Portland State University

PDXScholar

Dissertations and Theses

Dissertations and Theses

1991

Transient heat transfer

Eric Roth

Portland State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/open_access_etds

Part of the [Physics Commons](#)

Let us know how access to this document benefits you.

Recommended Citation

Roth, Eric, "Transient heat transfer" (1991). *Dissertations and Theses*. Paper 4264.

<https://doi.org/10.15760/etd.6148>

This Thesis is brought to you for free and open access. It has been accepted for inclusion in Dissertations and Theses by an authorized administrator of PDXScholar. Please contact us if we can make this document more accessible: pdxscholar@pdx.edu.

AN ABSTRACT OF THE THESIS OF Eric Roth for the
Master of Science in Physics presented May 17, 1991.

Title: Transient Heat Transfer.

APPROVED BY THE MEMBERS OF THE THESIS COMMITTEE:

Erik Bodegon, Chair
Jack Semura
Bijan Shahir
Carole Gatz

With the advent of the new high T_c superconductors, liquid nitrogen will be one of the preferred cryogens used to cool these materials. Consequently, a more thorough understanding of the heat transfer characteristics of liquid nitrogen is required. In our investigations we examine the

transient heating characteristics of liquid nitrogen to states of nucleate and film boiling under different liquid flow conditions. Using a platinum hot wire technique, it is verified that there is a premature transition to film boiling in the transient case at power levels significantly lower than under steady state nucleate boiling conditions. It is also shown that the premature transition can be reduced or eliminated depending on the flow velocity.

TRANSIENT HEAT TRANSFER

by

ERIC ROTH

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
PHYSICS

Portland State University
1991

TO THE OFFICE OF GRADUATE STUDIES:

The members of the Committee approve the thesis of Eric Roth presented May 16, 1991.

[REDACTED]

Erik Bodegom, Chair

[REDACTED]

Jack Semura

[REDACTED]

Bijan Shahrir

[REDACTED]

Carole Gatz

APPROVED:

[REDACTED]

Mark Gurevitch, Chair, Physics Department

[REDACTED]

C. William Savery, Interim Vice Provost
for Graduate Studies and Research

ACKNOWLEDGEMENTS

The culmination and success of this work is largely due to the efforts of people other than myself. At this time I would like to thank those that have had a large influence on my indoctrination and socialization as physical scientist. First, I would like to thank my advisor, Dr. Erik Bodegom for his help in all facets of my education in the laboratory. His patience with the lab neophyte who scarcely knew the difference between an op-amp and an oscilloscope was appreciated. Also his knowledge of both experimental and theoretical concerns provided a broad base for me to draw on and gave me a wider scientific perspective. More importantly though, his perspective and sense of humour about our projects (and life in general) kept things interesting and animated even when the experiments were not developing as we would have liked.

As the veteran experimentalists in the lab, Dr. Laird Brodies insight and skepticism into the techniques and results of my work kept me thinking and honest.

As our labs "resident theoretician" Dr. Jack Semura provided enthusiasm, new ideas and perspectives on projects. It would be fair to say he introduced "chaos" to our lab!

Lastly, I would like to thank the Science Support Shop for building and repairing many of the apparatuses used in

the experiments. Specifically, Brian McLoughlin and Lee Thannum for help and instruction in the electronics (Brian must have replaced at least one transistor for each device that I even thought of turning on); and Rudi Zupan and Garo Arakelyan for their skills in machining and constructing the mechanical devices.

