2014

The Effects of Asymmetric Micro Ratchets on Pool Boiling Performance

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THE EFFECTS OF ASYMMETRIC MICRO RATCHETS ON POOL BOILING PERFORMANCE

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctorate of Philosophy

in

The Department of Mechanical and Industrial Engineering

by
Lance Austin Brumfield
B.S., Louisiana State University, 2009
M.S., Louisiana State University, 2011
December 2014
This dissertation is dedicated to:

My wife
Allison
for standing by, supporting, loving me every day, and keeping me from working too hard. Every
day is better than the last and I look forward to our lives together.

My parents
Jon and Wendy
for helping shape me into the man I am today and always being there for me with support,
encouragement and unconditional love.

My brothers
Matthew and Grant
for being my first friends and the best men at my wedding.

To my Grandmothers
for being my biggest fans.

And to my friends
for showing me the lighter side of life.

In loving memory:
Eloise Langlois DuCote
2/28/1921- 1/15/2013
You brought joy to all those around you and the thought of your laughter brings a smile to my
face. The world is a little darker and colder now that you are gone. You will be forever missed.
Acknowledgements

I give sincere thanks, appreciation and gratefulness to my advisor Dr. Sunggook Park for his consistent guidance and support throughout my PhD research and academic studies.

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I also thank my advisory committee members, Dr. Dimitris Nikitopoulos, Dr. Michael Murphy, Dr. Shengmin Guo, and Dr. Michael Martin for their guidance throughout my time as a research assistant. My sincerest thanks also go out to the Louisiana State University Department of Mechanical Engineering faculty and staff members who have provided me with quality teaching instruction and support during my undergraduate and graduate studies.

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# List of Nomenclature

## Greek Letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>deg</td>
<td>dynamic receding contact angle</td>
</tr>
<tr>
<td>$\beta_T$</td>
<td>1/K</td>
<td>coefficient of thermal expansion</td>
</tr>
<tr>
<td>$\delta_T$</td>
<td>m</td>
<td>thermal boundary layer thickness</td>
</tr>
<tr>
<td>$\mu_l$</td>
<td>Ns/m$^2$</td>
<td>liquid absolute viscosity</td>
</tr>
<tr>
<td>$\rho_l$</td>
<td>kg/m$^3$</td>
<td>liquid density</td>
</tr>
<tr>
<td>$\rho_v$</td>
<td>kg/m$^3$</td>
<td>vapor density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>N/m</td>
<td>fluid surface tension</td>
</tr>
<tr>
<td>$\theta$</td>
<td>deg</td>
<td>contact angle</td>
</tr>
<tr>
<td>$\theta$</td>
<td>-</td>
<td>dimensionless surface roughness parameter</td>
</tr>
<tr>
<td>$\Theta_{\text{min}}$</td>
<td>deg</td>
<td>nucleation site cavity half angle</td>
</tr>
<tr>
<td>$\phi$</td>
<td>deg</td>
<td>horizontal surface angle</td>
</tr>
</tbody>
</table>

## Latin Letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>m$^2$</td>
<td>surface area</td>
</tr>
<tr>
<td>$AR$</td>
<td>-</td>
<td>ratchet aspect ratio</td>
</tr>
<tr>
<td>$Br$</td>
<td>-</td>
<td>Brumfield number</td>
</tr>
<tr>
<td>$C$</td>
<td>m/s</td>
<td>constant</td>
</tr>
<tr>
<td>$c_{p_l}$</td>
<td>J/kgK</td>
<td>liquid specific heat</td>
</tr>
<tr>
<td>$C_{s,l}$</td>
<td>-</td>
<td>constant</td>
</tr>
<tr>
<td>$D_b$</td>
<td>-</td>
<td>relative or absolute bubble departure diameter</td>
</tr>
<tr>
<td>$d_c$</td>
<td>$\mu$m</td>
<td>depth of nucleation site cavity</td>
</tr>
</tbody>
</table>


Do

m
droplet diameter

f

Hz
relative or absolute bubble departure frequency

g

m/s²
local gravitational acceleration

g_s

m/s²
standard gravitational acceleration

h

W/m²K
heat transfer coefficient

h

m
droplet release height

h_{fg}

J/kg
heat of vaporization

K

-
constant

k

W/mK
thermal conductivity

L

m
horizontal length

l_o

m
bubble diameter

P

m
ratchet period

Pr_l

-
liquid Prandtl number

n

-
constant

N

-
number of nucleation sites

r

-
roughness ratio

Ra

μm
average surface roughness

R_{rms}

m
root mean square roughness

S

μm
nucleation site spacing

T

K
temperature

T_B

K
temperature at point B

T_S

K
surface temperature

T_{SAT}

K
liquid saturation temperature
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{Wall}}$</td>
<td>K</td>
<td>temperature at heated surface</td>
</tr>
<tr>
<td>Q</td>
<td>J/s</td>
<td>total heat transfer</td>
</tr>
<tr>
<td>q&quot;</td>
<td>J/m²s</td>
<td>heat flux</td>
</tr>
<tr>
<td>$q''_{\text{CHF}}$</td>
<td>J/m²s</td>
<td>critical heat flux</td>
</tr>
<tr>
<td>q&quot;_e</td>
<td>J/m²s</td>
<td>evaporative heat flux</td>
</tr>
<tr>
<td>w</td>
<td>-</td>
<td>uncertainty of dependent variable</td>
</tr>
<tr>
<td>w</td>
<td>μm</td>
<td>diameter of nucleation site cavity</td>
</tr>
<tr>
<td>W</td>
<td>m</td>
<td>vertical length</td>
</tr>
<tr>
<td>We</td>
<td>-</td>
<td>Weber number</td>
</tr>
<tr>
<td>$w_R$</td>
<td>-</td>
<td>uncertainty of function</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>m</td>
<td>distance between thermocouples</td>
</tr>
</tbody>
</table>
Abstract

Nucleate boiling is an attractive method for achieving high heat flux at low superheat temperatures. It is frequently used for industrial applications such as heat exchangers and is being considered to cool advanced central processing units (CPU) which produce heat fluxes on the order of 1 MW/m$^2$ and are becoming increasingly less efficient to cool via forced conduction of air. The issue with implementing nucleate boiling as a cooling mechanism lies in the difficulty of quantifying the numerous and complex mechanisms which control the process. A comprehensive nucleate boiling model has yet to be formulated and will be required in order to safely and reliably cool high performance electronics.

Spatially periodic systems with localized asymmetric surface structures (ratchets) can induce directed transport of matter (liquid/particles) in the absence of net force. It was hypothesized that ratchets may enhance pool boiling heat transfer by aiding in the removal of vapor which forms on the heated surface. Therefore, preliminary experiments on pool boiling using asymmetric micro ratchets with de-ionized (DI) water and various concentrations of alumina particles and DI water as the working fluids were investigated. Results indicated that ratchets indeed improve heat transfer performance. However, few conclusions could be drawn regarding the underlying physics.

A more advanced boiling system was designed in order to more accurately measure heat transfer, test multiple working fluids, and perform condensing experiments. Various micro ratchet geometries were tested to study the effects of ratchet parameters on pool boiling performance using FC-72 as the working fluid. The samples underwent surface characterization to determine roughness and wettability which are important parameters influencing pool boiling heat transfer. Results indicate that, as in the previous study, micro ratchets significantly improve
heat transfer. Various parameters were studied in order to better understand the influence of surface geometry on heat transfer. The results were found to be under-predicted by various models found in the literature.
Chapter 1: Introduction

1.1 Motivation

Boiling has been the focus of a substantial amount of energy, but unfortunately has resulted in more empirical results and has not successfully resulted in knowledge on the underlying physics that govern the phenomena. This has led to the use of empirical correlations for system design and can result in significant error given system parameters. In order to remedy this, studies on the underlying physics will be required and are ongoing. The studies have progressed on both experimental and numerical fronts supported by improvements in data acquisition, sensors, high speed videography, improved numerical tools, and computer performance. This allows for the basic mechanisms of boiling to be more intimately explored, leading to results that can be increasingly used to develop boiling models based upon physics which are intrinsically more valid. An understanding of the underlying physical mechanisms of boiling will lead to more efficient system design and optimization, such as enhanced heat transfer surfaces, in a systematic manner as opposed to a trial and error experimental approach.

Pool boiling is an efficient method for dissipating heat in industrial settings due to the ability of the boiling fluid to achieve high heat fluxes while maintaining low wall superheat temperatures (i.e. the temperature difference between the heated surface and the working fluid). This is critical in applications where thermal stresses must remain low such as integrated circuit cooling in high performance computers and aerospace applications, as well as, the nuclear power sector in which understanding the underlying mechanisms is critical to normal operation and emergency situations. Continued heat dissipation will be required as computing power increases while shrinking circuit size. Current means by forced convection of air will no longer be an efficient means for circuit cooling. This makes nucleate pool boiling by circuit immersion an
attractive solution with the following advantages: heat transfer during boiling is very effective, boiling is an isothermal process, mass flow required for boiling is lower than single phase cooling due to the phase change (latent heat), and direct immersion eliminates thermal resistance between source and sink [1].

The immersing nature of pool boiling cooling does pose difficulties such as thermal hysteresis of the surface, surface temperature gradients due to non-uniform heat sources, variations in the distribution of activation sites and the decrease in heat transfer as the critical heat flux (CHF) is approached. These obstacles must be overcome in order to design robust and reliable cooling methods for circuits.

Fluids typically proposed for immersion cooling have relatively low boiling points and advantageous thermofluid properties. One particular fluid in a class of fluids known as fluorinerts is FC-72 which has properties which make it advantageous for its use such as dielectric strength, suitable boiling temperature and pressure, non-toxic, non-corrosive, and good thermal properties such as heat of vaporization and thermal conductivity.

Some basic mechanisms of boiling are elusive to fully understand. Continued analysis and prediction of pool boiling phenomena are required in order to predict the performance of various fluids and surface treatments and the relationship between the heat flux and surface superheat.

Fluids are conventionally driven by applying macroscopic net asymmetric potentials such as pressure gradients by a pump or compressor, and electric fields. However, these methods either require an external power source for driving a motion or limiting the displacement. On the other hand, spatially periodic systems with localized asymmetric structures (ratchets) can induce directed transport of liquid and/or particles in the absence of net force. The rectification and subsequent liquid motion can enhance pool boiling heat transfer by altering the surface boundary
layer and passively remove the insulating vapor layer which forms during pool boiling and inhibits heat transfer as superheat temperature increases.

This research on pool boiling heat transfer enhancement began in May 2009 at Louisiana State University with the collaboration of the Center for Biomodular Multi Scale Systems (CBMM). Once the original objective of experimentally proving that asymmetric micro ratchets indeed enhance heat transfer, the objective was expanded to further study the effect of varying surface geometry on heat flux and to perform simulation studies to understand the underlying enhancement mechanisms. Previous research performed at CBMM on the rectified motion of droplets on heated asymmetric ratchets has guided and inspired the use of ratchets in pool boiling heat transfer [2].

1.2 Outline of the Dissertation

Chapter 2 of the thesis covers an introduction to pool boiling and the hurdles to overcome, as well as a literature survey discussing the mechanisms behind nucleate pool boiling and asymmetric ratchets. Chapter 3 discusses the experimental sample and test chamber design and fabrication. It extends to cover sample surface characterization, experimental setup, thermocouple calibration, uncertainty and procedure. The chapter is capped with the results of the heat transfer study. Chapter 4 covers single bubble dynamics experiments. The conclusions, recommendations, and future work are discussed in chapter 5.
Chapter 2: Literature Survey

2.1 Pool Boiling Heat Transfer and the Pool Boiling Curve

In this chapter a review of the existing literature on pool boiling research from the early stage to most recent publications is presented. The first part includes boiling fundamentals explaining the boiling curve and its various regimes. The review continues with a comprehensive summary of mechanisms acting during nucleate pool boiling. System variables which affect the behavior of pool boiling are followed by boiling inception, and bubble dynamics. The chapter finishes with various critical heat flux correlations and methods to enhance pool boiling heat transfer including the author’s past work.

2.1.1 The Pool Boiling Curve

Boiling is the process by which evaporation occurs at a solid-liquid interface. In order for boiling to occur the surface temperature $T_s$ must exceed the saturation temperature of the liquid $T_{sat}$ at a given pressure. Boiling is characterized by bubble formation at the surface; these bubbles nucleate, grow and detach from the surface in a complex manner dependent on many variables such as superheat temperature, surface tension, surface geometries, etc. Newton’s Law of cooling describes the process in the form of

$$\frac{Q}{A} = q'' = h(T_s - T_{sat}) = h\Delta T$$  \hspace{1cm} (2.1)

where $Q$ is the total heat transfer, $A$ is the surface area over which the heat is transferred, $q''$ is the heat flux (heat transfer per unit area), $h$ is the heat transfer coefficient (HTC) and $\Delta T = T_s - T_{sat}$ is defined as the superheat temperature. Nukiyama [3] was the first to indentify the different regimes of pool boiling, as plotted on the boiling curve, using a heated Nichrome wire (due to its high melting temperature) in saturated water. The transition boiling region of the curve was not fully characterized until Drew and Mueller [4], but it was predicted by Nukiyama.
The pool boiling curve, as seen in Figure 2-1, is a standard graphical method for characterizing pool boiling phenomena and the performance of surface and/or liquid treatments. Pool boiling is divided into five regimes which are determined by the nature of the vapor formation: natural convection (I), nucleate boiling (II and III), transition boiling (IV) and film boiling (V).

Figure 2-1: Typical pool boiling curve (Pool Boiling [5]).
2.1.2 The Natural Convection Regime

If a saturated liquid is considered and the heated surface temperature is raised slightly above the saturation temperature, then no vapor forms and heat is transferred by means of the convection of superheated liquid which rises to the free surface to evaporate via buoyancy forces. This is regime I of the pool boiling curve. Nucleate boiling begins when the temperature of the heated surface rises high enough above the saturation temperature (wall superheat temperature) and bubbles begin to form on the surface which detach and float upward to the free surface.

