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PROGRESS REPORT
HIGH FLUX FILM AND TRANSITION BOILING

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The following is a summary of the important results that have been obtained during the initial phase of the research program. More details are given in Sankaran and Witte (1990a, 1990b).

Experimental Apparatus

Figure 1 shows a layout of the flow loop developed to produce steady, low temperature flows over an electric heater. Liquid velocity was controlled by a variable speed 450 gpm pump (1). The flow passed through various flow straightening sections (4-7) before passing through the transparent plexiglas test section (8) across which the heater was suspended. A water-cooled Filtrine POC-500 W chiller (13) of 16 kW cooling capacity was used to maintain the flowing coolant at the desired temperature. Working fluids temperatures down to 0 C were possible with the use of this chiller.

Flow rates which were used to calculate flow velocities in the test section were measured with an annubar element (3). A pitot tube traverse across the test section was used to verify that the calibration curve of the annubar was accurate. The pitot traverse also verified that the velocity profile was basically flat across the test section. Thermocouples (18) and pressure taps were installed at various points in the loop to yield the operating conditions of the working fluid.

Figure 2 shows a cutaway view of the electric heater. It was 0.635 cm in diameter and consisted of a thin-walled Hastelloy C outer heating shell (0.04 mm thickness) fitted over a machined lava insert. The lava insert provides for structural rigidity as well as

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Fig. 1. Schematic layout of the flow loop - chiller.

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Fig 2.a Cutaway view of the electric heater

Fig 2.b Schematic showing the mounting of the heater in the test section.

1, 2.	Outside thermocouples.
3, 7.	End thermocouples.
4.	Center thermocouple at 90 degree location.
5.	Center thermocouple at the lower stagnation point.
6.	Center thermocouple at the upper stagnation point.

additional thermal mass. It also served as the vehicle for situating five 38 gage chromel-alumel thermocouples at various strategic locations adjacent to the heating surface as shown in Figure 2.

The manner in which the heater was mounted through the test section wall is also shown in Figure 2. Two thermocouples were mounted on the bus bars outside the test section wall; they were used to estimate the end losses of the heaters during operation. The heat losses through the ends of the heater were less than 2% of the total heat dissipated even for the highest heat fluxes encountered.

Power was supplied to the heater by a Electroquip dc motor-generator set capable of providing up to 1500 amps of electric current. Diesel locomotive cables (3/0, 450 wire strand) connected the heater to the motor-generator set. The energy being dissipated in the heater was found by simultaneous measurements of voltage and current provided to the heater.

Experimental Conditions

Table 1 shows the range of conditions over which experiments were performed for Freon-113. It was found that the velocity was limited to about 3.8 m/sec with this apparatus. Above the flow rate corresponding to this velocity, large vibrations were imposed on the flow loop by the motor/controller combination. Only nucleate boiling data up to the critical heat flux could be obtained with this apparatus for water. Heat fluxes were so high that upon undergoing transition to film boiling, the heaters would burnout in highly subcooled water. Consequently, most of the discussion will be restricted to Freon-113 data, with a short discussion about how water and Freon-113 compared in the nucleate boiling region.

An error analysis showed that heat flux could be determined to within $\pm 3\%$, while the temperature accuracy is estimated at ± 1.5 C in T_{bulk} , and $< 2\%$ in T_{heater} . Velocity in the test section could be determined to within $\pm 3\%$.

Visual Observations of the Boiling Phenomena

A very important part of this study was to determine the flow patterns that occur when various boiling regions are encountered. This information can be used to gain insight into how the processes might be modelled. In addition to naked eye observations, a Spin Physics SP-2000 Motion Analyzer System was used for motion picture analysis while a Nikon still camera was used to capture various flow region information.

At very high subcoolings not much net vapor is produced around the heater, regardless of the boiling region. Bubbles quickly condense as they move away from the

hot surface, while vapor film regions that occur during film boiling are kept very thin by the influence of subcooling.

TABLE 1
RANGE OF OPERATING CONDITIONS
FREON-113

<u>Set No.</u>	<u>Velocity</u>	<u>T_{sat}</u>	<u>Subcooling</u>
1	2.95 m/sec	60.0 C	50.0 C
2	2.95	61.0	51.0
3	2.95	59.5	54.5
4	3.53	65.5	58.6
5	3.81	68.1	57.6
6	3.53	65.5	57.0
7	2.95	60.0	56.5
8	2.95	60.0	55.6
9	2.95	59.5	49.3
10	2.95	61.0	42.0

Nucleate Boiling: At low heat fluxes, no boiling was present and non-boiling forced convection correlations compared well with the experimental data. As the heat flux was increased and the surface temperatures increased well beyond the local saturation temperatures, nucleate boiling ensued. Bubbles were observed being formed on the surface and being swept around the periphery of the heater. A wake was formed, but it was a wake that consisted primarily of liquid rather than primarily of vapor as is the case for nearly saturated boiling, as described by Lienhard and Eichhorn (1976) and Ungar and Eichhorn (1988). Figure 3 is a sketch of the heater that shows how bubbles were swept away from the cylinder surface near the 90-degree line on the heater.

