I and Series II results, however, there is a slight increase in durations for the smooth surface.
Fig. 4.23: Liquid contact time fraction vs. superheat
Fig. 4.24: Average duration of contacts vs. surface superheat
Fig. 4.25: Contact frequency vs. surface superheat
The frequency of the liquid contacts is shown in Figure 4.25. There is substantial scattering of data in the oxidized surface runs. A slight trend exists suggesting that the frequency of contacts increases with decreasing superheats until peaking near 130°C surface superheat. The frequency drops off a small amount for further decreased superheat. The Series I data for the smooth surface exhibits less scattering, and the same trend is observed with the exception that the peak frequency occurs somewhat higher at roughly 160°C.

In summary, the data indicate that as surface superheat gradually decreases, the liquid contact time fraction increases steadily. At high superheats, liquid contacts on the heated surface are infrequent and are of short duration resulting in a low value of $F_{L,t}$. Gradually, the copper block loses its sensible heat resulting in a breakdown of the film boiling regime. In the ensuing transition boiling regime, liquid contacts were more frequent and their residence times on the surface increased causing the contact fraction to increase. Eventually, $F_{L,t}$ approaches unity as the surface superheat nears zero and the block is quenched.
V. DISCUSSION OF RESULTS

5.1 Superheat Effect on Liquid Contact Phenomena

The data indicated that during the initial stages of the quenching process at relatively high superheats, liquid contacts were very short in duration and infrequent in occurrence. This resulted in a very low liquid contact fraction (typically 0.01 and less) and was true for both the glass boiling surface and copper boiling surface experiments. In this film boiling regime, the liquid near the wall became vaporized, covering the surface with a relatively stable film. If and when a liquid drop could break through to contact the surface, the high wall temperature caused the quick evaporation of the liquid, resulting in brief contacts of less than 1 msec. This initial breakdown of the vapor film occurred at 230°C to 195°C for the copper block and at 750°C to 650°C for the glass plate. The higher temperatures for the glass plate are a result of its poor thermal conductivity. At lower superheats, as experienced with the copper surface, the glass is unable to supply heat fast enough to the surface to maintain stable film boiling. It was therefore necessary to heat the glass plate to temperatures in excess of 750°C for film boiling to be observed.

Gradually, the surfaces began to lose the ability to quickly vaporize the liquid contacts as the surface superheat was lowered. This resulted in longer duration
contacts. The contacting liquid and subsequent vapor bubbles created a more rigorous boiling regime. This introduced greater instability in the vapor film and the frequency of liquid contacts also increased with decreasing superheat. This positive feedback effect lowered the surface temperature until the vapor film began to break down and transition boiling was encountered. The contact fraction increased to 0.1 as the surface superheat dropped from 190°C to 120°C in the copper block experiment. Similarly, for a 60°C decrease in superheat on the glass plate from 650°C to 590°C, the liquid contact fraction approached 0.1.

The glass surface eventually lost its ability to supply sufficient heat to the test location to expel the liquid contacts as the superheat dropped another 40°C. The longer duration contacts and higher frequency increased the liquid contact fraction to nearly 1.0. Eventually, the glass plate quenched when the surface superheat reached 525°C.

The copper boiling surface was able to supply heat faster to the test location because of a higher thermal conductivity than the vycor glass. The thermal conductivity of the copper block is 386 $\frac{W}{m^{\circ}C}$ at room temperature compared to a value of 1.4 $\frac{W}{m^{\circ}C}$ for the thermal conductivity of the vycor glass. A comparison of the thermal diffusivities for both materials shows that
copper diffusivity is 124 times that of the glass plate. Thus, the copper block was able to maintain a vapor film at much lower temperatures. The vapor film existed ninety percent of the time for a superheat of 120°C. The duration of liquid contacts increased to an average value of 3 msec at this superheat and the frequency was roughly 50 Hz. As the superheat dropped further, the copper surface was no longer able to supply enough heat to quickly evaporate the contacting liquid. The slower evaporation rate resulted in a slight decrease in frequency of contacts but the greater residence times on the surface caused $F_{L,t}$ to increase. The high heat transfer rate to longer duration contacts lowered the superheat down to roughly 25°C where finally quenching occurred.