2.1.3 The Nucleate Boiling Regime

Nucleate boiling, regimes II and III, is characterized by a sharp increase in slope on the pool boiling curve and denotes the end of the natural convection (single phase) regime. Nucleate boiling is an efficient means of heat transfer due to the ability to dissipate large amounts of heat at relatively small wall temperatures thus its dominance in industrial settings. In the natural convection regime, the wall temperature rises with the heat flux increases until the first bubble forms at a nucleation site (isolated bubble regime). Increasing the heat flux activates more nucleation sites and results in improved heat transfer (partial nucleate boiling). This results in a steep increase in heat flux over a modest ΔT.

Vapor bubbles formed are the result of successive bubble nucleation and bubble growth dynamics until the bubble is released and departs from the wall. Due to a large portion of the heated wall remaining in contact with the liquid (which can only maintain small superheats), coupled with fluid agitation resulting from bubble motion, the efficiency of the single phase convective heat transfer is enhanced.
2.1.4 The Critical Heat Flux

As vapor formation becomes more regular, bubbles forming on the surface begin to coalesce vertically and horizontally which reduces heat transfer due to the vapor layer which is formed. This results in a sharp rise in surface temperature to maintain the heat flux and eventually a maximum heat flux is reached at point C, which is typically referred to as the critical heat flux (CHF).

2.1.5 The Film and Transition Boiling Regimes

Care must be taken when operating near the CHF of a system. If the heat flux is increased further in order to maintain equilibrium the surface temperature “jumps” to temperatures on the order of thousands of degrees (point E in Figure 2-1) in which film boiling occurs (regime IV). This region is also known as the Leidenfrost regime. This leads to a “burnout” condition since this jump in temperature is typically well above the melting point of most metals. If the surface temperature is decreased, the minimum heat flux, or Leidenfrost temperature, can be reached at point D and in this regime the vapor film is no longer stable. If the heat flux is controlled, surface temperature can fall suddenly, and if the surface temperature is controlled, transition boiling, regime IV, is reached. These boiling regimes are of less importance in practice due to inefficient heat transfer.

2.2 Nucleate Boiling Fundamentals

2.2.1 Heat Transfer Mechanisms

In this section, the basic heat transfer mechanisms driving the efficient dissipation of heat in the nucleate pool boiling regime will be discussed in detail. In this regime, whether discussing partial nucleate or the isolated bubble regime, transient conduction in the working fluid adjacent to the heated surface is an important mechanism.
2.2.1.1 Heat Transfer Overview

Nucleate pool boiling provides high heat transfer while maintaining low surface superheats and is widely used in industrial processes such as heat exchangers. There are various different mechanisms by which heat is transferred in this regime that contribute to the overall heat flux. These mechanisms include, but are not necessarily limited to, sensible heat removed due to liquid motion created by bubble dynamics and latent heat transfer caused by evaporation.

2.2.1.2 Bubble Agitation

Following bubble nucleation, the superheated liquid layer (thermal boundary layer) that resides near the heated surface is pushed away from the surface and mixes with the cooler bulk fluid nearby. The transient bubble growth and departure agitates the fluid causing it to repeatedly move near and away from the surface. This pumping action creates a localized forced convection near the surface removing sensible heat from the surface.

2.2.1.3 Vapor Liquid Exchange

As the bubble departs from the surface, the superheated liquid layer is cyclically disturbed and stripped. This process removes sensible heat which is proportional to the thickness of the layer, its temperature, the area affected by the bubble, the bubble departure frequency, and the active nucleation site density.

Buchholz [6] studied the effects of heat flux on the superheated layer temperature. It was found that at low heat fluxes the superheat temperature rises more slowly and does not fluctuate as quickly as higher heat fluxes which have lower superheat temperature swings. This means that at lower heat fluxes with fewer active nucleation sites the predominant heat transfer mechanism is convection.
2.2.1.4 Evaporation

Heat is conducted into the boundary layer and then to the bubble interface where the phase change occurs and latent heat is removed. Two different types of evaporation occur: macro-evaporation across the top of the growing bubble and micro-evaporation (microlayer evaporation) underneath the bubble in the thin liquid layer between the bubble and the heated surface.

Moor and Mesler [7], and further verified by Sharp [8], first suggested a microlayer vaporization model after performing boiling experiments with water at atmospheric pressure. It was found that the wall temperature would drop on average ~14°C in about 2 ms. These temperature oscillations at the wall temperature under the bubble led to the deduction of the existence of a microlayer under the bubble.

Even after decades of study, an effective and consistent model for bubble growth on a heated surface that appropriately includes the microlayer contribution and transient temperature and flow fields still does not exist. Currently, models of the microlayer are inconclusive and reliable experimental data on the microlayer thickness is not readily available.

2.2.2 Length Scale

The length scale at which physical phenomena occurs is important in determining the relative strength of various physical processes. When studying nucleate pool boiling, three different length scales exist that are associated with nucleating bubbles.

Processes near the wall are on the magnitude of a few bubble diameters which makes bubble diameter a natural division of the boiling process. Far from the wall, bubbles can be considered a fixed size and shape. This length scale ignores bubble growth dynamics and is referred to as the ‘two phase flow scale’. An intermediate scale known as the ‘mean bubble
growth scale’ considers a bubble of fixed geometry but not size. This occurs when the bubble takes on a spherical shape, but its size is dependent on dynamics occurring during bubble formation. The third scale known as the ‘local scale’ is associated with transient bubble geometry and size.

2.2.2.1 Two Phase Flow Scale

In this flow scale, the system is modeled as having bubbles leaving the wall of a fixed size and geometry where bubble and wall interactions are negligible. The mean space and time frequencies of the bubble are modeled and the rate of vapor flow from the wall is proportional to the wall heat flux. Zuber [9] performed analysis on this length scale has been used to derive correlations for the low heat flux regime, however, at higher heat fluxes bubble interaction is no longer negligible and the correlation breaks down.

2.2.2.2 Mean Bubble Growth Scale

This scale involves the near wall interaction of the fluid and bubble with the wall and permits the identification of several related heat transfer mechanisms. This length scale boiling is modeled as a set of sub-phenomena, the largest component being the cyclic process of bubble formation near the wall. Each sub-phenomena have been readily studied, analytically and empirically modeled. The cyclic creation of bubble creation consists of nucleation, growth, departure, and waiting. This length scale includes a wide range of sub-phenomena including: partitioning of the heat flux into latent heat transport, transient conduction, and natural convection, nucleation site density, bubble growth rate, bubble departure size, waiting time, and bubble interactions.
2.2.2.3 Local Scale

At high heat fluxes, bubbles readily cover the heated surface and modeling the boiling by applying the mean bubble scale becomes inaccurate. The local scale model is capable of describing the transient and spatially dependent nature of the bubble shape. In addition to the phenomena that occur at the mean scale, the additional phenomena revealed on the local scale are: local bubble curvature, capillary forces, pressure recoil at the interface, triple point thermodynamics and associated heat transfer, gravity, and the local heat conduction in the heated surface at the bubble base. The complexity of the problem requires a numerical solution.

2.2.3 Bubble Dynamics

Boiling is a cyclical process that requires an understanding of bubble thermodynamics and the resulting complex flow field near the heater surface. This is further complicated when considering the influences of contact angle, surface orientation, the thermal boundary layer, nucleation site density, thermal properties of the heated surface, and bubble shape, growth, and departure history. Bubble dynamics play an important role in any analytical model.

Hsu and Graham [10] described the growth process of bubbles as the progression of bubble nucleation, growth, and departure. Nucleation begins when the thermal boundary layer reaches a critical size compared to the nucleation radius. The bubble begins to grow and buoyancy forces eventually cause the bubble to leave the surface and disrupt the thermal boundary layer. A waiting period is created by the disturbance and the next bubble nucleates after the thermal boundary layer has settled.

2.2.3.1 Contact Angle

The contact angle describes the molecular interaction between a liquid and solid surface. Bubble dynamics considers static and dynamic contact angles. The static contact angle is
considered to be in a state of equilibrium on the heated surface and depends on the liquid, vapor, and surface properties. According to famous Young’s equation, it can be calculated based simply on the interfacial surface tensions.

It has been observed that the contact angle varies during the growth period of the bubble and does not remain static. The value of the contact angle varies between the receding and advancing contact angle as the minimum and maximum angle respectively. This variation in contact angle results in altering the bubble dynamics.

2.2.3.2 Bubble Nucleation and Nucleation Site Density

The vaporization that results in bubble growth usually begins with a nucleation site, or embryo, in the superheated layer as proposed by Carey [11]. Once the embryo is of a critical size the vapor bubble will form.

There are two types of nucleation as proposed by Cole [12], homogenous and heterogeneous. Homogenous nucleation occurs if the vapor embryo forms completely within the superheated liquid. It is typically associated with high degrees of superheat and rapid vapor generation. Heterogeneous nucleation occurs at the interface between a phase boundary and is typically associated with low superheats.

The proximity of nucleation sites can have a profound effect on nature of bubble growth and departure, and even on nucleation site activation. Chekanov [13] later refined by Judd [14], performed experiments studying nucleation site spacing using the ratio between nucleation site spacing and bubble departure diameter as a parameter. Judd found evidence that large nucleation site spacing results in independent bubble growth and departure. As spacing decreases, one nucleation site can reduce bubble departure frequency at the neighboring sites. Reducing spacing
results in a promotive region in which active nucleation site bubble departure frequency increases.

2.2.3.3 Bubble Growth and Departure

After a bubble nucleates, it begins the growth process during which the pressure inside the bubble decreases along with the saturation temperature at the bubble interface. Superheated liquid in the vicinity of the interface evaporates and causes the interface temperature to fall. The fall in interface temperature causes thermal diffusion in the region around the bubble at a rate equal to that of the release of latent heat of evaporation. During this process momentum is imparted to the surrounding liquid as the bubble grows.

If it is assumed that the vapor pressure of the bubble is equal to the saturation pressure at the vapor temperature, bubble growth under this condition is controlled by inertia and heat diffusion. Initial bubble growth is rapid and, as a result, imparts inertia to the surrounding fluid causing it to displace away from the bubble. As the bubble grows, inertial effects wane and bubble growth is controlled by heat diffusion from the superheated liquid to the bubble interface and growth rate is slower.

The proximity of the heated wall alters the idealization of the bubble growth, as well as the localized flow field. This, coupled with the inertial effects, can distort the bubble to a hemispherical or other complex geometry. The wake of departing bubbles and neighboring bubble growth can also alter the velocity field around the bubble.

The diameter of the departing bubble is controlled by inertia and buoyancy, causing it to leave the surface while surface tension and drag forces attempting to pin the vapor bubble to the surface.
2.2.3.4 Bubble Frequency

By knowing the waiting and growth times of the bubble, the bubble frequency can be estimated as the inverse sum of these times. However, this is overly simplified and does not match well with experiments. More complex bubble frequency models include buoyancy, drag, and surface tension forces.

2.2.4 Effects of System Variables

It has been proposed by Dhir [15] that nucleate pool boiling has several system variables. These variables can alter significantly and shift the overall pool boiling curve left or right including: surface wettability, surface finish, gravity, system pressure, thermal properties of the heater surface, degree of subcooling, heater geometry, surface contamination, and experimental procedure.

2.2.4.1 Surface Properties

The surface micro geometry and wettability of the heated surface affects the heat transfer performance. Augmentation of nucleation site density has been shown to enhance heat transfer to a degree, but high nucleation site densities can inhibit heat transfer by aiding lateral bubble coalescence. Such investigations have been performed by Haled et al. [16] and Yu et al [17].

Luke [18] and Kang [19] have performed boiling experiments with propane and water, respectively, on surfaces of varying roughness and have shown that the influence of roughness decreases with increasing heat flux. Benjamin et al. [20] performed similar experiments showing that average surface roughness has a marked effect on nucleation site density and hence pool boiling heat transfer.
2.2.4.2 Gravity

Early studies regarding the influence of gravity on boiling were performed in drop towers at NASA facilities. The conclusions from the tests were contradictory which is likely caused by the short test durations. The most significant impact of reduced gravity is the large increase in bubble size, but the heat removal mechanism for a surface under reduced gravity is not fully understood.

Zell et al. [21] used rockets to test increased earth gravity with flat plates and Freon 12, Freon 113, and water as the working fluids. Little change in heat transfer was observed, but large increases in bubble departure diameter were observed. The conclusion was that surface tension and not buoyancy causes the bubble to depart and that evaporation was the main mode of heat transfer.

Boiling experiments with water were performed by Siegel [22] at atmospheric pressure on smooth horizontal nickel surfaces with varying degrees of reduced earth gravity. The experiments showed small bubbles merging into a larger previously departed bubble which remains near the heated surface as a result of the low departure velocity at low gravity. Also, heat flux decreased with decreasing gravity.

Kim et al. [23] performed experiments with subcooled FC-72 on micro-scale heaters under high and low earth gravity. As with Siegel, smaller bubbles coalesced with previously formed larger bubbles. The larger bubbles lead to surface dryout and low CHF.

2.2.4.3 System Pressure

Increasing the system pressure will ultimately increase the saturation temperature of the working fluid and result in higher system operating temperatures. Reducing the system pressure
has the reverse effect. Kim et al. [24] concluded that sub-atmospheric conditions result in higher bubble growth rates than experiments run at higher pressures.

2.2.4.4 Thermal Properties of the Heater Surface

Zhou and Bhir [25] conducted experiments involving boiling on tubes with a copper coating of varying thicknesses between 2 and 1000 μm with the same surface roughness. Results showed an increase in the heat transfer coefficient by 80% with iso-pentane and R-12 as the working fluids.

Arik et al [26] developed a model based upon the properties and thickness of the heater while varying pressure and subcooling.

2.2.4.5 Subcooling

Jacobs and Shade [27], analyzing schlieren images, showed that bubbles at any level of subcooling were superheated when leaving the heated surface and those bubbles carried a thin layer of hot liquid at their apex, followed by a turbulent wake.

Subcooling affects bubble size, frequency and, in turn, CHF. Demiray and Kim [28] showed that the departure diameters of the bubbles and the energy transfer were greater during subcooling, resulting in an increase in overall heat transfer. This trend continues with increasing subcooling.

2.2.4.6 Heater Geometry

There are numerous examples of the effects of heater geometry on pool boiling heat transfer. Lienhard [29] covers the phenomena from various heater dimensions and the trends show that overall heat transfer increases as the heater size decreases.