Film Boiling: The first appearance of film boiling on the heater was somewhat random; in some cases it began on the ends of the heater and in other cases a small film boiling patch developed on the top of the cylinder as sketched in Figure 4. As heat flux was increased slightly, film boiling would ensue on the top of the cylinder near the ends. These film boiling patches increased in size as heat flux was increased, eventually covering the entire heater surface, top and bottom. It was clear that even for the conditions of high subcooling

Fig. 3. End view of heater showing the pattern of bubbles being swept from the heater during nucleate boiling.

Fig. 4. Side and end view showing how bubbles and a film boiling patch can coexist on the heater.

Fig. 5. End view during film boiling.

encountered in these experiments, film and nucleate boiling could coexist on the heater surface. These regions were separated by transition "fronts" which took on a significantly different appearance than nucleate or film boiling. The region near the front was characterized by the production of many small bubbles that were rapidly diffused into the surrounding liquid.

Film boiling for all these high velocity, high subcooling experiments showed a much thinner wake, more like a tear drop, than the nucleate boiling wake, as sketched in Figure 5. An oscillating separation line was observed slightly past the 90-degree point on the heater, also shown on Figure 5.

Once film boiling was established and the heat flux was decreased slowly, the vapor film would begin to collapse on the bottom of the heater which was colder than the top which was covered by the wake. The collapse was characterized by the disappearance of the liquid-vapor interface at the lower stagnation point of the heater. A transition front as described previously separated film from nucleate boiling, and it was characterized by accentuated bubble activity as described before. The situation of film boiling on the top of the heater and nucleate boiling on the bottom was highly stable and could be (and was) maintained for several hours in some experiments. As heat flux was decreased further the film boiling on the top of the heater collapsed in a patchy manner leading to complete nucleate boiling on the heater.

Heat Transfer Results

It is logical to assume that the bottom of the heater should always be colder than the top of the heater because the cold liquid comes into contact with the heater at the lower stagnation point, and a thermal boundary layer of sorts develops as the liquid moves around the heater. While in general this was always the case for both film and nucleate boiling, some unexpected behavior of the temperatures was observed.

Nucleate Boiling:

The effect of subcooling - The top and bottom thermocouples behaved differently as the subcooling was varied for a given velocity. At the center of the heater (midway across the test section) the bottom, middle and top thermocouples refer to the bottom stagnation point (TC 5 in Fig. 2a), the 90-degree point (TC 4) and the top stagnation point (TC 6) respectively in the discussion that follows. Two "end" thermocouples (TC 3 and 7) were mounted 0.5 inches (1.27 cm) from the ends of the active heater length, as shown in Figure 2a.

Figures 6 and 7 show the influence of subcooling on the behavior of the thermocouples for different heat fluxes in the nucleate boiling region up to the peak heat flux. At the intermediate subcooling level, 49.5 C, as shown in Figure 6, the

Fig. 6. Nucleate boiling curves for 49.5 C subcooled Freon-113.

Fig. 7. Nucleate boiling curves for 57.0 C subcooled Freon-113.

thermocouples behaved as one might expect; i.e, a consistent increase in temperature up to the peak heat flux point.

However, at the highest subcooling level, 57 C (Fig.7), the bottom and middle thermocouples showed an unexpected decrease in temperature as the peak heat flux was approached. Such a decrease obviously means that the heat transfer coefficient over that thermocouple location must have increased dramatically with heat flux because of the constant heat flux condition at the surface. This could be explained by a dramatic increase in the population of bubbles at this transition point. However, as stated in the previous section, there was no visual evidence that such an increase in the bubble density occurred at these transition points. Many tests for repeatability of this temperature behavior were made to insure the integrity of the measurement system. In all cases the data were repeatable.

Such behavior has been observed in other nucleate boiling systems. Jung and Bergles (1989) observed this type of behavior for saturated Freon-113 boiling from plain, polished, electrically-heated copper tubes as well as from "enhanced" tubes, such as Gewa-T tubes. This behavior is attributed to the suppression of nucleate boiling up to wall temperatures typical of well-developed nucleate boiling, followed by a sudden onset of nucleate boiling as heat flux is increased. The literature related to cooling of electronic cooling by immersion boiling is also filled with references to the "temperature overshoot" problem, see for example, Anderson and Mudawwar (1988) and Bergles and Kim (1988). It is possible that such a phenomenon is occurring in our experiments but the population of bubbles at the conditions of very high subcooling is so small that changes are visually undetectable.

Figures 6 and 7 also show the correlation of Churchill and Bernstein (1977) for forced convection heat transfer from a cylinder in crossflow for comparison. The curve is extended past the saturation temperature of Freon-113 to show how the heat fluxes increase as bubbles are nucleated.