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENTS	iii
LIST OF FIGURES	vi
CHAPTER	
I INTRODUCTION	1
II BASIC HEAT TRANSFER CHARACTERISTICS	4
III EXPERIMENTAL PROCEDURE	7
IV ANALYSIS OF DATA	15
V RESULTS AND DISCUSSION	17
VI CONCLUSION	32
REFERENCES	33

LIST OF FIGURES

FIGURE	Page
1. Circuit Schematic	10
2. Superheat Temperature ΔT vs. Time, with no Forced Convection.	18
3. Superheat Temperature ΔT vs. Time, with no Forced Convection	20
4. Superheat Temperature ΔT vs. Time, with Forced Convection	23
5. Heat Flux Q vs. Time, with no Forced Convection	24
6. Heat Flux Q vs. Time, with Forced Convection	25
7. Superheat Temperature ΔT vs. Time, with Forced Convection	27
8. P_v/P_{nbhf} vs. wire velocity	28

CHAPTER I

INTRODUCTION

With the discovery of the new high T_c superconductors, as well as the increasing use of cryo-cooled conventional electronics, the use of liquid nitrogen as a coolant could expand significantly. The reason for this is twofold. First is that the new ceramic superconductors have transition temperatures around 120 Kelvins, and for these superconductors to have electrical characteristics that are relatively stable with respect to temperature variations they need to be cooled to values approximately two thirds of its transition temperature. Therefore a fluid that has its boiling point approximately at two thirds of this temperature is necessary¹. Liquid nitrogen (LN2) has a normal boiling point at 1 atmosphere of 77 K so it satisfies that requirement. Second, it has been found that many conventional semiconductor devices have enhanced electrical performance when cooled to cryogenic temperatures. Such enhancements include faster switching speeds, lower noise levels, and greater reliability². Also, there are a number of reasons why LN2 is to be the preferred cryogen to both technologies. One is the fact that LN2 is a good dielectric thus preventing any undesirable electrical interactions with the electronic apparatus being cooled. Two,

LN2 is chemically inert, so that there is little worry that the LN2 will degrade the devices that it cools. Lastly, compared to other cryogenics there is a virtually unlimited supply of nitrogen and it is generally the least expensive and one of the most widely used cryogenics in industry.

Therefore, assuming LN2 as the optimal cryogenic coolant, a qualitative as well as quantitative knowledge of its heat transfer characteristics is required. Thus knowing the answer to the following questions are essential. How much heat will the LN2 need to carry away and what is the maximum allowed internal temperature of the device? These factors will have different importance for conductors, superconductors, and semiconductors. For example, typically one does not expect superconductors to generate any heat as they have no electrical resistance. However, in a type 2 superconductor magnetic flux lines (fluxoids) penetrate into the superconductor, and as a result of their inevitable motion generate heat. At this point or region where the fluxoid moves there will be some small amount of heat generated. Another source of heat generation is due to the extreme mechanical stresses occurring in say, a superconducting magnet assembly. What is critical is that this heat be conducted away before it causes a local temperature rise of the superconductor above its transition temperature. Otherwise, the material would become resistive and the resultant Joule heating could destroy the device. For many applications, the

surrounding structure is sufficient to conduct the heat away efficiently as the average power generation is low, but it is very important that the local temperature not exceed the critical temperature of the superconductor. Conversely, for conventional semiconductor chips the power generated can be quite high. In fact one of the limiting factors in going to higher chip densities or higher speeds is the problem of dissipating sufficient amounts of heat so that the chip does not overheat and fail ³.

The purpose of this project is to examine some of the important characteristics for obtaining the efficient transfer of heat from a solid into LN2 and to determine if there is a significant distinction between steady state and transient heating conditions. A distinction was found by one group of researchers and not by another⁴. Some of the issues addressed are: how much can the liquid be superheated before film boiling occurs and how much heat flux can the liquid allow before going into film boiling ? In the next chapter these terms will be defined and explained.

CHAPTER II

BASIC HEAT TRANSFER CHARACTERISTICS

Heat transfer is known to occur in several modes. These different modes are conduction, convection, boiling, and radiation. Conduction heat transfer is due to the interatomic interaction of molecules, ie. sharing of energy through collisions when there is a temperature gradient across it. This can occur in any type of material. Convection is a form of conduction that can only occur in a fluid (gas or liquid) in a gravitational field. This occurs when a temperature gradient causes the density of the fluid to be different in different parts of the fluid. This fluid density imbalance is the driving force for the mixing of the fluid. Heat transfer is thus enhanced over straight conduction conditions. However, it is still an intrinsically conduction process. Boiling is fundamentally different in that its energy transfer occurs through the latent heat of vaporization of the fluid. That is, energy is removed from the hot surface when a vapor bubble is formed from the liquid and then is transported to a cooler environment where it collapses back into the fluid or is vented to the outside atmosphere. This is generally the most efficient form of heat transfer. However, each of these modes are dominant under different conditions, such as temperature,