Kim et al [30] performed boiling experiments with wires of various sizes in saturated FC-72 and water. The vapor volume flow rates and departure frequencies were measured. The heat
transfer increases as the wire diameter decreases. It was hypothesized that this was due to the reduction in the effect of surface tension. Bubble size decreased and departure frequency increased.

Surface inclination also alters the heat transfer and has been investigated by several authors such as Nishikawa et al. [31]. Nishikawa immersed a copper plate into saturated water and the inclination angle was varied from 0° to 175°. The effect was most noticeable at low heat fluxes but was negligible at higher heat fluxes.

Jabardo et al [32] performed a study on the effects of refrigerants on copper and brass tubes of various average surface roughness. The results generally confirm the results found by others that high roughness increases the heat transfer coefficient, particularly at low heat fluxes. At higher heat fluxes this enhancement decays and smoother surfaces begin to outperform.

2.2.4.7 Surface Contamination

Surface contamination such as corrosion products that lead to surface oxides result in higher temperature differences for a given heat flux as shown by Joudi and James [33] using boiling methanol.

2.2.4.8 Experimental Procedure

Simple and seemingly small variations in experimental procedure can alter the results. These variations can include degassing, surface prep and cleaning, etc.

2.3 Pool Boiling/CHF Correlations

Nucleate boiling involves many processes by which heat is transferred which makes modeling of the process very difficult. Typically, these correlations involve characterizing bubble formation, growth, departure and coalescence, along with surface to liquid and bubble to liquid interactions. An overview of these relationships can be viewed in Figure 2-2.
Three nucleate pool boiling mechanisms Micik and Rohsenow [35] identified were transient conduction to the liquid layer near the surface, evaporation of the liquid layer below the bubble and liquid circulation induced by bubble growth.

Figure 2-3 shows several mechanisms summarized by Kenning [36]. Latent heat transport from the wall to the bubbles (a), micro convection caused by bubble collapse (b), fluid exchange to/from the surface caused by bubble growth (c), transient conduction to the surface (d), wake flow caused by the departing bubble (e), enhanced convection created by cellular flow patterns above the heated surface (f), and variations in surface tension around the bubble which causes liquid flow away from the wall (g).
2.3.1 Nucleate Pool Boiling Correlations

Since the maximum heat transfer with minimal wall superheat occurs in the nucleate boiling regime this has been the area of the most rigorous research. The first and most widely used accepted correlation describing heat transfer in the nucleate regime was proposed by Rohensow [38].

\[
q'' = \mu_l h_f g \left[ \frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left( \frac{c_{pl} \Delta T}{C_{sf} h_f g \rho_l P_{rl}^{n}} \right)^3
\]

(2.2)

where \( \mu_l \) is the dynamic viscosity, \( h_f g \) is the heat of formation of the vapor, \( g \) is the local acceleration, \( \rho_l \) is the density of the liquid phase, \( \rho_v \) is the density of the vapor phase, \( \sigma \) is the liquid surface tension, \( c_{pl} \) is the specific heat of the liquid phase, \( \Delta T \) is the superheat, \( P_{rl} \) is the Prandtl number and the coefficients \( C_{sf} \) and \( n \) are experimentally determined values which are
dependent on the solid/liquid combination. Rohsenow suggested that heat transfer under pool boiling conditions is the result of local liquid circulation in the region near the heated surface, which is enhanced by bubble detachment. This correlation has been plotted for saturated water at atmospheric pressure and can be viewed below in Figure 2-4.

![Rohsenow Correlation for DI Water](image)

Figure 2-4: Rohsenow correlation for nucleate pool boiling heat transfer for DI water at atmospheric pressure.

2.3.2 Critical Heat Flux Correlations

Over the years, many researchers have attempted to predict CHF with various models and equations. Many of these models have been shown to be deficient in fully encompassing the nature of CHF and therefore a unified theory and governing equation has yet to be formulated.
This is an indication of the complexity of the driving mechanisms behind pool boiling phenomena.

Kutateladze [39] postulated that the critical heat flux was due to hydrodynamic instability that resulted from the vapor phase velocity reaching a critical value. After performing dimensional analysis he proposed the following correlation.

\[ q''_{\text{CHF}} = Kh_f g \rho_v^{1/2} [\sigma g (\rho_l - \rho_v)]^{1/4} \]  

(2.3)

Where \( q''_{\text{CHF}} \) is the heat flux at CHF and the value K is a constant determined experimentally to be 0.16.

Borishanskii [40] offered a modification to the value K modeling the system by considering the phase boundary instability caused by the coaxial flow of the liquid stream and vapor. The equation also takes viscosity (\( \mu_l \)) into account, but it does not play a significant role.

\[ K = 0.13 + 4 \left( \frac{\rho_l g^{3/2}}{\mu_l [g (\rho_l - \rho_v)]^{1/2}} \right)^{-0.4} \]  

(2.4)

Rohsenow and Griffith [41] postulated that the increased number of bubbles that occur at high heat fluxes inhibits the flow of liquid to the heated surface. They proposed the following correlation for CHF.

\[ q''_{\text{CHF}} = C h_f g \rho_v \left( \frac{g}{g_s} \right)^{1/4} [\rho_l - \rho_v]^{0.6} \]  

(2.5)

Where the coefficient \( C = 0.012 \) m/s, \( g \) is the local gravitational acceleration and \( g_s \) is the standard gravitational acceleration 9.81 m/s².

Zuber [42] postulated that instability is created between the vapor flow leaving the heated surface and the liquid toward the surface as CHF is approached. He further suggested that vapor patches form and collapse on the heater surface and Taylor and Helmholtz instabilities are the cause of CHF. He formulated an equation similar to Kutatelazde [43], but with K = 0.131.
Very few investigators have studied the effects of the liquid surface contact angle on CHF even though it is considered to be a very crucial parameter. Kirishenko and Cherniakov [44] developed a model based on the dynamic receding contact angle. The dynamic receding contact angle ($\beta$) was chosen because as the bubble grows along the surface the contact angle between the surface and the receding liquid/vapor interface characterizes the wettability of the surface.

$$q''_{CHF} = 0.171 h_{fg} \rho_v^{1/2} \left[ \sigma g (\rho_l - \rho_v) \right]^{1/4} \frac{\left( 1 + 0.00324 \beta^2 \right)^{1/4}}{0.018 \beta^{1/2}}$$

Diesselhorst [45] found that this model overestimates CHF for large contact angles and found it to overestimate CHF values for water, but the trend on increasing CHF with decreased contact angle was correct.

Kandlikar [46] developed a model considering a force balance on a bubble and the presence of a thin liquid micro layer under the bubble. It was proposed that near CHF the momentum created by the evaporation on the sides of the bubble exceeded gravity and the surface tension forces causing the bubble to grow along the heated surface. He expanded this model by considering the critical wavelength for the onset of vapor layer instability.

$$q''_{CHF} = h_{fg} \rho_v^{1/2} \left( \frac{1 + \cos \beta}{16} \right) \left[ \frac{2}{\pi} + \frac{\pi}{4} (1 + \cos \beta) \cos \phi \right]^{1/2} \left[ \sigma g (\rho_l - \rho_v) \right]^{1/4}$$

Where $\beta$ is again defined as the dynamic receding contact angle and $\phi$ is the angle of the surface relative to the horizontal. This model was tested experimentally and compared to previous models and has been shown to be quite accurate for predicting CHF for various fluids. Equation 2.7 has been plotted in Figure 2-5 for DI water using dynamic receding contact angles found by Kandlikar [47] by dropping liquid droplets at various surface temperatures, roughness and materials (typical values for water were found to be in the range of 45 - 80°).
Kandlikar CHF Correlation for DI Water

Figure 2-5: Kandlikar correlation plotted for various receding contact angles on a copper surface using DI water.

Kandlikar proposed that the working fluid is pushed away during bubble growth and the interface experiences the dynamic receding contact angle at the triple point. The model was later revisited by Chu et al. [48] and incorporated surface roughness ratio, \( r \) (the roughness factor defining the ratio of the true area in contact with the liquid to the projected area), and intrinsic wettability, \( \theta_{\text{eq}} \), and can be observed in Equation 2.8 where \( \alpha = r\cos\theta_{\text{eq}} \). The surface roughness aids to maintain the vapor bubble contact line at the surface delaying the spread of the bubble.

\[
q'^{\text{CHF}} = h_f g \rho_v \left( \frac{1}{2(1+\alpha)} \right) \left[ \frac{2(1+\alpha)}{\pi(1+\cos\beta)} + \frac{\pi}{4}(1+\cos\beta)\cos\phi \right]^{1/2} \left[ \sigma g (\rho_l - \rho_v) \right]^{1/4} \quad (2.8)
\]
2.4 Enhancing Pool Boiling and CHF Heat Transfer

Nucleate pool boiling has several system parameters as proposed by Dhir [49] such as: surface wettability, surface finish, gravity, system pressure, substrate thermal properties, subcooling, heater geometry, surface contamination, and experimental procedure which can alter the performance of pool boiling systems.

Changing surface properties, such as increasing surface roughness, lowers boiling incipience temperature and moves the boiling curve to the left (lower superheat). Increasing surface wettability shifts the boiling curve to the right (higher superheat), but Takata [50] has shown that highly wetted surfaces improve CHF by coating TiO$_2$ on various surfaces. Experiments studying the thermal properties of the heated surface such as those performed by Zhou and Bier [51] have also shown to alter heat transfer performance by varying the thickness of copper coatings on heated tubes. Increasing the thickness resulted in an increase in heat transfer coefficient. Jeong et al. [52] quenched stainless steel samples in various concentrations of alumina nanoparticle and tri-sodium phosphate solutions. Contact angle measurements using the solutions and DI water showed that increasing quenching concentration reduced the contact angle and surface tension. A discussion involving Kandlikar’s [53] correlation concluded that surface wettability is far more important to CHF than surface tension.

Increasing the system pressure shifts the boiling curve to the right. This is due to the higher saturation temperature of the liquid, which requires higher wall superheats to initiate boiling.

Subcooling has essentially the opposite effect of increasing system pressure, which leads to a decrease in necessary wall superheat and has been show by Kim et al. [54] to increase CHF.
Parker and El-Genk [55] have shown that HTC increases with increasing subcooling by boiling FC-72 on porous copper and graphite surfaces.

Researchers have used various heater geometries to perform their experiments. Yu et al. [56] and Wei and Honda [57] used various pins and micro cavities respectively and have shown they both improve heat transfer, but as the concentration of these structures increased, the bubbles formed coalesce more easily and enhancement is lost. Kim et al. [58] and You et al. [59] use platinum wires immersed in various fluids and have shown that the geometry alters the bubble nucleation size and departure frequency.

Surface contamination has been shown to require higher superheat temperatures to maintain the same heat flux as shown by Joudi and James [60] using stainless steel substrates. Even though Dhir [61] explained that surface contamination increased wettability, which would improve pool boiling heat transfer, surface contamination reduces system performance.

Modifying the fluid properties with the addition of surfactants and/or solid particles has also been studied. You [62] observed CHF enhancements of 200% for small additions of alumina nanoparticles using a platinum wire. Lee [63] showed substantial improvements in the thermal conductivity of water with small additions (< 5 % wt) of alumina or cupric oxide nanoparticles. Kim [64] performed pool boiling experiments on various surfaces with varying concentrations of nanoparticles and has shown a tendency for increasing surface wettability with increasing particle concentration. The addition of various surfactants, as studied by Wen et al. [65] showed improvements in heat transfer.

The methods by which the experiments are run also affect experimental results. For example, boiling hysteresis, degassing, surface cleaning, surface aging etc have been determined...
to alter heat transfer data. Therefore, experimental procedure must be carefully studied to ensure variables are minimized.

2.5 Heat Transfer Enhancement via Asymmetric Micro Ratches

This section will discuss the use of ratchets of various scales to modify the motion of fluid droplets and multiphase systems.

2.5.1 Flow Rectification

The use of topologically asymmetric ratchets as heat transfer surfaces was studies by Linke et al. [66] in which rectified droplet motion was observed on heated millimeter scale ratchet surfaces using varying fluids. The driving mechanism behind the droplet motion that they proposed in the paper was the pressure differential on the droplet created by the vapor layer which formed underneath it, which caused the droplet to move in the direction perpendicular to the ratchets (Figure 2-6). A model for the droplet motion was created in which a ratchet force was balanced by viscous forces. The surface temperature was in the Leidenfrost regime and it was discovered that high and low temperature regimes existed in which drastic differences in droplet speed and acceleration were observed. Droplet speeds of 5 cm/s and accelerations of 2 m/s² were witnessed by Ok et al. [67].

Ratchet pumping phenomena has been studied by Sedler [69], who created millimeter scale channels with 2 mm period 0.3 mm height ratchets making up the sidewalls and channel widths of ~3 mm. The top and bottom surfaces were covered except for small passageways at the base of the ratchets to allow for vapor to escape. The unit was heated using cartridge heaters to
Figure 2-6: Figure showing (a) a liquid droplet hovering on a layer of vapor above a heated flat surface and (b) a liquid droplet hovering on a vapor layer above a ratcheted surface where the vapor would drag the droplet to the right along the long side of the ratchet while the vapor on the short side of the ratchet is expelled in and out of the page. Linke [68].

achieve temperatures above the Leidenfrost temperature for water (~250°C) with the surface temperature being measured along the ratchet at several locations. Fluids reservoirs were designed so that a constant stream of DI water could be applied to the unit and flow rates could be calculated. Results showed that a peak mass flow rate of 6.42 g/min occurred at surface temperatures of 300°C which results in an estimated average liquid velocity of 0.56 cm/s.