The general trend was for liquid contact duration to increase steadily as the surface lost the thermal potential necessary to evaporate contacting liquid droplets. This was true for both boiling surfaces. The general trend exhibited for frequency of contacts was to increase as superheat decreased to a value near the quenching temperature. A slight drop in occurrence of contacts occurred when the superheat dropped further. An explanation of this could be that before contacting liquid droplets could be vaporized, other droplets also contacted the surface and combined to be measured as an
individual contact. The surface condition could also play an important role in this occurrence and will be discussed further in the following section.

5.2 Surface Condition Effect on Liquid Contact Phenomena

Thermocouple traces for typical quenching runs on the smooth and oxidized copper surfaces are shown in Figures 4.21 and 4.22. The effect of the oxidization was to steepen the temperature history profile which lowered the time before quenching occurred. A modified inverse heat conduction computer program developed by Lee (18) was used to construct boiling curves (Fig. 5.1) from the temperature history during a complete quench. The results indicated a slight shift in the boiling curves. This is consistent with data from Berenson (3) shown in Figures 5.2 and 5.3. The critical heat flux value is not greatly affected, only the superheat at which it occurred. The values obtained for CHF in this study were roughly $2 \times 10^6$ W/m$^2$ which are consistent with those found in the literature (25,26). Of special importance is the fact that the minimum heat flux or minimum film boiling temperature and the film boiling region are essentially independent of surface roughness in Berenson's experiment. The data obtained in this study support this viewpoint. Liquid contact fraction
Fig. 5.1: Boiling curves obtained from thermocouple traces for copper-water boiling system.
Fig. 5.2 Copper-pentane test results: effect of roughness.

From Berenson (24)

Fig. 5.3 Inconel-pentane test results: effect of roughness.
Fig. 5.2 Copper-pentane test results: effect of roughness.

From Berenson (24)

Fig. 5.3 Inconel-pentane test results: effect of roughness.
data at high superheat (in film boiling) are similar for smooth and oxidized surfaces. At lower superheats, the smooth surface allowed a higher liquid contact fraction than the oxidized surface at comparable superheat. The average duration was likewise affected at only lower superheats. The frequency data are scattered for the oxidized copper surface and somewhat less scattered for the smooth copper surface and the glass plate. These results suggest that the surface condition greatly affects liquid contact phenomena in pool boiling experiments and further studies are needed to fully examine these effects.

5.3 Time and Area-Average Contact Fraction

Liquid contact fraction data appear as either time fraction or an area-averaged fraction. The liquid contact time fraction $F_{L,t}$ can be defined as:

$$F_{L,t} = \frac{\text{total duration of all liquid contact}}{\text{total time elapsed in sampling period}} \quad (5.1)$$

This time fraction is observed at a local measurement point on the boiling surface during a sufficient large sample period in quasi-steady or steady-state conditions. In this experiment, the high thermal capacity of the copper block allowed quasi-steady conditions and all measurements are liquid contact time fraction.

An alternative to the time fraction is the liquid contact average area fraction, $F_{L,a}$, which can be defined as:
The area fraction is measured over a sufficiently large and homogeneous area.

Conceptually, the two liquid contact fractions are different but can be shown to be equal for a given boiling system. A liquid contact function $f$ can be defined for the system such that $f$ is a function of position and time, $f = f(r,t)$ for constant system properties and conditions. The time fraction can be now defined as:

$$F_{L,t}(R) = \frac{\int_0^\tau f(R,t)dt}{\int_0^\tau dt}$$  \hspace{1cm} \text{(5.3)}$$

where $\tau$ is the sample period at location $R$.