temperature gradient, ambient pressure, type of fluid involved and so forth ⁵. For this study, since I am concerned with the first three modes, and in particular with boiling, radiation can be neglected. In this experiment the heat flux was measured from a platinum wire into LN2.

Actually, for boiling there are two regimes that occur. One is nucleate boiling and the other is film boiling. Heterogeneous nucleate boiling is commonly what one observes. Bubbles form at particular "nucleation sites" on the material, they grow in size and then detach themselves from the surface when the buoyant forces overcome the surface cohesion. Typically these "sites" are microscopic cracks and crevices in the material.

This is to be contrasted to homogeneous nucleation. It is known that a homogeneous liquid can withstand a certain amount of superheat (ie. heated above its normal boiling point) in the absence of external initiating influences, before a transition to the vapor phase takes place. This transition occurs when a sufficiently large number of vapor nuclei, induced by thermodynamic fluctuations in the liquid, can generate and grow spontaneously in the liquid. This causes the very rapid formation of many bubbles in the superheated liquid adjacent to the wire. This process of spontaneous initiation of nucleation restricts further increases in the temperature and is called homogeneous nucleation ⁶. Though this temperature at which this occurs is

not rigorously precise, the kinetic theory of homogeneous nucleation, predicts the nucleation rate to depend exponentially on parameters related to the degree of superheat ⁷. Thus in practice a relatively sharp superheat maximum is attained. For LN2 this temperature is 110 K at 1 atmosphere of pressure.

Film boiling is really just an extreme case of either heterogeneous or homogeneous nucleation. That is, the bubble formation on the surface of the material is occurring so rapidly that the bubbles do not have time to detach and be replaced by liquid. The result is that a film of vapor covers the surface and impedes further heat transfer due to the insulating effect of the vapor film.

In particular, some authors have found that for sudden step increases of power application the maximum allowed power before filmboiling occurs can be as little as 40% of the maximum applied power in which this power level is achieved by slowly increasing the power until film boiling occurs ⁸. This effect is called a premature transition to filmboiling.

Note however, that this phenomena has apparently not been observed by other investigators albeit under slightly different circumstances, so there is still some question as to the existence of this phenomena or under which specific conditions this phenomena occurs. This study seeks to resolve this question and investigate methods in order to reduce or eliminate this "premature" transition to filmboiling.

CHAPTER III

EXPERIMENTAL PROCEDURE

This experiment was conducted with two separate dewars at atmospheric pressure; one a large (30 liters) storage dewar, the other a long glass double dewar. In both dewars the heat leak small and consequently resulted in a very quiescent bath of LN₂. This condition may explain the reason Giarratano did not observe the premature transition.

The two primary physical quantities that had to be measured were the temperature and heat flux into the fluid. The method of heat generation and temperature measurement were accomplished by the same instrument by what is known as a hot wire technique⁹. The basis for this technique is essentially resistance thermometry, with the additional condition that the surface we use to measure the temperature is also the one that generates the heat flux into the fluid. In our case we used a thin (.1 mm diameter) platinum wire as our heater/thermometer. A brief explanation of resistance thermometry follows.