This work was furthered studied by Ok et al. [70] in which micro and nanoscale ratchets were used to propel fluid droplets near and above the Leidenfrost regime. He showed that droplet motion on simple asymmetric structures can be improved with the use of hydophobic coatings. Micro and nanoscale brass ratchets at a fixed aspect ratio were coated with fluorinated silane and heated. Small droplets were released onto the surface and the resulting motion was observed. On an 800 nm period, 200nm depth ratchet, the average speed of the droplets reached 50 cm/s which is 2-8 cm/s faster than uncoated ratchets of the same dimensions. This indicates that the threshold temperature in which droplet motion begins can be reduced with the application of superhydrophobic coatings on the surface. The hydrophobic coating also increased droplet speed. A trend was also identified that decreasing ratchet period increased average droplet velocity.
2.5.2 Author’s Previous Work

It is hypothesized that the use of micro and nano scale asymmetric ratchets will enhance nucleate boiling by a combination of liquid entrapment, flow rectification, and enhanced convection caused by the potential created due to the unique surface topography. Liquid entrapment in the crevices of the ratchets will act as bubble nucleate sites. The latent heat absorbed by the formation of the bubble is a characteristic of boiling. Liquid entrapment is commonly used in heat pipes to enhance heat transfer. Typically, during boiling multiple convective cells are formed. This is caused by buoyancy forces created due to the liquid being heated, rising and cooling, and falling back to the heated surface. If multiple cells are formed, the horizontal velocity of the liquid along the heated surface will be reduced, but if a single, larger convective cell is formed, the liquid velocity will necessarily increase to maintain mass flow balance across the surface as the fluid is heated. By creating a potential on the heated surface, the asymmetric surface topography may increase the horizontal fluid velocity and, in turn, increase the heat transfer coefficient. It is hypothesized that when a bubble is formed on the surface the liquid above the bubble will act in a similar manner to the liquid and vapor layer, as the droplet experiments described above, and be propelled along the surface due to the surface potential.

This section covers the design and fabrication of a test apparatus used for this experimental study. The main purpose of this apparatus was to provide the evidence that asymmetric ratchets can enhance pool boiling heat transfer.

2.5.2.1 Experimental Setup

Two small aquariums were fabricated as a proof of concept. 101.6 mm x 50.8 mm x 25.4 mm brass blocks (alloy 360, McMaster-Carr) were machined to accept a 2 x 3 array of thermocouples to measure heat flux at the block centerline (Figure 2-7). The thermocouple arrays
allowed for the measurement of heat flux and heat transfer coefficient variations across the heated surfaces, as well as allowing for the calculation of averages for these values. One aquarium had a ratcheted surface and the other was polished to be used as a reference.

Figure 2-7: The completed test aquarium (post experimentation).

The 150 μm x 30 μm brass (alloy 360, McMaster-Carr) ratchets were fabricated by a KERN MMP2522 micro milling machine into a 101.6 mm x 50.8 mm x 4.6 mm brass block. The ratchets rough cut with an 800 μm diameter end mill (PMT Tools) at 200 mm/min with a finishing pass at 75 mm/min with a 100 μm diameter end mill (PMT Tools). The spindle was run at 40,000 rpm for all passes. A jig was used to angle the brass surface to 11.54° off the horizontal which achieves the 5:1 length to height aspect ratio. The reverse side of the block was planed and the angled edge left on the ends of the block were machined square which allowed for the glass to be sealed around the block. The polished surface was fabricated by successive sandings with
decreasing grit up to 1000#. The surface was then polished using various polishing compounds (Harbor Freight Tools) until a mirror finish was achieved. The surface was then cleaned with acetone, IPA and DI water.

The test began by coating the base of the aquarium with conductive paste then filling the aquarium with DI water to a predetermined height and placed on a hot plate. Once a steady steady-state boiling was assured, the six thermocouples were measured as well as, the water temperature. Video (Sony DSC-V1, 16 frames per second) and still images (Sony DSC-S650, 7.2MP) were taken at this time to record the nature and direction of the flow in the aquarium and relative bubble size and departure frequency.

Once measurements were taken, the set point of the hot plate was increased by 20 °C, DI water was slowly added to replenish boil off and the system was allowed to reach steady state for at least 10 minutes. This process was repeated from 100 to 400°C which was the maximum working temperature of the hot plate. The array of thermocouples allowed for the calculation of an average heat flux and heat transfer coefficient for the surface, as well as allowing for analysis of the location dependence of the heat flux and heat transfer coefficient.

2.5.2.2 Results of Previous Work

For the 150 μm ratchets, significant improvement in heat flux was seen over the polished surface. Strong rectified flow was also observed with the 150 μm ratchets as evidenced by the single convective cell formed while testing. The heat transfer performance of the two surfaces can be reviewed in Figure 2-8.
The results of the experiments performed indicated that ratchets may be an innovative method for enhancing pool boiling heat transfer and suggests self-pumping pool boiling may be a reality. Further testing is required to determine the critical heat flux with asymmetric ratchets using various fluids and ratchet scales in order to compare ratchets to contemporary attempts to improve critical heat flux.

2.6 Conclusions

Since nucleate pool boiling has begun in the early 20th century, a significant, some may say overwhelming, amount of information and publications are available. As a consequence, the myriad of experiments, models, and methods result in significant contradictions which cannot be
mended. One possible explanation for these contradictions can be that the very nature of pool boiling heat transfer is a complex process and is difficult to wholly and simultaneously comprehend the numerous, inherent system variables. This and the continuous effort of going behind the involved physics during nucleate boiling, proven by the amount of publications these days, keep boiling research challenging and interesting.

A summary of the relevant topics concerning this study are given which are mainly nucleate boiling mechanisms, bubble dynamics, liquid and boiling substrate interaction, and nucleation site interaction. Nevertheless, the reader is urged to recognize that this literature survey is not and does not claim to be complete.
Chapter 3: Nucleate Boiling and Critical Heat Flux Experimental Work

3.1 Introduction

This chapter covers the design and fabrication of the test equipment used for this experimental study. The main purpose of this apparatus was to perform atmospheric nucleate pool boiling experiments on brass substrates using heaters and thermocouples to investigate how ratchet period, height, and aspect ratio alter heat transfer performance. The experimental setup had to be designed in such a way to prevent any contamination from the ambient environment and to use only materials that are compatible with various possible working fluids. The size of the system needed to be minimized in order to expedite experimental procedure and to minimize the amount of working fluid to be used. The design of the experiment also required the ability to study condensing heat transfer, be economical, and easy to operate. The chapter will also cover the fabrication, surface characterization of the samples, data acquisition, and experimental procedure.

3.2 Boiling Chamber Design and Fabrication

The designed and completed experimental testing device is shown in Figure 3-1. The system was built from a second hand stainless steel vacuum chamber that was modified to fulfill the purposes of the experiment. Other materials were chosen in such a way as to not introduce corrosion products or other impurities into the system. Viewports were added so that the boiling process could be observed via multiple means. The system was designed to be operated at atmospheric pressure and at a maximum temperature of 260 °C.
Figure 3-1: The boiling chamber used in this study.

The main chamber (TFS Tech Inc.) has 203.2 mm conflat flanges on the top and bottom and for 152.4 mm conflat flanges in the horizontal plane. The four viewports are fused silica glass (TFS Tech Inc.) allow for viewing of the sample and condition of the boiling chamber. In order to minimize heat loss, expedite system warm up, degas the working fluid, and maintain the
saturation temperature of the working fluid, a 720 W heater tape coated in conductive paste (Omega Engineering) was wrapped around the chamber. This was followed by layers of aluminum foil and several layers of 50.8 mm wide fiberglass wrap. Four 12.7 mm diameter cartridge heaters (Omega Engineering) with a total power of 3000 W were coated in conductive grease and inserted into a brass heater block which was then inserted into the base of the boiling chamber. In order to insulate and seal the heater block and ratchet sample, it was sheathed in a castable silicon oxide (Aremco) lined Teflon (McMaster Carr) cylinder with o-ring glands at the top and bottom to accept silicone o-rings (McMaster Carr). A Teflon cap was machined to fit over and seal the ratchet sample and Teflon cylinder. The cap had a 3.2 mm thick alumina sheet (McMaster Carr) was machined to fit inside the Teflon cap and slip over the ratchet sample as it is installed. The power to the heaters was controlled with a 120 V variable transformer (Starco Energy). K-type thermocouples (Omega Engineering) were used to measure the heat flux by inserting them in the heater block after coating them with conductive grease. Drawings for the test chamber can be found in Appendix B.

The lid and base of the chamber were made from 203.2 mm stainless steel blind flanges (TFS Tech). The base was machined to accept the heater block and Teflon sheathing and drain ports. The lid was machined to accept several Swagelok™ fittings which were used as feed throughs for stainless steel K-type thermocouples (Omega Engineering), a non-condensable gas vent, and a reflux condenser made from 9.5 mm stainless steel tubing (Onlinemetals.com). The gas vent was connected to a 457.2 mm length of 6.35 mm stainless steel tubing (Onlinemetals.com) which then connects to plastic tubing leading to a fume hood. The condenser coil connects to plastic tubing which connects to a lab faucet and returns to the lab sink. A plastic sight tube was used to connect the bottom drain port to a port in the lid which allows for easy
system draining, as well as monitoring system fluid level during operation. The temperatures were measured by connecting the thermocouples to an Extech ML 720 multimeter.

The boiling chamber was placed inside a custom steel (Onlinemetals.com) frame which allows for the system to be easily leveled. The frame was bolted to a vibration isolation table (500 Series, Kinetic Systems). The setup can be observed in Figure 3-2.

Figure 3-2: The complete experimental setup.
3.3 Ratchet Sample Fabrication and Characterization

3.3.1 Ratchet Sample Fabrication

Six brass (alloy 360, McMaster-Carr) ratchets of various geometries were fabricated by a KERN MMP2522 micro milling machine into the 38.1 mm x 38.1 mm heated surface on the sample blocks. The ratchets rough cut with an 800 μm diameter end mill (PMT Tools) at 200 mm/min with a finishing pass at 75 mm/min with a 100 μm diameter end mill (PMT Tools). The spindle was run at 40,000 rpm for all passes. Jigs were used to angle the brass surface to 5.7°, 11.5°, and 45.0° off the horizontal which achieves the 10:1, 5:1, and 2:1 length to height aspect ratio. These variations allow not only for the study of the effects of ratchet period, but also of the aspect ratio on pool boiling performance. The samples that were studied can be reviewed in Table 3-1 and a review of the fabrication process can be seen in Figure 3-3. The lowest aspect ratio currently possible is 2:1 due to milling constraints.

Table 3-1: The samples used in this study.

<table>
<thead>
<tr>
<th>Sample (Period x Height)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished</td>
<td>n/a</td>
</tr>
<tr>
<td>750x75 μm</td>
<td>10</td>
</tr>
<tr>
<td>150x30 μm</td>
<td>5</td>
</tr>
<tr>
<td>150x15 μm</td>
<td>10</td>
</tr>
<tr>
<td>150 μm symmetric (S)</td>
<td>2</td>
</tr>
<tr>
<td>100x10 μm</td>
<td>10</td>
</tr>
<tr>
<td>75x7.5 μm</td>
<td>10</td>
</tr>
<tr>
<td>450x45 μm</td>
<td>10</td>
</tr>
</tbody>
</table>
The polished surface was fabricated by successive sanding with decreasing grit up to 1000#. The surface was then polished using various polishing pads and alumina until a mirror finish was achieved. Each surface was then cleaned with acetone, IPA and DI water and stored in a container with a desiccant when not in service. A sample block can be observed in Figure 3-4. In order to aid the heat transfer process, the bottom of each sample was given a light polish to reduce thermal contact resistance, reducing the load on the cartridge heaters during operation.
After fabrication, the overall condition of the surfaces was viewed using a Hitachi S-3600 scanning electron microscope. The images revealed that the milling process left burs on the surface that needed to be removed. In order to accomplish this, the samples were hot embossed into 50 mm x 50 mm x 5 mm PMMA sheets (Regal Plastics).

Hot embossing was achieved by preheating an Atlas Series Hydraulic Press (Specac) to 70 °C and placing the brass mold into the hot plate to warm. The protective sheet was removed from the PMMA sheet and cleaned with compressed air. It was then placed on top of the brass mold and a steel plate placed on top of the PMMA. A slight pre-load was placed on the specimen by tightening the handle, the set temperature was increased to 165 °C and the setup was left to warm for 5 minutes. A load of 3 tons was then applied for an additional 5 minutes. Upon completion of molding, the set temperature was decreased to 70 °C and left to cool for approximately 45 minutes. The sample was then removed from the machine and the now molded PMMA sheet was then gently pried off the brass mold. This process was repeated ten times for all, including the polished, samples to ensure that all of the burs had been removed and so that all
of the samples underwent the same process. After all samples were hot embossed, they were again viewed under the scanning electron microscope to ensure all burs had been removed. The samples before and after the hot embossing process can be viewed in Figure 3-5.

![Figure 3-5: SEM images of the 75x7.5 μm sample before (a) and after (b) hot embossing.](image)

The swirling striations seen in the images on the flat portions are the result of the tool as it removes material. Some samples had a lip on the tip of the ratchet that is the result of material flow during machining. The lip features were removed by repeated polishing and checking the topology via mechanical profilometer. The white particles observed, using energy-dispersive X-ray spectroscopy (EDX), on the polished surface were confirmed to be alumina which were imbedded during polishing. The samples after preparation can be studied in Figure 3-6.

In order to measure the heat flux, a 3.2 mm diameter hole was drilled in the center of the sample and ended approximately 1 mm below the heated surface to allow for the insertion of two K type thermocouples.

To better achieve one-dimensional heat transfer, a pocket was milled into two samples around the heated surface after an initial round of heat transfer measurements. It was initially
Figure 3-6: SEM images of the surfaces used in this study. The 450x45 μm sample is not shown.

Hypothesized that this pocket was unnecessary, but for assurance it was performed on the polished and 100x10 μm samples. A thin section of brass was left at the bottom of the pocket to ensure dimensional fidelity. An image of the milled pocket in one of the sample can be studied in Figure 3-7.

After all other experiments were performed it was found that an additional data point would bring significant value to the data. In order to do this a 450x45 μm sample was fabricated
in the same way as previously described followed by imprinting in PMMA. This size was chosen as it is halfway between the 150 and 750 µm samples and would complement the existing data most effectively. Since the sample was fabricated on the trailing end of the research period, contact angle experiments were not performed. Also, SEM images were not taken, but the geometry was confirmed via surface profilometer and microscopic observation. However, surface roughness and heat flux measurements were taken.