The intent of our investigation was to see what the influences of very high velocity and subcooling were on the boiling curves, so a wide range of velocities were not used in these tests. Instead, we were interested in producing the largest velocity possible with our apparatus. For Freon-113, that limit was about 3.8 m/sec.

Film Boiling: Azimuthal temperature differences were more pronounced in the film boiling region than in the nucleate boiling region. In film boiling, the top could be more than 115 C hotter than the bottom of the heater. Extensive experiments were carried out at 2.95 m/sec at different subcooling levels, and the effect of velocity was measured at a subcooling of 58 C.

The Effect of Subcooling - Figures 8 and 9 show the effect of subcooling at 2.95 m/sec. Near q_{min} , the temperature differences between the top and bottom decreased. As the heat flux was decreased slowly, the vapor film collapsed on the bottom and film boiling prevailed at the top as described previously. Thus, at the top the temperatures remained high typical of film boiling, while the bottom and center did not immediately fall all the way into the range typical of nucleate boiling. Rather, as seen in Figure 9, for example, the temperatures arranged themselves in decreasing temperature from hottest at the top to coldest at the bottom. Thus we see discontinuities in the bottom and middle thermocouple readings, as shown on Figure 9, prior to the entire surface being enveloped in nucleate boiling. The simultaneous existence of film and nucleate boiling on the surface affects the temperature that can exist at the bottom and middle thermocouples locations even though it is clear that film boiling no longer exists over those thermocouple locations. The middle thermocouple reads a higher temperature than the bottom one because it is closer to the film boiling patch at the top of the heater.

Chang and Witte (1988) observed similar behavior for an electric heater in flowing Freon-11 using a single surface thermocouple designed to detect liquid-solid contact during film boiling. In their experiments, which were for very low levels of subcooling, they observed curious intermediate jumps from film boiling temperatures down to a much lower temperature but not down to the ultimate nucleate boiling temperature range as the heat flux was decreased. They speculated that this must be a stable operating point that could be supported because of the existence of different boiling regions on the surface of the heater. The present results now show more clearly that this is indeed what is happening.

The existence of different regions of boiling in close proximity on a surface can produce discontinuities in temperature at a particular location as the heater goes through the process of transition from film to nucleate boiling. And these are not unstable points because tests for repeatability show that these points can be created either by increasing or decreasing the heat flux. Both the data of Chang and Witte and our experiments verify this.

Whether or not these intermediate temperature points represent a form of transition boiling or true nucleate boiling could not be ascertained from our visual observations, and remains to be investigated.

The Relationship of q_{max} to q_{min}

Figure 10 is a plot of the observed ratio of q_{min} to q_{max} in terms of subcooling for various velocities. The data of Yilmaz and Westwater (1980) at very low subcooling levels are shown for comparison. This plot summarizes the effect that we set out to investigate - i.e., whether or not high levels of subcooling and velocity could bring the two

Fig. 8. Boiling data showing nucleate and film boiling data for 49.5 $^{\circ}\text{C}$ subcooled Freon-113. (Nucleate boiling data same as Fig. 6.)

Fig. 9. Boiling data showing nucleate and film boiling data for 58 $^{\circ}\text{C}$ subcooled Freon-113.

Fig. 10. The influence of subcooling on the ratio of minimum to peak heat flux.

Fig. 11. Nucleate boiling data for subcooled water showing the hysteresis between increasing and decreasing heat flux.

transition points closer together. It is clear that subcooling has a dramatic effect in this regard, as our data clearly show the trend toward unity as subcooling is increased. Although our experiments did not cover a wide range of velocities, it seems clear that subcooling has a much more profound influence on the ratio of $q_{\min}$ to $q_{\max}$ than does velocity.

Nucleate Boiling of Highly Subcooled Water

Steady state film boiling could not be maintained with water at the subcoolings of interest in our research. Four heater assemblies were destroyed (burnt out) because of the very high temperatures attained as film boiling ensued. The highest steady state nucleate boiling heat flux attained was 11.6 MW/m^2 , with 17.8 kW (897 amps at 19.88 volts) of power dissipation in the heater. The heater surface temperatures were around 300 C, and upon further increase in heat flux, the heater was destroyed.

Figure 11 shows one set of nucleate boiling data for water at 93 C subcooling and 2.98 m/sec velocity. The data demonstrate the same type of behavior as Freon-113, with the temperature overshoot existing for the thermocouples on the lower parts of the heater. Figure 11 also shows that upon decreasing the heat flux in contrast to increasing it, a hysteresis occurs. This is very similar to what happens in pool boiling systems.

It is clear that water and Freon-113 demonstrate similar behavior in the nucleate boiling region even though the heat fluxes in water are at least an order of magnitude higher than for Freon-113. However, the inability of the current apparatus to achieve film boiling without burnout prevented the determination of the ratio of $q_{\min}$ to $q_{\max}$ for highly subcooled water.

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