The electrical resistance is a well characterized property of a pure metal. In particular this property is a monotonically increasing function of the temperature and it typically has a linear dependence on the temperature over a narrow temperature range. However, some metals are more

strongly temperature dependent (ie. they possess a larger temperature coefficient) than others, and some are more linear in their dependence on temperature than others. The value of these properties determine the sensitivity with which the temperature can be measured and the ease in calibrating such a device. The metal we used was platinum, which is one of the most linear and has one of the largest temperature coefficients of the metals. At 77 K platinum's resistivity changes about 1% per degree. Platinum also has the advantage that its properties are very stable over time and it does not react readily with other substances. Since our temperature range of interest will exceed 77 K by no more than about 30 K, our method of calibration was just to take resistance measurements at these two temperature extremes and interpolate. The two end points can be conveniently chosen as the saturated bath temperature T_b , (77.3 K @ 1 atmosphere pressure) and the homogeneous nucleation temperature T_h (110 K @ 1 atmosphere). Frequently what one does is give the superheat temperature $\Delta T(t)$. This is just the temperature change about the normal boiling point (ie. for LN2,

$$\Delta T(t) = T(t) - 77.3 \text{ K}$$

What one does to calculate the temperature is to pass a known current through the material and simultaneously measure the voltage difference between two points of the "resistor" . From these measurements one calculates the resistance using Ohm's law. If the temperature changes as a function of time so

does the resistance of the material. If the temperature dependence of the resistivity is explicitly known, as is true for most pure metals and common alloys, one can calculate the temperature of the metal. Explicit formulas for this are given later.

Another consideration was since these measurements were to measure transient behavior of the temperature and heat flux, we had to make sure that the thermometer was able to track the temperature changes on the time scale of interest (of the order of tens of milliseconds.) That is, the heater thermometer had to be in thermal equilibrium with the fluid immediately surrounding it at all times. This thermal response time is a function of the material and its geometry, and is calculated by the following equation.

$$\tau = d^2 / \kappa \quad \text{where } \kappa = k / \rho c \quad (1)$$

Where d is a characteristic dimension of the material. In this case, the diameter of the wire. κ is the thermal diffusivity, k is the thermal conductivity, ρ the density and c the specific heat. For our platinum wire at 77 K is about 60 μ sec. Note that these thermophysical properties do change with temperature but that in our temperature range this only amounts to about 20% change in the time constant. The overall uncertainty in determining the temperature is estimated to be 0.5 K. The circuit schematic for the platinum heater/thermometer set up is shown in Figure 1.

Figure 1. Circuit Schematic. The resistor R_1 is the platinum heater/thermometer located in the dewar.

A pulse generator is connected to a current amplifier which is configured to supply a constant current to the platinum wire. In series with the platinum wire are two 100 W 0.25 ohm resistor. These resistors have a low temperature coefficient so as to minimize heating errors when reading the current. Instrumentation amplifiers 1 and 3 amplify the voltage $V_{Pt}(t)$ across the platinum wire R_1 , and the voltage V_I across resistor R_3 respectively. The temperature coefficient of platinum is small thus the majority of the measured signal of $V_{Pt}(t)$ is due to the temperature independent part of the resistance R_0 , and is called V_0 . Since we are only interested in changes about ambient (77 K) in order to get a signal reflecting only the temperature change, the constant portion V_0 must be electronically subtracted out from $V_{Pt}(t)$ to yield $\Delta T(t)$. This is accomplished by manually adjusting the gain from amplifier 2 so that the output of amplifier 4 is zero when no superheating has occurred. This balancing procedure is implemented when the platinum is known to be at 77 K as is the case at the very beginning of the heat pulse. The signals from amps 3 and 4 are then recorded on a digital oscilloscope. Then the digitized data is stored in the computer for further manipulation.

The equations to solve for the superheat temperature ΔT follow.

$$V_{Pt}(t) = V_0 + \Delta V(t) = I * (R_0 + \Delta R(t)) \quad (2)$$

$$V_{Pt}(t) = I * R_0 (1 + \alpha \Delta T(t)) \quad (3)$$

or in terms of $\Delta T(t)$

$$\Delta T(t) = \frac{\Delta R(t)}{R_0 \alpha} = \frac{(V_{Pt}(t) - IR_0) / I}{R_0 \alpha} \quad (4)$$

where, $V_{Pt}(t)$ is the total voltage difference between two points on the platinum wire.

V_0 is the voltage due to the temperature independent part of the platinum resistance R_0 .