3.3.2 Surface Profiling

The dimensions and roughness of the samples were confirmed using a Tencor P11 Mechanical Surface Profilometer. Surface roughness is an important parameter for comparison in pool boiling heat transfer and can sometimes be overlooked by researchers. An optical profilometer was available, but it was found during previous research that the sharp crevice at the base of the ratchet can lead to artifacts so the results from this method were in question. The results of the surface profiling can be observed in Table 3-2. Error for these measurements is believed to be ± 0.05 µm.
Table 3-2: Results of the surface profilometer study.

<table>
<thead>
<tr>
<th>Overall Roughness (μm)</th>
<th>Polished</th>
<th>750x75</th>
<th>150x30</th>
<th>450x45</th>
<th>150x15</th>
<th>150 S</th>
<th>100x10</th>
<th>75x7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Roughness</td>
<td>0.20</td>
<td>17.70</td>
<td>6.95</td>
<td>10.6</td>
<td>4.10</td>
<td>17.50</td>
<td>2.15</td>
<td>2.30</td>
</tr>
<tr>
<td>RMS Roughness</td>
<td>0.25</td>
<td>21.10</td>
<td>8.20</td>
<td>12.3</td>
<td>4.95</td>
<td>20.35</td>
<td>2.50</td>
<td>2.75</td>
</tr>
<tr>
<td>Roughness Ratio (r) or Surface Area Enhancement</td>
<td>1.00</td>
<td>1.11</td>
<td>1.22</td>
<td>1.11</td>
<td>1.11</td>
<td>1.41</td>
<td>1.11</td>
<td>1.11</td>
</tr>
</tbody>
</table>

As expected, the 750 and 150 S μm have the highest roughness. This is followed by the other 150 μm ratchets with the 100 and 75 μm ratchets having effectively the same roughness. The roughness ratio or surface area enhancement is also shown and expresses the increase in surface area created by the ratchets relative to the polished surface. This value is controlled by the aspect ratio.

3.3.3 Surface Wettability Study

The most common manner by which one can measure surface wettability is to measure the contact angle the fluid drop makes with the heated surface. This can be done statically or dynamically. As discussed earlier, the dynamic contact angle is more appropriate to use when discussing pool boiling.

The manner in which a liquid droplet impacts a surface is an important mechanism in many physical phenomena. A droplet impacts the surface and spreads along it due to momentum, reaches a maximum contact angle, then recoils to a minimum contact angle due to surface tension. This minimum contact angle, known as the dynamic receding contact angle, has been found to be of great importance in determining critical heat flux. Kandlikar [71] released water droplets from a fixed height onto multiple surfaces, with varying surface roughness and surface temperatures (which varies the Weber number, We) and measured the dynamic contact angles. It is also important to analyze the results of the heat transfer experiments to get, at a minimum, a...
qualitative value to how the ratchets alter surface wettability. See Figure 3-8 for a better understanding of the advancing and receding contact angle during an equilibrium contact angle.

![Figure 3-8: An illustration of advancing and receding contact angle. Image courtesy of Adhesionbonding.com [72].](image)

The dynamic advancing and receding contact angles of 5 μl water droplets were experimentally measured via the droplet impingement technique on the brass samples. Droplets were released from varying heights (altering Weber number) and the impacts studied via high speed camera. The Weber number is defined as:

$$We = \frac{\rho v^2 g h D_0}{\sigma}$$

(3.1)

Since ρ and σ are fluid properties, and D₀ and g are constant during the experiment, the change in We number can be correlated to change in droplet height. The Weber number has been used for future comparison between different fluids. It relates the potential or kinetic energy in the droplet to its surface tension.

3.3.3.1 Surface Wettability Experimental Setup and Procedure

Equilibrium advancing and receding contact angles were measured by placing a 5 μl water droplet on the surfaces and tilting it until the droplet slides. The droplet experimental setup can be viewed in Figure 3-9.
Figure 3-9: An image of the contact angle measurement experimental setup.

Droplet experiments began by blowing off the sample with compressed air, rinsing with ethanol, and allowing the sample to dry. The sample was then placed on the vibration isolation table and the gratings were aligned in the parallel and perpendicular directions and leveled. An HMI 575 back light (Cinemills) is set up across from the high speed camera and a frosted glass diffuser is placed between the light and boiling chamber. The light is then turned on and allowed
to warm. The droplets were filmed with a Kodak Model HRC1000 High Speed Camera set to 1000 frames per second. A model NE-300 Syringe pump with a 27 gauge needle set to a flow rate of 1.20 ml/min, which had been determined to release room temperature DI water droplets of 5 μl, was placed at a predetermined height above the sample surface. The droplets were released and the advancing and receding contact angles measured three times at six locations on each sample at heights of 98, 73.5, 49, and 24.5 mm. This was repeated to measure the contact angles parallel and perpendicular to the ratchet grating direction.

The dynamic contact angle was taken by importing the relevant frames into a computer aided design software (Solidworks) and manually measuring the contact angles at the triple point. The static contact angle was measured in a similar manner except the droplet was allowed to settle to a static position before images were taken. The equilibrium contact angle was measured, before the droplet starts sliding, by releasing the droplet very near the sample surface (We = 0, h~0 mm) and tilting the sample and measuring the advancing and receding contact angle with a protractor attached to the test apparatus. Except for the 150 μm symmetric sample in the parallel direction, the surfaces were titled to 90° without sliding. This was also performed in both the parallel and perpendicular directions

3.3.3.2 Surface Wettability Experimental Uncertainty

Analyzing the data obtained from the droplet impingement experiments via the analysis of variance method [73] reveals the error. It is taken as the worst case average error for a given height between the advancing and receding contact angle in the parallel and perpendicular directions. These values can be observed in Table 3-3 and are considered acceptable.
Table 3-3: Uncertainty of the sample contact angle measurements.

<table>
<thead>
<tr>
<th>Weber Number</th>
<th>Release Height (mm)</th>
<th>CA Error ±(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>h=2.5mm</td>
<td>15</td>
</tr>
<tr>
<td>0 (equilibrium)</td>
<td>h=2.5mm</td>
<td>9</td>
</tr>
<tr>
<td>7.4</td>
<td>h=24.5mm</td>
<td>14</td>
</tr>
<tr>
<td>14.7</td>
<td>h=49.0mm</td>
<td>15</td>
</tr>
<tr>
<td>22.1</td>
<td>h=73.5mm</td>
<td>17</td>
</tr>
<tr>
<td>29.4</td>
<td>h=98mm</td>
<td>13</td>
</tr>
</tbody>
</table>

3.3.3.3 Surface Wettability Experimental Results

The Kandlikar model assumes that critical heat flux is instigated by the spreading of a vapor bubble along the surface which is constrained by the dynamic receding contact angle of the fluid/surface combination. Therefore, the dynamic receding contact angle will be the focus of this study.

Due to the asymmetric surface geometry, a contact angle hysteresis exists between the two edges of the droplet for both the advancing and receding cases. This implies that a hydrophilic preference exists on the ratchet surface. However, the hysteresis values are well within the uncertainty and so this cannot be confirmed.

In the direction perpendicular to the ratchet gratings, the dynamic receding contact angle shows a minimum around We = 22.1. This is in good agreement with the trends found by Dussan who measured contact angle versus contact line velocity [74]. The ratchet surfaces showed a
decreased receding contact angle compared to the polished surface in this direction. These results can be viewed in Figure 3-10.

Figure 3-10: The average perpendicular dynamic receding contact angle for the samples.

In the parallel direction, along the gratings, all samples shows a maximum receding contact angle around $\text{We} = 7.4$ then decreases with increasing We number. The polished surface has the lowest overall receding contact angle. These results can be viewed in Figure 3-11.

An explanation for the discrepancy in the performance between the parallel and perpendicular directions is that in the parallel direction the droplet recoils along the surface with
Figure 3-11: The average parallel dynamic receding contact angle for the samples.

little interference with the interface motion. In the perpendicular direction, as the droplet recoils across the ratchets, the motion is resisted by the surface roughness and the peaks of the ratchets aid in pinning the triple point, resulting in lower receding contact angles.

In the perpendicular direction, the dynamic advancing contact angle saturates around $\text{We} = 7.4$ which is in good agreement with the literature. The ratchet surfaces have a higher advancing contact angle than the polished surface over the We number range. These results can be viewed in Figure 3-12.
Figure 3-12: The average perpendicular dynamic receding contact angle for the samples.

In the parallel direction, the dynamic advancing contact angle again saturates around $We = 7.4$. The ratchet surfaces showed an increased advancing contact angle over the polished surface in the perpendicular direction. The polished surface has the highest overall advancing contact angle for this orientation. These results can be viewed in Figure 3-13.

The discrepancy in the performance between the parallel and perpendicular directions is that in the parallel direction the droplet spreads along the surface with the ratchets perhaps reducing the wettability due to enhanced roughness while in the perpendicular direction, as droplet spreads across the ratchets and may “skip” across the ratchets as a stone on a still pond, resulting in higher advancing contact angles.
Figure 3-13: The average parallel dynamic receding contact angle for the samples.

It has been found by several authors, experimentally and numerically, that heat transfer at low superheats is improved as a surface becomes less wetting [75 – 78]. This is due to the vapor volume growth rate being primarily controlled by the advancing contact angle versus the receding contact angle and it increases as the surface becomes less wetting. Since the vapor volume growth rate is proportional to the latent heat transfer, it increases as well. Secondly, as the bubble base shrinks leading toward departure, fluid vortices are created in the region near the triple point. A higher advancing contact angle leads to larger departing bubbles which create larger vortices and are more effective at disturbing the thermal boundary layer which leads to higher sensible heat transfer.
This implies that larger contact angle hysteresis would result in better pool boiling performance. A lower receding contact angle inhibits the bubble from spreading as the triple point spreads during initial bubble growth, preventing bubble coalescence while a larger advancing contact angle allows for the bubble to grow larger before departure, better disturbing the boundary layer.

The 750x75 μm was corroded before heat flux experiments began and is explained in a later section, but the values for roughness and contact angles are those reported in this section.

3.4 Heat Flux Data Acquisition

Heat flux can be simply measured by knowing the distance between two thermocouples, the thermal conductivity of the sample, and the temperatures at the thermocouples. The heat transfer coefficient can be measured after knowing the heat flux.

3.4.1 Thermocouple Calibration

Temperatures in the block were measured using an Extech ML 720 multimeter with a maximum temperature resolution of 1 °C and a base accuracy of ±0.3 %. The thermocouples were calibrated in an ice water bath and were found to have an error of ±2.6 %. Since the Multimeter reads only to the nearest whole degree, a more precise method for temperature calculation had to be implemented. Therefore, using laboratory refrigerators and ovens, various temperatures and their corresponding voltages were measured (since voltages could be measured to the nearest hundredth of a millivolt). These values were then plotted to determine the multimeter sensitivity as shown in Figure 3-14.
Figure 3-14: Measured multimeter sensitivity.

The linear fit equation allows for temperature measurements to be calculated to the nearest hundredth of a degree by using an Excel spreadsheet. This is done during the experiment by measuring the voltage differential with the multimeter and inputting the values into Excel.

3.4.2 Uncertainty

The overall error for the experiment has been calculated using the method defined by Kline and McClintock [79]

\[
    w_R = \pm \left( \left( \frac{\partial R}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} w_2 \right)^2 + \left( \frac{\partial R}{\partial x_3} w_3 \right)^2 + \cdots \left( \frac{\partial R}{\partial x_n} w_n \right)^2 \right)^{1/2}
\]  

(3.2)
where \( R = R(x_1, x_2, x_3, \ldots x_n) \) and \( w_1, w_2, w_3, \ldots w_n \) are the uncertainties of the dependent variables \( x_1, x_2, x_3, \ldots x_n \). In order to calculate the heat flux and heat transfer coefficient the driving equations 3.3 and 3.4 were analyzed for the experiment

\[
q'' = \frac{k(T_B-T_{Wall})}{r\Delta x}
\]  

(3.3)

The variables in equation 3.3 are defined as: \( q'' \) is the heat flux, \( k \) is the thermal conductivity of the brass, \( \Delta x \) is the distance between the two thermocouples where \( T_A \) is the temperature measured near the surface and \( r \) is the roughness ratio. The percent uncertainties were found to be 5 % for \( k \), 10 % for \( \Delta x \), and 2.6 % for temperature measurements. It is estimated that radial heat losses are less than 1 % of the nominal critical heat flux which validated the one dimensional heat flux assumption. Also, hand calculations and simple heat transfer simulations showed that the temperature gradient across the surface is less than 0.2 °C so it can be neglected.

\[
h = \frac{q''}{T_{Wall}-T_{SAT}}
\]  

(3.4)

The remaining undefined variables in Equation 3.4 are defined as: \( h \) is the heat transfer coefficient and \( T_{SAT} \) is the saturation temperature of the working fluid. The results of the uncertainty analysis indicate that error for heat flux and heat transfer coefficient falls between 10 -16 % in Table 3-4 which is typical for values found in the literature.

In order to check experimental repeatability, the 150 S sample was run twice. The heat flux at CHF was within 3 % between runs which This is well within acceptable limits. However, there was some variation between the two runs in the intermediate superheat range, but this is to be expected due to inherent variations that arise in pool boiling experiments.
Table 3-4: Uncertainty of the heat flux measurements.

<table>
<thead>
<tr>
<th>Sample (Period x Height)</th>
<th>Heat Flux and Heat Transfer Coefficient Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished</td>
<td>10.0</td>
</tr>
<tr>
<td>750x75 μm</td>
<td>10.0</td>
</tr>
<tr>
<td>450x45 μm</td>
<td>12.0</td>
</tr>
<tr>
<td>150x30 μm</td>
<td>12.3</td>
</tr>
<tr>
<td>150x15 μm</td>
<td>11.1</td>
</tr>
<tr>
<td>150μm symmetric (S)</td>
<td>15.4</td>
</tr>
<tr>
<td>100x10 μm</td>
<td>11.1</td>
</tr>
<tr>
<td>75x7.5 μm</td>
<td>12.0</td>
</tr>
</tbody>
</table>

3.5 Boiling Fluid

The working fluid for the boiling experiment was fluorinert FC-72 (perfluorohexane C₆F₁₄, 3M). FC-72 is a non-flammable, non-toxic, non-corrosive liquid that is commonly used in boiling experiments. It is also clear and colorless which allows for easy observation of bubble nucleation and departure. It has a low boiling temperature (T_{SAT} ≈ 57 °C, at 1 bar) and high dielectric strength which make it possible to completely immerse electrical components.