Similarly, the area fraction is defined as

$$F_{L,a}(T) = \frac{\int_{R_0}^{R_0} f(r,T)dr}{\int_{R_0}^{R_0} dr}$$  \hspace{1cm} \text{(5.4)}$$

for the measurement area $R_0$ at time $t=T$.

For a uniform surface and quasi-steady or steady state conditions, $F_{L,t}$ cannot be a function of position and $F_{L,a}$ cannot be a function of time. Therefore, equation 5.3 and 5.4 can be rewritten as:

$$F_{L,t}(R) = F_{L,t}(R+\Delta r) = \frac{\int_0^\tau f(R+\Delta r,t)dt}{\int_0^\tau dt}$$  \hspace{1cm} \text{(5.5)}$$
\[ F_{L, r}(T) = F_{L, a}(T + \Delta t) = \frac{\int_{R_0}^{R_o} f(r, T + \Delta t) dr}{\int_{0}^{R_o} dr} \quad (5.6) \]

Since \( \Delta r \) and \( \Delta t \) can assume any value, equations 5.5 and 5.6 are reduced to

\[ F_{L, r}(R) = F_{L, r}(r) = \frac{\int_{0}^{\tau} f(r, t) dt}{\int_{0}^{\tau} dt} \quad (5.7) \]

\[ F_{L, a}(T) = F_{L, a}(t) = \frac{\int_{0}^{R_o} f(r, t) dr}{\int_{0}^{R_o} dr} \quad (5.8) \]

Integrating the numerator and denominator of equation 5.7 over total measurement area yields:

\[ F_{L, r}(R) = \frac{\int_{0}^{\tau} \int_{R_0}^{R_o} f(r, t) dr dt}{\int_{0}^{\tau} \int_{R_0}^{R_o} dt dr} \quad (5.9) \]

Similarly for equation 5.8 over total time yields:

\[ F_{L, t}(T) = \frac{\int_{0}^{\tau} \int_{0}^{R_o} f(r, t) dr dt}{\int_{0}^{\tau} \int_{0}^{R_o} dr dt} \quad (5.10) \]

Therefore, \( F_{L, r}(R) = F_{L, t}(T) \) for a quasi-steady state system with a uniform surface. This allows comparison of contact area fraction and contact time fraction measurements for a given superheat when sufficiently large sample areas and sample time periods are used.
5.4 Comparisons with Previous Investigations

There have been few actual measurements of liquid contacts on a heated surface in high temperature boiling experiments. The liquid contact data obtained by Yao and Henry (12, 13) is from a gold-plated copper surface and the contact fraction is normalized with the Taylor instability wavelength for this system. Direct comparison with this data is difficult, however, the same general trends exist for the present study and the gold-plated surface experiment. Yao and Henry's data, although somewhat scattered (Fig. 2.1 and 2.2), indicated the normalized area fraction and duration times increased as the interface temperature decreased.

Liquid contact time fraction data from Ragheb and Cheng (14, 15) are shown in Figure 5.4. This data is from flow boiling experiments using a zirconium probe. The vapor film in the film boiling regime is likely to have different characteristics (thickness, stability, etc.) for pool boiling and flow boiling experiments. This is a possible explanation for the difference in results obtained in this study.

The data from Lee (18) were obtained under conditions very similar to those used in this study. Lee was able to plot liquid contact fraction, duration,
Fig. 5.4: Measured wetted area as a function of wall temperature
Fig. 5.4: Measured wetted area as a function of wall temperature
and frequency as a function of the average surface superheat using a microthermocouple probe. The pool boiling experiment were performed on a similar copper block with varying surface roughness.