V_I is the voltage across the 0.25 ohm resistor and is directly proportional to the current I through the platinum wire.

α is the temperature coefficient for the platinum.

$\Delta T(t)$ is the calculated superheat temperature above 77.3 K.

The heater/thermometer assembly was composed of a approximately 8 cm length of platinum wire 0.1 mm in diameter. To minimize the effect of heat loss through conduction into the multiple connections, fine wires were used as the voltage sensing leads, and were soldered approximately 1.5 cm. from

each end of the wire. So the effective thermometer length was about 5 cm.

As mentioned previously, I was looking for methods to enhance heat transfer. One common technique is to use forced convection. Rather than go to the expense and complications of developing a pumping system to create forced convection past the platinum wire, an alternative method was developed. Instead, the wire was moved vertically in the stationary liquid. This method also let one test for the effects of gravity on boiling heat transfer as the assembly could move up or down. Briefly, it worked like this. An electric motor had a round gear at one end of its drive shaft. This gear was meshed with a linear rack (approximately 50 cm long) oriented vertically. Thus, there was just under 50 cm of vertical travel. With the particular gear ratios and motor assembly chosen, maximum velocities of about 50 cm/sec were possible. Both the "flow" and the heater/thermometer devices had their functions controlled and coordinated by a computer. A typical run went as follows. First, the computer sends a signal to initiate the flow. Second, after allowing sufficient time for the flow to stabilize (0.2 sec) the platinum wire is pulsed with current (typically for 0.65 sec) and the resulting signals are recorded on the digital oscilloscope. Third, the flow stops, and the oscilloscope sends the digitized traces to the computer for storage. The thermometer assembly is backed up to its original position. This sequence was then

repeated after at least 2 minutes to allow the LN2 to settle down.

CHAPTER IV

ANALYSIS OF DATA

As mentioned in Chapter 2, the only two measurements we make during a "run" are the voltage across the platinum heater/thermometer and the current through it as a function of t . From these data we can calculate the resistance, and thus temperature of the wire, the total power dissipated in the wire, and the total heat flux out of the wire and into the liquid. This latter quantity is not simply the total power dissipated per unit area, as is the case for steady state heat flux experiments. There is a correction term due to the non-zero heat capacity of the wire. It is given by the following equation.

$$p(t) = q(t) + C \frac{dT}{dt} \quad (5)$$

Where $P(t)$ is the total applied power per unit surface area of the wire (ie. $I^2R(t)/A$). Note that this value slightly increases with time since the resistance of the wire is increasing with temperature. This is accounted for when we make the calculation of $P(t)$ on the computer. Often however, references are made between different heating curves by indicating their initial power dissipation at $t=0$.

C is the heat capacity per unit surface area of the

wire. Since the temperature of LN2 is significantly below the Debye temperature of the platinum the heat capacity varies substantially as a function of temperature. This is accordingly when we make the calculation.

$dT(t)/dt$ is the time rate of change of the temperature of the wire. This differentiation is done numerically.

Thus it is seen from Eq. 5 that in the transient case, the heat flux into the fluid can be greater than or less than the applied power. In the steady state case the two are equal.

In addition to the transient measurements made above, we also made measurements to determine the peak steady state heat flux. The maximum value of this was 9.5 W/cm^2 .

CHAPTER V

RESULTS AND DISCUSSION

Figure 2 shows the superheat temperature vs. time under no flow conditions. Note the minimum initial power level at which the liquid goes into film boiling. The figures were labeled in terms of the initial applied power. This was done to provide a reference since in the constant current experiments the resistance is increasing with time and thus the power level increases also. For an applied power of 2.3 W/cm^2 the temperature rises steadily. At this particular current the onset of nucleate boiling occurs at about 800 ms (this is off the graph) after which the temperature of the wire drops to 14 K above the bath temperature. At a slightly larger power (2.4 W/cm^2) a transition to film boiling occurs as can be observed by the abrupt change in the slope of the temperature-time curve. This transition is called the premature transition to film boiling since the peak steady state nucleate boiling heat flux for this wire is 9.5 W/cm^2 . Note that the premature transition occurs at only 25% of the peak nucleate boiling heat flux. At higher power levels the transition to film boiling is seen to occur at earlier times and higher superheat temperatures are reached before film boiling commences.