It is important to keep the temperature of the boiling liquid below approximately 200 °C because FC-72 may form hydrofluoric acid with dissolved water, which can lead to destruction of materials and test sections and be extremely harmful. Some relevant thermophysical fluid properties during atmospheric boiling of FC-72 are given in Table 3-5 with water given for comparison.
Table 3-5: Properties of FC-72 and water during atmospheric boiling.

<table>
<thead>
<tr>
<th>Property</th>
<th>FC-72</th>
<th>Water</th>
<th>Water/FC-72</th>
</tr>
</thead>
<tbody>
<tr>
<td>At saturation temperature, atmospheric pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat (J/kgK)</td>
<td>1098</td>
<td>4216</td>
<td>3.84</td>
</tr>
<tr>
<td>Liquid Density (kg/m³)</td>
<td>1598</td>
<td>959</td>
<td>0.60</td>
</tr>
<tr>
<td>Vapor Density (kg/m³)</td>
<td>13.5</td>
<td>0.6</td>
<td>0.04</td>
</tr>
<tr>
<td>Kinematic Viscosity (m²/s)</td>
<td>0.00000028</td>
<td>0.00000029</td>
<td>1.04</td>
</tr>
<tr>
<td>Dynamic Viscosity (kg/ms)</td>
<td>0.00045</td>
<td>0.00028</td>
<td>0.62</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>0.054</td>
<td>0.68</td>
<td>12.59</td>
</tr>
<tr>
<td>Surface Tension (N/m)</td>
<td>0.0082</td>
<td>0.0059</td>
<td>7.18</td>
</tr>
<tr>
<td>Heat of Vaporization (J/kg)</td>
<td>94,200</td>
<td>2,250,000</td>
<td>23.90</td>
</tr>
<tr>
<td>Compressibility (K⁻¹)</td>
<td>0.0016</td>
<td>0.00075</td>
<td>0.47</td>
</tr>
<tr>
<td>Prandtl Number</td>
<td>9.1</td>
<td>1.8</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Another important reason to choose FC-72 is due to its high wettability which completely wets most engineering surfaces and can be used to an advantage. By completely wetting surfaces variations in geometry have less of an effect on surface wettability, unlike water whose contact angle can change significantly with surface geometry. This means that the heat transfer performance of vastly different geometries can be more easily compared.

3.6 Boiling Heat Flux Experimental Procedure

Prior to any testing, the system was assembled and tested for leaks. Once the system was assured to be leak-fit tests could begin. Before the sample was installed the base of the sample was coated with a thin layer of thermally conductive grease. The hole for the thermocouple was liberally filled with grease. The vertical side walls near the heater surface were coated with a thin layer of RTV silicone to ensure sealing between the Teflon cap and the sample. The thermocouple spacing was checked and measured before installing the sample and screwing it to
the heater block, being sure to align the gratings parallel with the high speed camera. The Teflon cap was then installed and screwed down. The countersink holes in the Teflon cap were then filled with RTV to ensure sealing around the screws. The system is then purged with compressed air for at least 30 minutes to allow the RTV to “skin” and partially harden. The continuous flow of gas ensures that the volatile acids that are released by the RTV as it cures can be diluted before being vented and alleviates corrosion issues. The interior of the chamber is then wiped down with ethanol to remove dust, oils, and other contaminants.

After the RTV has “skinned”, the boiling chamber is then filled with FC-72 to a predetermined fill line and a cursory leak check is performed. The chamber is checked for level with a digital level. A p-trap is formed in the vent line between the boiling chamber and the fume hood and is primed with water. The p-trap prevents the continuous flow of material from being pulled from the chamber by the fume hood. The cooling water to the condenser is turned on and checked for leaks. The chamber is then purged with argon at a flow rate of approximately 100 ml/min for one hour by connecting the argon to the lid side of the sight tube and plugging the sight tube connection at the chamber lid. Once this process is complete, the sight tube is reconnected. It is at this point that chamber heating begins. The external heater is turned on to 45 % power and the chamber is left to heat and boil for two hours.

The back light is set up with the viewport across from the high speed camera and a frosted glass diffuser is placed between the light and boiling chamber. The light is then turned on and allowed to warm. The high speed camera is turned on, set up (1000 FPS, 50 μs exposure, 10 mm lens spacer), aligned and focused on the sample. A camcorder (Sony DSC-V1, 16 frames per second) is setup on a tripod facing one of the open viewports.
The fluid is ensured to be at saturation by measuring the thermocouples and ensuring a fluid temperature between 56 – 58 °C. The heater block thermocouples are measured repeatedly until steady state operation is ensured. The variable transformer power is then increased a few percent and the system is allowed to reach steady state. This process is repeated until boiling is observed on the heater surface. Once boiling incipience on the heater surface is observed the thermocouple values are recorded, high speed and nominal speed video recordings are taken, and photographs are taken parallel and perpendicular to the gratings with an IPhone 4. After recordings and measurements are taken, the power to the transformer is increased in 5 % power increments and the data recording process is repeated until the vicinity of critical heat flux is reached. The power level increments are then reduced in anticipation of overshoot to the film boiling regime. The film boiling regime, overshooting the critical heat flux, is observable by a marked change in bubble nature and a rapid rise in heater block temperature. It is important to be near the system at this point due to the rapid change in temperatures and the possibility of decomposing the FC-72.

If overshoot occurs, the heater is immediately turned off and the heater block is allowed to cool and return to the nucleate boiling regime at which point the heater power is returned to a power level just below the point at which overshoot occurred. The system is allowed to return to steady state. This process may need to be repeated several times in order to ensure that the critical heat flux has been satisfactorily measured. Data is taken at all relevant power settings. The power settings are then reversed by 10 % power increments, the system is allowed to reach steady state, data is taken to measure system hysteresis. This is repeated until surface boiling stops.
The variable transformer, external heater, cameras, and light are turned off and the system is allowed to cool ensuring that the water to the condenser is not interrupted. Once the system is cooled to room temperature the FC-72 can be drained and the system can be prepared for the next sample.

3.7 Heat Transfer Results

The experimental heat flux values between the original and modified (pocket milled) polished and 100x10 μm samples were compared. An average heat flux discrepancy of approximately 43.5% was found over the boiling ranges. Milling all other samples, which is time consuming and runs the risk of damaging the ratchet surface, and repeating the boiling experiments would have been an inefficient use of time. The heat flux values from the original, unmodified heat flux experiments at each temperature were multiplied by 1.435. This necessarily resulted in the increase of the heat transfer coefficient.

The 750x75 μm sample was severely corroded due to exposure to the volatile acids released by the RTV. This was a result of it being one of the first samples tested. The sample was setup in the chamber and the RTV was left to sit overnight without a compressed air purge. Aluminum foil was placed over the top opening to prevent dust contamination, but this confined the vapors and resulted in unwanted surface corrosion which undoubtedly altered the heat transfer results from the sample. So the results from the sample in question should be studied with caution.

Table 3-6 below shows that the 75x7.5, 150x15 and 750x75 μm samples provide the highest CHF performance and the table also gives comparisons between the performance of the ratcheted surfaces and the polished surface.
Table 3-6: CHF results for the samples with FC-72 as the working fluid.

<table>
<thead>
<tr>
<th>Sample (μm)</th>
<th>Overall RMS Roughness (μm)</th>
<th>Aspect Ratio</th>
<th>Critical Heat Flux (kW/m²)</th>
<th>Heat Transfer Coefficient (kW/m²K)</th>
<th>Critical Heat Flux Enhancement over Polished Surface (%)</th>
<th>Heat Transfer Coefficient Enhancement over Polished Surface (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150x15</td>
<td>4.9</td>
<td>10</td>
<td>310.5</td>
<td>9.3</td>
<td>130</td>
<td>139</td>
</tr>
<tr>
<td>75x7.5</td>
<td>2.8</td>
<td>10</td>
<td>279.7</td>
<td>9.3</td>
<td>117</td>
<td>139</td>
</tr>
<tr>
<td>750x75</td>
<td>21.1</td>
<td>10</td>
<td>278.8</td>
<td>10.6</td>
<td>112</td>
<td>158</td>
</tr>
<tr>
<td>150x30</td>
<td>8.2</td>
<td>5</td>
<td>261.7</td>
<td>7.5</td>
<td>109</td>
<td>112</td>
</tr>
<tr>
<td>100x10</td>
<td>2.5</td>
<td>10</td>
<td>256.8</td>
<td>11.9</td>
<td>107</td>
<td>176</td>
</tr>
<tr>
<td>450x45</td>
<td>12.3</td>
<td>10</td>
<td>249.8</td>
<td>6.2</td>
<td>104</td>
<td>-7</td>
</tr>
<tr>
<td>150 symmetric (S)</td>
<td>20.3</td>
<td>2</td>
<td>249.2</td>
<td>7.3</td>
<td>104</td>
<td>109</td>
</tr>
<tr>
<td>Polished</td>
<td>0.3</td>
<td>n/a</td>
<td>239.7</td>
<td>6.7</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3-6 reveals that the highest performing samples have a 10:1 aspect ratio and the heat flux enhancements of 130, 117, 112 % over the polished surface with the 150x15, 75x7.5, and 750x75 μm samples respectively. The heat transfer coefficients of the various surfaces show significant enhancement over the polished surface as well with the 100x10 μm sample showing the highest enhancement of 176 %. The 450x45 and 150 S samples had the lowest enhancement of 104%. 

The heat flux boiling curves can be observed in Figure 3-15 and show that variations in period and aspect ratio can create large discrepancies in heat flux performance as superheat is increased, but performance begins to converge as critical heat flux is reached.
Figure 3-15: The heat flux results for the samples with FC-72 as the working fluid.

The boiling curves can be observed in Figure 3-16 and show that variations in period and aspect ratio can create large discrepancies in the heat transfer coefficient performance as superheat is increased, but performance begins to converge as critical heat flux is reached. The figure also shows a trend mirrored in the literature that show an optimal heat transfer coefficient.
Figure 3-16: The heat transfer coefficient results for the samples with FC-72 as the working fluid.

In order to better observe the heat transfer coefficient, the 750x75 μm sample is removed and can be studied in Figure 3-17. This allows for better study of the remaining ratcheted surfaces.

Additionally, a common form of presenting the results is to plot the heat flux versus the heat transfer coefficient as seen in Figure 3-18. Again, the 750x75 μm sample is removed from the figure for ease of viewing.
The 750x75 μm curve reports behavior indicative of secondary incipience, but this can be explained by the fact that the sample was moderately corroded due to previous experimental activity and this created additional nucleation sites in the surface oxide. These additional nucleation sites aid in the formation of vapor bubbles and ease the activation of nucleation sites which enhance heat transfer in the lower heat flux regime. An image from the author’s
Figure 3-18: The heat flux and heat transfer coefficient results for the samples with FC-72 as the working fluid with the 750x75 μm sample removed.

previous work shows how the corrosion created additional nucleation sites on a brass 150x15 μm sample as shown in Figure 3-19

Figure 3-20 shows the heat flux for the samples with the aspect ratio of 10:1 with the 750x75 μm sample removed. The figure shows that the smaller period samples show a faster rise in heat flux with temperature over the 150 μm sample. The polished sample shows a nearly.
linear increase in heat flux with temperature. However, while the 75 and 100 μm have a faster rise in heat flux, the samples saturate earlier than the 150 μm sample and have lower CHF performance. The 450x45 sample generally underperformed the polished surface except near CHF where it showed enhancement within the margin of error.

This discrepancy in performance may be partially explained by possible differences in nucleation site density. If each grating has a similar number of nucleation sites then a lower period sample would result in more overall nucleation sites on the surface. Higher nucleation sites would result in a faster rise in heat flux but as the bubble nucleation rate becomes high, nucleation sites can interact and inhibit heat transfer as seen by Yu [80] and Nikmar [81].
Figure 3-20: The heat flux results for the 10:1 aspect ratio samples with FC-72 as the working fluid with the 750x75 μm sample removed.

Figure 3-21 shows the heat flux for the samples with the 150 μm period and varying aspect ratio. The figure shows a similar trend to Figure 3-19 in that the 5:1 and 2:1 samples show a faster rise in heat flux with temperature over the 10:1 sample. However, while the 5:1 and 2:1 have a faster rise in heat flux the samples saturate earlier than the 10:1 sample and at CHF have lower performance.
Figure 3-21: The heat flux results for the 150 μm samples with FC-72 as the working fluid.

The higher performance seen by the 5:1 and 2:1 samples in the lower superheat regime may be explained by their higher advancing contact angles. Higher advancing contact angles have been shown to result in larger bubble departure diameters. Larger departing bubbles create local circulation near the heated surface and are more effective at disturbing the thermal boundary layer which results in improved heat transfer.

The thermal boundary layer thickness can be estimated by using the correlation for the turbulent natural convection heat transfer [82] which is defined as:
\[
\delta_T = 7.14 \left( \frac{\nu_l \alpha_l}{g \beta_T \Delta T} \right)^{\frac{1}{2}}
\]  
(3.5)

where \( \delta_T \) is the thermal boundary layer, \( \nu_l \) is the kinematic viscosity, \( \alpha_l \) is the thermal diffusivity of the liquid, \( g \) is gravity, \( \beta_T \) is the coefficient of thermal expansion, and \( \Delta T \) is the superheat. For FC-72, this value is between 17 and 58 \( \mu m \) which decreases with increasing superheat. So at lower superheats the 10:1 ratchet may not be able to effectively disturb the boundary layer, but at higher superheats it becomes more effective. The 5:1 and 2:1 aspect ratchets are more than capable of disturbing the thermal boundary layer and the asymmetric geometry on all samples may partially rectify the fluid in the region near the surface inducing bulk fluid motion.