The $F_{L,t}$ data from Lee (18) is plotted in Figure 5.5. Comparison with data obtained in this study reveal that lower contact fractions were obtained using the thermocouple probe as opposed to the fiber optic probe under similar superheats. One reason for this may be that the response time of the thermocouple probe was not sufficiently fast and the signal could not recover quick enough to record all contacts. Another explanation is the superheat temperatures used in Lee's data is actually an average value taking into account the lowering of surface temperature due to liquid contacts. The superheat temperature in this study did not include the temperature drop associated with transient liquid contacts. The thermocouple used in this study was not capable of detecting the individual contacts and produced a steadily decreasing temperature trace for the quenching process (Figs. 4.21, 4.22). By using a lower average surface temperature, the $F_L$ curve will be shifted to the left which is the case in Lee's data compared to the present data.
Fig. 5.5: Comparison of Liquid Contact Fraction
Initial contacts were first detected in the present experiment at temperatures around 230°C. Baumeiser, et al. (27) proposed a correlation to predict the Leidenfrost temperature, which is the limiting temperature below which liquid contacts can occur. This correlation predicts temperatures ranging from 170°C to 225°C depending on the fluid and boiling surface properties. The data obtained here were in general agreement with this correlation and those obtained by Lee.

The average duration of contacts and frequency of contacts of this study compare favorably with those obtained by Lee. Generally, data from both probes indicated that the average duration of contacts increased monotonically with decreasing superheat. Frequency also steadily increased as the surface superheat dropped until reaching a maximum value and then slightly decreasing as superheat further decreased. The frequency data obtained on the copper surface were considerably more scattered than the data taken on the glass surface. It appears that for smooth surfaces, frequency of contacts follows a more general trend than that of fully oxidized surfaces. Data from Lee support this viewpoint, indicating that surface finish plays an important role in liquid contact behavior.
The discrepancies between the data obtained in both studies which measured the effect of surface aging could be explained as a result of the growth of an oxide layer on the surface. The oxide possessed a thermal conductivity much less than that of the copper block. The thermocouple probe senses the presence of liquid contacts as a sudden drop in surface temperature. The poor conduction through the oxide layer could prevent the transient temperature drop from penetrating through to the probe tip, resulting in erroneous liquid contact data. The fiber optic probe inherently measured the presence of liquid or vapor at the surface and was not adversely affected by the growth of the oxide layer.

Kalnin, et al. (28) have attempted to empirically correlate liquid contact fraction and wall temperature. The total surface heat flux in the transition boiling regime is composed of:

\[ q_{\text{total}} = f_L (q_{\text{NB}}) + (1-f_L) q_{\text{FB}} \]  

(5.11)

and

\[ f_L = \frac{q_{\text{total}} - q_{\text{FB}}}{q_{\text{NB}} - q_{\text{FB}}} \]  

(5.12)

where \( q_{\text{NB}} \) represents the nucleate boiling heat flux and \( q_{\text{FB}} \) is the film boiling heat flux. The fraction of the wetted surface is represented by \( f_L \). It is
possible to obtain values of $q_{NB}$ and $q_{FB}$ from existing correlations and $q_{total}$ could be obtained from experimental data in the transition boiling regime. Therefore, one could derive the expression of $f_L$ in terms of the wall temperature, and the corresponding temperatures at the minimum and maximum heat flux. However, the correlation assumes that $q_{NB}$ and $q_{FB}$ can be extrapolated into the transition regime which may not be the case.

Tong and Young (29) proposed a similar correlation for flow boiling systems assuming $q_T$ is composed of the sum of the transition boiling heat flux $q_{TB}$, and the film boiling heat flux $q_{FB}$. Later, Tong (30) suggested that the contact fraction could be derived from:

$$f_L = \frac{q_{TB}}{q_{NB}} \quad (5.13)$$

The nucleate boiling heat flux was taken to be the critical heat flux. The correlations of Kalnin and Tong have been plotted along with the data of Ragheb and Cheng in Figure 5.4. Good agreement exists between Tong's correlation and the data obtained in this present investigation. The fiber optic probe could be used in a similar flow boiling system to better test these correlations.
VI. CONCLUSIONS