Figure 2. Superheat Temperature ΔT vs. Time, with no Forced Convection. The temperature response as a function of time is shown for the platinum wire with a step function of current initiated at $t=0$. The value adjacent to each curve indicates the initial applied power per unit area in W/cm^2 .

Figure 3 shows the nucleate boiling stage from a different data set, in a little more detail. For comparison we have also included a heating curve (curve A) which shows the theoretical result for a wire with constant power dissipation. It is assumed that only conduction occurs and that there is no temperature gradient in the wire. This latter assumption is justified because platinum's thermal conductivity is about 600 greater than LN2. The analytical solution is given by ¹³.

$$T(t) = \frac{2Q\alpha^2}{\pi^3 K} \int_0^{\infty} \frac{(1 - e^{-\frac{\kappa t u^2}{a^2}}) u^{-3} du}{[uJ_0(u) - \alpha J_1(u)]^2 - [uY_0(u) - \alpha Y_1(u)]^2} \quad (6)$$

where

$$\alpha = \frac{2\rho_{LN2} C_{LN2}}{\rho_{Pt} C_{Pt}} \quad (7)$$

is a parameter which is twice the ratio of the heat capacity of an equivalent volume of the medium (LN2) to that of the conductor (platinum). It is approximately 1.75 at 80 K. κ is the thermal conductivity of the LN2, and Q is the heat generated per unit length of the wire. $J_0(u)$ and $J_1(u)$ are Bessel functions of the first kind, of order zero and one respectively.

Figure 3. Superheat Temperature ΔT vs. Time, with no Forced Convection. The temperature response as a function of time is shown for the platinum wire with a step function of current initiated at $t=0$. The initial applied power is 3.7 W/cm^2 .

$Y_0(u)$ and $Y_1(u)$ are Bessel functions of the second kind, of order zero and one respectively.

For a short time it can be seen that the analytical curve and the experimental curve agree. When the curves begin to diverge it is assumed that modes of heat transfer other than conduction are commencing.

The three other curves (curves B,C,D) are from experiment under "identical" conditions of an initial applied power of 3.7 W/cm^2 and without forced convection. Curve A begins to deviate from the others at approximately 50 milliseconds. It can be seen that a more efficient mode of heat transfer occurs in the experiment since the experimental curves show less superheat than the theoretical curve. The three experimental curves also initially coincide but at 50 milliseconds begin to separate. At approximately 125 milliseconds they go into nucleate boiling as seen by the sharp decrease in temperature. The temperature of the surrounding fluid finally relaxes to about a 4 degree superheat. The difference between the maximum temperature superheat (approximately 12 degrees) and the steady state nucleate boiling superheat (4 degrees) is called "overshoot". It is due to a time lag in the onset of heterogeneous nucleation at the surface of the wire. The value of this overshoot is an important design criteria say for superconductors, as one wants to prevent the critical temperature from being exceeded.

One of the other features that stand out in the three experimental curves in Figure 3 is that the curves do not remain identical after a short period of time. This feature is generally true for all the data taken under "identical" conditions. (Another example will be shown later.) The origin of this is that the experiment is not done under equilibrium conditions. That is, the very definition of superheating a liquid is to put in a metastable state. The higher the superheat the further from equilibrium one is, thus the system becomes more unstable. This instability makes the systems evolution extremely sensitive to its initial conditions. For example, a slight difference in the temperature profile, the convection pattern, or even a stray bubble in the liquid might make a difference as to whether as to which path the system "chooses". Figure 4 shows that under identical conditions of flow and applied power the system either goes into nucleate boiling or film boiling. Thus, these initial conditions appear to be on the dividing line between the two routes the system can take. Keep in mind that this line is rather blurred.