This discrepancy in performance may also be explained by possible differences in nucleation site density. The lower ratchet heights for a given period will have higher roughness which has a notable effect on nucleation site density. Higher nucleation sites would result in a faster rise in heat flux but as the bubble nucleation rate becomes high, nucleation sites can interact and inhibit heat transfer as seen by Yu [82] and Nikmar [84]. Also, higher structured surfaces can inhibit the flow of liquid to the heated surface after a bubble has departed from the surface.

Practically speaking, it may not be necessary or prudent to operate near the critical heat flux and it is typically accepted that the optimal superheat for electronics is between 15 – 25 °C. Looking at the heat flux data in this range with a marker at 20 °C in Figure 3-22, shows that there exists a large variation in performance between the samples. All samples showed higher heat transfer than the polished sample with the 75x7.5, 100x10, 450x45, and 750x75 \( \mu m \) samples showing the highest heat transfer performance.
Figure 3-22: The heat flux results for the samples with FC-72 as the working fluid in a practical superheat range used in electronic cooling.

As a part of a systematic study, the various pertinent aspects of the heater surface such as period, aspect ratio and height, and roughness are compared to help understand what causes the heat transfer enhancement. Also, the goal is to determine the optimal ratchet geometry for various fluids.

3.7.1 Effect of Ratchet Period

A graph comparing the critical heat flux to the ratchet period can be studied in Figure 3-23. A trend is revealed showing that the optimal ratchet period is most likely around 150. Further experiments may need to be performed in order to determine the actual optimal value. The polished surface is defined with a period of zero.
Figure 3-23: The critical heat flux versus ratchet period results for the samples with FC-72.

3.7.2 Effect of Aspect Ratio/Height

If the period of the ratchet is fixed, then the height of the ratchet is fixed by the aspect ratio or vice versa. The three 150 μm were milled with various aspect ratios to determine the effect aspect ratio has on heat transfer performance. However, all samples were plotted for observation. Figure 3-24 shows the influence of aspect ratio on critical heat flux. It can be quickly seen that the highest performance is reserved for the 10:1 aspect ratio.
Figure 3-24: The critical heat flux versus aspect ratio results for the samples with FC-72.

Reducing the scope to only the three 150 μm samples and comparing their results implies that an optimal aspect ratio of 10:1 or perhaps higher exists as shown in Figure 3-25. Samples of higher aspect ratios would need to be tested, but it is hypothesized that increasing values of aspect ratio for a given period reduces the ratchet height to a point that the sample resembles a flat surface and the enhancement mechanism is lost. Lower aspect ratio values for a given period, will result in higher ratchet heights and may interfere with liquids rewetting the surface after bubble departure as observed by Yu et al. [85] on structured surfaces. Also, low aspect ratios may interfere with hydrodynamic forces.
3.7.3 Effect of Surface Roughness

It has been well established that surface roughness can alter boiling heat transfer performance. Plotting the critical heat flux versus RMS roughness yields similar results to those achieved in Figure 3-26 that an optimal roughness exists somewhere between the 0 and μm roughness as seen in Figure 3-25. Further experiments may need to be performed in order to ensure the optimal value.

Figure 3-25: Critical heat flux versus aspect ratio with FC-72.
These results correlate well with the results of Jabardo [86] who found that the heat transfer coefficient and heat flux increases and then decreases with increasing surface roughness. Jabardo also observed that the slope of the heat transfer coefficient versus heat flux curve performs similarly with optimal average roughness being around 3.0 μm for refrigerants.

The model proposed Benjamin and Balakrishan [87] who predicts the nucleation site density based upon fluid properties and the average surface roughness. This model predicts an optimal average roughness for FC-72 to be ~4.6 μm (~5.1 um RMS) which is only 12% higher than the measured roughness of the 150x15 μm sample which had the highest heat transfer performance.
In order to study the effects of machining on roughness, a brass sample was polished and face milled in the same manner as described in 3.3.1. No jig was used which resulted in ~ 500 μm period gratings with a swirl pattern left by the end mill. The surface was profiled and the RMS roughness was found to be ~0.1 μm. This is actually rougher than the polished surface and only ~ 4 % of the RMS roughness of the smoothest ratchet. So, it would be safe to assume that the roughness due to milling has little effect on nucleation site density and heat transfer.

The optimal trend may be more easily observed in Figure 3-27 which plots the critical heat flux against the heat transfer coefficient at the critical heat flux. It shows a similar trend as the above figure in that an optimal roughness exists for the heat transfer.

![Heat Flux versus Heat Transfer Coefficient](image)

Figure 3-27: The critical heat flux and heat transfer coefficient results for the samples with FC-72 as the working fluid comparing overall surface roughness.

Benjamin et al. [88] provided a model to estimate the nucleation site density as a function of average surface roughness, surface tension, Prandtl number, superheat, surface properties, and
fluid properties. The equation for nucleation site density is:

\[
\frac{N}{A} = 218.8Pr_l^{1.63} \frac{1}{\gamma} \theta^{-0.4} \Delta T^3
\]  

(3.5)

Where \( \theta \) is defined as:

\[
\theta = 14.5 - 4.5 \left( \frac{R_a P}{\sigma} \right) + 0.4 \left( \frac{R_a P}{\sigma} \right)^2
\]  

(3.6)

and \( \gamma \) is defined as

\[
\gamma = \left( \frac{k_w \rho_w C_p_l}{k_l \rho_l C_p_l} \right)^{0.5}
\]  

(3.7)

The critical heat flux values for the samples in this study were plotted against the calculated nucleation site density and can be studied in Figure 3-28. The graph corroborates the findings of Benjamin et al. that peak heat transfer occurs at a particular roughness. The author explains that this optimal roughness is caused by the roughness reducing the necessary superheat required for nucleation which increases the nucleation site density and past the optimal point individual bubbles are nucleated from the same nucleation site, causing the decrease in nucleation site density.

Jabardo [89] hypothesized that nucleation site activity is associated with surface roughness and that increasing surface roughness increases not only the cavity sizes but also the range of cavity sizes. Therefore, roughening the surface increases the number of nucleation sites that can become active at a given superheat. However, as the size of the cavities increase, the larger cavities may be filled with liquid and become inactive. Also, larger cavities become active at lower superheats so rougher surfaces have few nucleation sites available at higher superheats to further increase heat transfer.
Critical Heat Flux versus Estimated Nucleation Site Density

Figure 3-28: The comparison between the critical heat flux and calculated nucleation site density.

3.7.4 Boiling Hysteresis

One aspect of pool boiling that is frequently overlooked is the hysteresis of the boiling curve. This is performed by simply measuring data points as the power to the heater is reduced until boiling ceases. If there is little hysteresis in the system, the two curves formed will be very similar. Significant system hysteresis will create discrepancy between the increasing and decreasing power curves. It is believed that this hysteresis is caused by nucleation sites becoming active as superheat increases. As the power is reduced, the nucleation sites continue to produce
bubbles at superheats below which they were activated. This typically has the effect of enhancing the heat transfer.

There are occasions in which heat transfer is reduced when power is decreased which is believed to be caused by nucleation sites interfering with or even deactivating some nucleation sites. This can be observed in the 100x10, 150x30, 150S, and 750x75 μm samples in Appendix A. The figures agree with the various forms of hysteresis as described by Poniewskie and Thome [90].

3.8 Comparison to Literature

The experimental results obtained were compared to other experimental data in the literature using similar conditions and FC-72 as the working fluid. The values of the heat transfer performance can be observed in Table 3-7 along with the enhancement method and surface material. The peak value from each author is reported.

Table 3-7: The experimental data from other authors using FC-72.

<table>
<thead>
<tr>
<th>Author</th>
<th>Experimental Critical Heat Flux (kW/m²)</th>
<th>Experimental Heat Transfer Coefficient (kW/m²)</th>
<th>Enhancement, Surface Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferjancic [91]</td>
<td>115</td>
<td>n/a</td>
<td>Surface roughness, SS</td>
</tr>
<tr>
<td>Pastuszko [92]</td>
<td>~100</td>
<td>5.2</td>
<td>micro fin array, Cu</td>
</tr>
<tr>
<td>Guglielmini [93]</td>
<td>70</td>
<td>2</td>
<td>micro fin array, Cu</td>
</tr>
<tr>
<td>Ujereh [94]</td>
<td>158</td>
<td>2.2</td>
<td>CNT’s, Si</td>
</tr>
<tr>
<td>Ramaswamy [95]</td>
<td>180</td>
<td>n/a</td>
<td>Various enhanced structures, Si</td>
</tr>
<tr>
<td>Yu [96]</td>
<td>210</td>
<td>8</td>
<td>Various cavities, Si</td>
</tr>
</tbody>
</table>

The experimental results obtained were also compared to promising models from the literature shown in Table 3-8. These models were previously discussed in chapter 2.
Table 3-8: Models used to predict ratchet performance.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kutateladze – Zuber (Equation 2.3)</td>
<td></td>
</tr>
<tr>
<td>( q_{c''} = K h_f g \rho_g^{1/2} \times [\sigma_{lv} g (\rho_l - \rho_v)]^{1/4} )</td>
<td></td>
</tr>
<tr>
<td>Kandlikar et al. (Equation 2.7)</td>
<td></td>
</tr>
<tr>
<td>( q_{c''} = h_f g \rho_g^{1/2} \left( \frac{1 + \cos \beta}{16} \right) \times \left[ \frac{\pi}{2} + \frac{\pi}{4} (1 + \cos \beta) \cos \phi \right]^{1/2} \times [\sigma_{lv} g (\rho_l - \rho_v)]^{1/4} )</td>
<td></td>
</tr>
<tr>
<td>Chu et al. (Equation 2.8)</td>
<td></td>
</tr>
<tr>
<td>( q_{c''} = h_f g \rho_g^{1/2} \left( \frac{1 + \cos \beta}{16} \right) \times \left[ \frac{2(1 + \alpha)}{\pi (1 + \cos \beta)} + \frac{\pi}{4} (1 + \cos \beta) \cos \phi \right]^{1/2} \times [\sigma_{lv} g (\rho_l - \rho_v)]^{1/4} )</td>
<td></td>
</tr>
</tbody>
</table>

The appropriate data was plotted and can be studied in Figure 3-39. The Chu model under predicts the ratchet performance considerably (average 18%, peak 36%). The models do predict the other experimental data well. Possible reasons for the discrepancy are that the models do not account for the ratchet enhancement mechanism since they are based on hydrodynamic instability and the bubble spreading at the critical heat flux.

Additional sub-micron scale roughness exists on the ratchet surface as a result of the milling process and this was incorporated by taking a line weighted RMS roughness of the sides of the ratchets and dividing by the overall root mean square roughness of the polished surface. This ratio was then multiplied by the roughness ratio discussed in chapter 3.3.2. This product was then used in the appropriate model and is able to take the sub-micron scale roughness into account even though the 750x75 and 75x7.5 μm samples lie atop each other. That is why only seven data points are seen in Figure 3-29.
3.9 Videography Results

The boiling experiments were recorded via high speed videography in hopes of observing individual bubble growth and departure. Unfortunately, even with a powerful backlight, only the low heat flux regimes revealed any discernable images. This was also due to the difficulty magnifying the surface and the relatively low frame rate. Magnifying the surface was
accomplished using lens shims, but a limit of magnification was reached after which focusing became impossible. A higher frame rate would have allowed better temporal resolution.

3.10 Non-dimensional Analysis

One of the goals of the current research was to attempt to find a simple model to associate the optimal ratchet geometry with fluid properties. This would allow for the easy design of micro ratchets for a given fluid. A nondimensional technique was implemented comparing the bubble diameter, ratchet period, height, and aspect ratio. The advantage of this method is that the ratchet surface can be designed without needing any surface characterization such as surface roughness.

One of the most basic length scales using in boiling research is the estimate of the bubble diameter defined as:

$$l_o = \sqrt{\frac{\sigma}{g(\rho_f - \rho_v)}}$$  \hspace{1cm} (3.8)

which for FC-72 at saturation temperature at atmospheric pressure is 0.73 mm. For comparison, the estimated bubble diameter is 2.5 mm for water. It is hypothesized that whatever the underlying enhancement mechanism, ratios that are too large or small diminish the enhancement mechanism. In order to nondimensionalize the data the ratio of the ratchet period to bubble diameter was taken as an initial study. The results can be viewed in Table 3-9.

The initial attempt lead to the development of the Brumfield number ($Br$) and can be seen below.

$$Br = \frac{P(AR)}{l_o}$$ \hspace{1cm} (3.9)

The graph of the resulting analysis can be seen Figure 3-30.
Table 3-9: Critical heat flux versus ratchet period and period to bubble diameter ratio with FC-72.

<table>
<thead>
<tr>
<th>Sample (μm)</th>
<th>Critical Heat Flux (kW/m²)</th>
<th>Period (μm)</th>
<th>Period/Bubble Diameter (P/l₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150x15</td>
<td>310.5</td>
<td>150</td>
<td>0.21</td>
</tr>
<tr>
<td>75x7.5</td>
<td>279.7</td>
<td>75</td>
<td>0.10</td>
</tr>
<tr>
<td>750x75</td>
<td>278.8</td>
<td>750</td>
<td>1.03</td>
</tr>
<tr>
<td>150x30</td>
<td>261.7</td>
<td>150</td>
<td>0.21</td>
</tr>
<tr>
<td>100x10</td>
<td>256.8</td>
<td>100</td>
<td>0.14</td>
</tr>
<tr>
<td>450x45</td>
<td>249.8</td>
<td>450</td>
<td>0.62</td>
</tr>
<tr>
<td>150 symmetric (S)</td>
<td>249.2</td>
<td>150</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Figure 3-30: The data plotted using the proposed Br number.

This data may allow one to calculate the optimal ratchet geometry for various fluids. For example, using this data would imply that the optimal ratchet period for water would be 500 μm.
This process was repeated incorporating RMS roughness and is designated the non-dimensional roughness ratio (NRR). This does require surface characterization, but may add to the accuracy of the results. The non-dimensional roughness ratio is defined as:

\[ NRR = \frac{l_d}{AR^2R_{rms}} \]  

(3.10)

The result of the above analysis can be studied in Figure 3-31.

![Critical Heat Flux versus Non-dimensional Ratchet Roughness](image)

Figure 3-31: The data plotted using the proposed Non-dimensional Roughness Ratio.