The applicability of optical techniques to detect liquid-solid contact on a heated surface was demonstrated in the glass boiling surface experiment. A fiber optic probe, based on the same principles, was then developed to provide quantitative measurements of liquid contact phenomena in pool boiling experiments on a copper surface. The probe proved to have a sufficient response time for measuring liquid contacts and demonstrated exceptional durability when exposed to hostile boiling conditions. The following conclusions can be made from the present study:

1. Stable film boiling and no liquid contact was observed on the copper surface with surface superheats greater than 230 °C. The glass surface required substantially higher superheats in order to achieve a stable film due to poor conductivity through the glass plate.

2. The liquid contact fraction, average duration, and frequency generally increased monotonically as the wall temperature decreased for both the glass and copper surfaces.

3. Surface condition greatly affected liquid contact behavior and heat flux in the copper block experiment. The liquid contact fraction and
average duration was affected more so in the transition boiling regime than the film boiling regime.  

4. Comparisons with existing results showed good agreement in the general trends exhibited for contact behavior as a function of surface superheat. It is recommended for future studies that the fiber optic probe be used in flow boiling systems to determine the characteristics of the film and transition boiling regimes. Information could be obtained to better predict the behavior of high temperature surfaces during rewetting and reflooding conditions.

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References


APPENDIX - Analysis of Errors and Uncertainties

There were basically two types of errors encountered in this study. First, there may be certain fixed or systematic errors in the probe system and associated data collection equipment. The second type are random in nature and may occur in the apparatus and instruments (i.e. electrical noise).

The surface temperature measurement contained systematic errors due to the presence of the thermocouple and fiber optic probe in the copper block. Care was taken to minimize these errors by using as small as possible fiber optic probe and thermocouple. In addition, the thermocouple was brazed flush onto the surface and did not disturb the surface homogeneity as much as the fiber probe. Errors due to the presence of inhomogeneities within the block are relatively small compared to the surface inhomogeneities. Beck(31) studied the effect of an imaginary void and the uncertainty was typically +/- 3%.

The fiber optic probe was considerably smaller than the average liquid droplet which contacts the surface resulting in a relatively small disturbance by the probe. The uncertainty of the measured contact fraction could be taken as +/- 5% due to the presence of the optic probe at the surface. It was
imperative that the fiber probe be mounted exactly flush with the surface otherwise readings could be erroneous. This is because the vapor film in the film boiling regime is quite small and was measured to be only 0.05 mm by Iida (32). When the probe was mounted slightly higher than the surface, it introduced atypical disturbances in the vapor film and would detect erroneous liquid contacts.

The response time of the thermocouple may have affected results taken at lower superheats. In the film boiling regime, the block temperature dropped slowly and the thermocouple could sufficiently respond in this quasi-steady state region. However, the time constant is directly related to the surface heat flux and in deep transition boiling (preceeding CHF), the thermocouple reading may have lagged behind the actual block temperature.

These uncertainties are tolerable for the measurement of liquid contact behavior which is somewhat random in nature.
VITA

Timothy Butrie was born January 18, 1960 in Palmerton, Pennsylvania. He is the son of Nicholas and Margaret Butrie of Lansford, Pennsylvania and is the middle of five children. During his childhood, he attended Saint Michael's Grade School. From there he went to Panther Valley High School where he graduated as an honor student in June 1977.

Both his Bachelor's and Master's degrees were attained at Lehigh University. The years 1977 through 1981 he spent as an undergraduate. During those years he was elected a member of Pi Tau Sigma Honorary Mechanical Engineering Society, Tau Beta Pi National Engineering Honor Society and was a student member of the American Society of Mechanical Engineers. From 1981 until 1983 he attended Graduate school on a fellowship granted him by Lehigh University. Upon graduation he will be a member of the technical staff at Bell Laboratories.