Figures 5 and 6 are from the same data sets as Figures 3 and 4 respectively. However, these show the calculated heat flux $Q(t)$ vs. time curves as discussed previously. These curves also seem to follow similar paths for a short time and then separate. The abrupt heat flux peaks in Fig 6 indicate that profuse boiling is occurring.

Figure 4. Superheat Temperature ΔT vs. Time, with Forced Convection. The temperature response as a function of time is shown for the platinum wire with a step function of current initiated at $t=0$. The initial applied power is 5.4 W/cm^2 .

Figure 5. Heat Flux Q vs. Time, with no Forced Convection. The transient heat flux per unit area through the surface of the wire. The transient heat flux should be compared with the steady state peak nucleate boiling heat flux of 9.5 W/cm^2 for this wire.

Figure 6. Heat Flux Q vs. Time, with Forced Convection. The transient heat flux per unit area through the surface of the wire. The transient heat flux should be compared with the steady state peak nucleate boiling heat flux of 9.5 W/cm^2 for this wire.

This would support the observation that these curves are the ones that result in film boiling.

That is the intense boiling developed over such a short period of time that the bubbles did not have time to migrate away from the wire surface, consequently a film was formed. Though it probably cannot be said that under these "identical" conditions that there is an exact heat flux for which film boiling definitely will occur. However, the value of heat flux appears to be a parameter that is more useful than the temperature for predicting whether film boiling occurs.

Figure 7 shows the effects of various flow rates at a fixed applied current. The premature transition to film boiling occurs under zero flow condition at 280 ms. With increasing wire velocities this transition is delayed by an increasing time. Finally, at a high enough velocity film boiling is prevented. This pattern of increasing the delay to film boiling is obtained for higher power levels as well. However, the maximum we were able to delay film boiling if it was going to occur at all, was about 500 ms. So at higher power levels then shown in the figure, an maximum extra delay to the onset of film boiling of about 400 ms was obtained.

Figure 8 shows the maximum applied power per unit area (relative to the peak nucleate steady state boiling heat flux of 9.5 W/cm^2) vs. flow velocity.

Figure 7. Superheat Temperature ΔT vs. Time, with Forced Convection. The temperature response as a function of time is shown for the platinum wire for a fixed step input of current initiated at $t=0$. The number adjacent to each curve indicates the velocity of the wire in cm/sec.

Figure 8. P_v/P_{nbhf} vs. wire velocity. P_{nbhf} is the steady state peak nucleate boiling heat flux. P_v is the threshold power for the transition to film boiling when the wire velocity is equal to v .

There are two data sets for this graph, as data was taken in two different dewar configurations. Also, one set was limited to a maximum flow velocity of 7.5 cm/sec. Note that at the higher velocities the premature transition to film boiling is eliminated.

In comparing the two curves, it is seen that the storage dewar data indicates that the premature transition occurs at lower power levels. However, it also appears to be more strongly affected by forced convection. This seems reasonable as this dewar had less heat leak into it and consequently the bath of LN₂ was more quiescent. These data obviously do not lie on a very straight line. It is not certain at this point whether they should follow some simple power law. Keep in mind though, that the power levels plotted are a lower bound for a particular flow velocity. Overall, there is probably a 15% scatter in the heat flux data.

As noted previously the effects of gravity were to be considered. Preliminary experimental results indicate there was no significant difference in the nature of the superheat versus time curves for the flow velocities used (up to 7.5 cm/s). Upon analysis of the forces involved using a simple model, we found that the viscous drag forces were larger than the buoyant forces due to gravity. This is true for bubbles whose radius is smaller than about 0.1 mm which is the case at the sites where nucleation commences. In other words, the bubbles are sheared away from the surface by the viscous

forces before they can grow and coalesce into a film surrounding the wire. The equation is given below. The model which it is based upon is of a rigid sphere moving through a viscous fluid of a different density. In this example the sphere is a vapor bubble of LN2.

$$F_d = 6 \pi a \eta v \quad (8)$$

Where a is the radius of the sphere (bubble), which we estimate to be .01cm from photographic evidence (Tsukamoto).

v its velocity through the fluid (10 cm/s). η is the dynamic viscosity of LN2 at 77 K (1.58×10^{-3} g/cm-sec). The drag force calculated is 0.015 dynes.

The buoyant force on the bubble are given by

$$F_b = (\rho_{fluid} - \rho_{bubble}) g \frac{4}{3} \pi a^3 \quad (9)$$

Where ρ is the density of the different phases (.807 and .004 g/cm³ respectively), a the radius of the bubble, and g the gravitational acceleration (980 cm/s²).

A plot of these two equations is given in the Appendix.

Rough calculations were made on the velocity necessary to prevent film boiling at a particular power level. It was determined that one has to replenish the liquid near the surface fast enough so that the bubbles forming cannot coalesce into a film. This amounts to moving the wire through a distance equal to its length in the amount of time equal

required for the stationary wire to go into film boiling. For instance from Figure 2 at an applied flux of 3.6 W/cm^2 , it is observed that the time until film boiling is 250 milliseconds. Since the wire length is 10 cm, so the velocity is 40 cm/sec.

CHAPTER VI

CONCLUSION

It has been verified that the premature transition to film boiling exists for a thin wire geometry. However, the question arises as to the magnitude of this effect for surfaces of different sizes, geometries and different dewars. Further investigations are required to quantify the effects of these parameters. Also methods have been investigated to eliminate this premature transition by creating flow around the surface. Depending on the initial power level the premature transition can be eliminated at a certain velocity. At lower flow velocities the premature transition is not totally eliminated, but the delay time until film boiling occurs can be increased by several hundred milliseconds. It seems the heat flux is a better indicator than the temperature as to when film boiling will occur.

REFERENCES

1. P. Komarek, The implications of higher critical temperature superconductive materials, in "Proceedings of the twelfth Int. Cryogenic Engineering Conference" Butterworth, Guildford, U.K. (1988) p. 64
2. R.K. Kirschman, Cold electronics: an overview, Cryogenics (25) 115 (1985)
3. G.M. Chrysler, and R.C. Chu, cooling of high power density electronic chips, in: "Advances in Cryogenic Engineering," vol. 35, Plenum Press, New York (1990) p.
4. P.J. Giarratano, Transient boiling heat transfer from two different heat sources: small diameter wire and thin film flat surface on a quartz substrate, Int. J. Heat Mass Transfer 27(8):1311 (1984)
5. J.R. Holman, Heat transfer, 1st ed. McGraw-Hill, New York (1981)
6. D.N. Sinha, L.C. Brodie, and J.S. Semura, Liquid-to-vapor homogeneous nucleation in liquid nitrogen, Phys. Rev. B36(7):4082 (1987)
7. V.P. Skripov, Metastable liquids, Wiley, New York, (1974)
8. D.N. Sinha et al, Premature transition to stable film boiling initiated by power transients in liquid nitrogen, Cryogenics 19(4):225 (1979)
9. O. Tsukamoto, T. Uyemura, and T. Uyemura, Observation of bubble formation mechanism of liquid nitrogen subjected to transient heating, in: "Advances in Cryogenic Engineering," Vol. 25, Plenum Press, New York (1980), p. 476.
10. B. HaOkansson, P. Andersson, and G. Bäckström, Improved hot-wire procedure for thermophysical measurements under pressure, Rev. Sc. Instrum. 59:2269 (1988)
11. H.M. Müller-Steinhagen, Fouling phenomena during boiling of cryogenic liquids, Cryogenics 28(6):406 (1972)

12. C.J. Crowley, S.S. Kang, and P.H. Rothe, Boiling on a cryogenically cooled pulsed conductor, in: "Advances in Cryogenic Engineering," Vol. 33, Plenum Press, New York (1987), p.371
13. H.S. Carslaw, J.C. Jaeger, Conduction of heat in solids 2nd ed., Oxford University, London (1959) p.344
14. N.B. Vargaftik, Tables of thermophysical properties of liquids and gases, 2nd ed. Hemisphere Publishing, Washington D.C. (1975)