Unfortunately, it does not appear that much can be gleaned from this analysis. If the 450x45 and 750x75 μm points were removed from the data then it would appear that a lower NRR value would be better for heat transfer performance.
In an attempt to predict the critical heat flux using non dimensional analysis in a similar manner which lead to Zuber’s [97] correlation, non-dimensional groups were plotted to see if a relation could be found. The results of this analysis can be observed in Figure 3-32 and shows that a very linear relationship exists between the non-dimensional groups and the experimental data.

![Nondimensional Study](image)

Figure 3-32: The results of the non-dimensional study showing a linear relationship.

Using the slope of the line as a constant to relate the two non-dimensional groups, an equation can be found for the system with the constant most likely being related to the surface fluid combination. This constant was found to be 0.403 with an $R^2$ value of 0.989. The resulting
An equation to estimate the critical heat flux can be studied below, but unfortunately is independent of ratchet geometry.

\[ q'' = 2.5 \sqrt{\sigma gh_f (\rho_l - \rho_v)} \]  \hspace{1cm} (3.11)

For FC-72 Equation 3.11 predicts a heat flux of 266 kW/m\(^2\). This has an average error of 5\% with a standard deviation of 0.09\% and a maximum error of 16\% when compared to the experimental ratchet data points. Equation 3.11 was then plotted against the data points with a ±15\% error bars and can be studied in Figure 3-33. While Equation 3.11 under predicts the peak value of the critical heat flux, its error is significantly lower than other values in the literature as discussed in chapter 3.8.

![Equation 3.11 versus Experimental Data](image)

Figure 3-33: Equation 3.11 shown in red plotted against the experimental data.
It may be possible to use this to estimate the critical heat flux for ratchets. However, this would require a few samples to be run in order to get the equation constant. This is not a practical solution and experiments would need to be run for various fluid/surface combinations.

3.11 Modeling

An attempt was made to predict CHF performance of the ratcheted by modifying Equation 2.8 using the Br number. The Br number was inserted in to equation 2.8 during derivation assuming that the ratchet geometry modifies the Taylor instability wavelength which was assumed to be approximately half of the bubble diameter. This implies that the ratchets may alter the bubble diameter or, at minimum, the bubble diameter and ratchet geometry are somehow related. Bubble size modification is believed to be one of the reasons for heat transfer enhancement. The modified equation 2.8 can be observed below.

\[ q_c'' = h_f g \rho_g \frac{1}{2} \left( \frac{1 + \cos \beta}{16} \right) \left[ \frac{2(1 + \alpha)}{\pi \text{Br}(1 + \cos \beta)} + \frac{\pi}{4} \text{Br}(1 + \cos \beta) \cos \Phi \right]^{1/2} \times [\sigma \lambda g (\rho_l - \rho_v)]^{1/4} \quad (3.11) \]

Plotting the results for several relevant Br values versus \( \alpha \) can be studied in Figure 3-34 below. The results show that \( \text{Br} = 2 \) fits the experimental data reasonably well and is also approximately the Br number of the 150x15 \( \mu \text{m} \) sample (\( \text{Br} = 2.1 \)).

Figure 3-35 shows the results of choosing \( \text{Br} = 2 \) and applying \( \pm 15 \% \) error bars. The data is reasonably well predicted on par with correlations found in the literature. Since the data is reasonable well predicted with Equation 3.11, it suggests that the ratchets may indeed modify the bubble diameter which is more capable of disturbing the superheated boundary layer and enhances heat transfer.
Experimental Data versus Modified Chu using Br Number

Figure 3-34: The data plotted using the modified Chu model against various Br numbers.

3.12 Conclusions

Seven brass samples, six micro ratchet and one polished control, were fabricated and characterized. The surfaces of each sample were characterized by measuring the surface wettability and roughness. The wettability was measured by studying released droplets via high speed camera and measuring the various contact angles. Overall surface roughness was measured using a mechanical profilometer.

A pool boiling chamber was designed and the various samples fabricated were tested for pool boiling heat transfer performance using the low boiling point organic liquid FC-72 as the working fluid. The boiling curve up to the critical heat flux and the heat transfer hysteresis were measured for each sample by increasing the power to cartridge heaters in a block in which the
Figure 3-35: The data plotted using Br = 2 with 15 % error spread.

A sample is attached. Temperatures of the fluid and sample block were measured with thermocouples. The thermocouples allowed for the measuring of the heat flux and heat transfer coefficient. Images of the experiment were taken using various methods.

Results show that with FC-72 the ratchets have a dramatic effect on heat transfer over the polished surface, increasing the flux by 130 % with the 150x15 μm sample and increasing the heat transfer coefficient 176 % with the 750x75 μm sample. The heat flux and heat transfer coefficient were also improved over the polished surface for nearly the entirety of the nucleate boiling regime. When looking at practical superheat values for electronic cooling, the ratchets showed improvement over the polished surface, but in this superheat region the 75x7.5, 100x10, and 750x75 μm samples had the highest performance.
The effects of ratchet period and aspect ratio were then systematically studied. The results show that for the sample sizes studied the 150 μm period and 10:1 aspect ratio provide the highest critical heat flux. Comparing the critical heat flux with the RMS roughness shows that an optimal roughness exists for heat transfer and this is a similar trend as found by various authors in the literature.

The boiling hysteresis of each sample was found by decreasing the power of the heater until bubble production ceased. It was found that the polished surface had little hysteresis while the 75x7.5, 150x15 μm showed hysteresis with improved heat transfer which is consistent with the literature. The 100x10, 150x30, 150S, and 750x75 μm showed reduced heat transfer hysteresis which is possible due to nucleation site activity. A hysteresis curve for the 450x45 sample was not found for the sake of experimental expedience.

The experimental data was compared to various models and other data found in the literature. The models predict the other experimental data, but significantly under predict the current experimental data. This is most likely the result of the underlying assumptions and simplifications made while deriving the model.

Various attempts were made to nondimensionalize the data in order to be able to design micro ratchets for various fluids. Some models require experimental data in order to use them. So, the proposed equations were designed to be simple to implement.

It is hoped that simulations will provide insight into the underlying ratchet enhancement mechanism. Currently, it is believed that the enhancement mechanism is the result of one or more of the following:

1. Contact angle hysteresis results in bubble spreading in an orthotropic manner which creates a pumping effect on the surface, increasing mass flow of liquid to the surface.
2. The ratchets help pin the triple point which result in lower receding contact angles that better prevent surface bubbles from coalescing. This obviates the insulative vapor layer on the surface that results in the critical heat flux.

3. The higher advancing contact angles that are created by the ratcheted surface in the perpendicular direction which results in larger bubbles upon departure and more efficient disruption of the thermal boundary layer, which results in higher overall heat transfer. The disturbance of the thermal boundary layer may induce rectified bulk motion of the fluid which would also enhance both latent and sensible heat transfer by increasing mass flow of liquid to surface.

4. Research has been shown that nearby bubbles can merge during growth and form a single bubble [98]. This bubble merger process may be rectified by the ratchets and again result in a pumping phenomenon mentioned earlier.
Chapter 4: Single Bubble Dynamics on Ratcheted Surfaces

4.1 Introduction

This chapter covers the design and testing of samples used to augment the heat transfer experiments discussed in the previous chapter, as well as providing experimental background and support for simulation work. The main purpose of the experiment is to observe the isolated bubble ebullition on ratcheted surfaces. Studies of individual bubbles on well-defined isolated nucleation sites have served useful roles in elucidating bubble dynamics.

4.2 Nucleation Site Interaction

The spacing of nucleation sites has a marked influence on bubble dynamics. As bubbles grow, they can influence the behavior of the nearby nucleation sites in manners that can positively or negatively affect the heat transfer. The magnitude of these interactions can be determined largely by the ratio of the distance between nucleation sites and the bubble diameter. As this ratio decreases, the interactions between nucleation sites become stronger.

When the wall superheat increases at a particular nucleation site, the waiting time between the nucleation of a new bubble and the departure of the previous bubble becomes shorter. If a certain critical temperature is reached, succeeding bubbles merge to form a mushroom-like bubble. This merger can also involve pairs, consisting of a large bubble followed by a small one, departing from the same nucleation site. This is known as the region of interference - bubbles interfere with each other and form continuous vapor columns and patches.

Buyevich and Webbon [99] investigated the limit of the isolated bubble regime. They identified four contributing mechanisms that lead to this limit: 1) the upward flow of the rising bubble which obstructs the downward flow of liquid required to compensate for the vapor removal from the wall; 2) lateral coalescence of bubbles from several nucleation sites to form
large bubbles and extended vapor patches on the surface; 3) longitudinal coalescence close to the wall; 4) and longitudinal coalescence in the bulk. The authors identified the last mechanism as the most important effect for the termination of the isolated bubble region, as it can lead to the critical heat flux.

From their boiling experiments studying nucleation site interaction Zhang and Shoji [100] found three crucial effect factors: hydrodynamic interaction between bubbles, thermal interaction between nucleation sites, and horizontal and declining bubble coalescence. They hypothesized four intensity regions for the three effect factors based upon the ratio of the nucleation site spacing (S) and bubble diameter (l_o). As nucleation site spacing becomes smaller, interaction between sites becomes stronger. This can be studied in Table 4-1.

<table>
<thead>
<tr>
<th></th>
<th>S/l_o &gt; 3</th>
<th>2 &lt; S/l_o ≤ 3</th>
<th>1.5 &lt; S/l_o ≤ 2</th>
<th>S/l_o ≤ 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrodynamic interaction between bubbles</td>
<td>negligible</td>
<td>important</td>
<td>important</td>
<td>important</td>
</tr>
<tr>
<td>thermal interaction between nucleation sites</td>
<td>negligible</td>
<td>negligible</td>
<td>important</td>
<td>important</td>
</tr>
<tr>
<td>declining bubble coalescence</td>
<td>negligible</td>
<td>negligible</td>
<td>negligible</td>
<td>important</td>
</tr>
</tbody>
</table>

Creating artificial nucleation sites is a common practice in this field, allowing researchers to predict the location of nucleating bubbles and make observing bubble ebullition process possible [101]. Artificial nucleation sites are geometric variations such as holes, grooves, scratches, etc., which makes bubble nucleation thermodynamically favorable in a given location.

When designing experiments to study bubble dynamics, it is beneficial to study the individual bubbles. In order to do this, it is necessary to ensure that the S/l_o > 3 which means that for FC-72 the nucleation site spacing needs to be 2.19 mm at minimum to ensure operation within the isolated bubble regime. This will allow observation of the bubble at low superheats
possible and make modeling easier. If the nucleation site spacing is less than 2.19 mm, bubble dynamics are no longer decoupled, making modeling more complex and makes observation difficult.

4.3 Single Bubble Dynamics Experiments Sample Fabrication

Two additional brass (alloy 360, McMaster-Carr) ratchets of 150 and 750 μm period with a 10:1 aspect ratio were fabricated by a KERN MMP2522 micro milling machine into the 38.1 mm x 38.1 mm heated surface on the sample blocks. The ratchets rough cut with an 800 μm diameter end mill (PMT Tools) at 200 mm/min with a finishing pass at 75 mm/min with a 100 μm diameter end mill (PMT Tools). The spindle was 40,000 rpm for all passes. A 5.7° jig was used to angle the brass surface off the horizontal which achieves the 10:1 aspect ratio. This process can be studied in more depth in chapter 3.3.1. The polished sample from chapter 3 was reused for this experiment.

To remove the burrs left by milling, the samples were hot embossed into 50 mm x 50 mm x 5 mm PMMA sheets (Regal Plastics). Hot embossing was achieved by preheating an Atlas Series Hydraulic Press (Specac) to 70 °C and placing the brass mold into the hot plate to warm. The protective sheet was removed from the PMMA sheet and cleaned with compressed air. It was then placed on top of the brass mold and a steel plate placed on top of the PMMA. A slight pre-load was placed on the specimen by tightening the handle, the set temperature was increased to 165 °C, and the set-up was left to warm for 5 minutes. A load of 3 tons was then applied for an additional 5 minutes. Upon completion of molding, the set temperature was decreased to 70 °C and left to cool for approximately 45 minutes. The sample was then removed from the machine and the now molded PMMA sheet was then gently pried off the brass mold. To ensure that all of the burrs had been removed this process was repeated five times for the samples.
In order to measure the heat flux, a 3.2 mm diameter hole was drilled in the center of the sample and ended approximately 1 mm below the heated surface to allow for the insertion of two K type thermocouples.

To better achieve one-dimensional heat transfer, a pocket was milled into the two ratchet samples around the heated surface after an initial round of heat transfer measurements. This process had already been performed on the polished surface. A thin section of brass was left at the bottom of the pocket which was partially back filled with high temperature epoxy to ensure dimensional fidelity.

A requirement of a nucleation site is to entrain vapor. As mentioned above, artificial nucleation sites make bubble formation more thermodynamically favorable and, by trapping a small vapor seed, bubbles are able to grow at lower superheats than the surrounding homogenous surface. However, certain geometric constraints must be satisfied for a nucleation site to be effective. Following Wang and Dhir’s [102] criterion, a cavity will trap a vapor seed if

$$\theta < \phi_{\text{min}}$$

(4.1)

where $\phi_{\text{min}}$ is the minimum half angle of a spherical, conical, or sinusoidal cavity. This means a highly wetting liquid like FC-72 with its contact angle $\approx 0^\circ$ must have cavity slopes perpendicular to the surface. Practically speaking, the only way to create artificial nucleation for FC-72 is by drilling holes or creating reentrant cavities.

If the artificial nucleation sites are to be drilled, then a second requirement for the holes is that they must satisfy

$$d_c > \frac{w}{\tan \theta}$$

(4.2)

where $d_c$ is the critical cavity depth and $w$ is the cavity width or diameter. This means that FC-72 requires a cavity depth of approximately eleven times the diameter to ensure vapor entrapment.
Due to the bottom of the cavity having a higher superheat than the surface and dissolved gases in the working fluid, it may be possible to activate a nucleation site that does not satisfy the depth criteria.

Attempts were made to drill the holes using 50 μm diameter bits with a 15:1 aspect ratio (Harvey Tool) using the KERN MMP2522 micro milling machine, but the bits broke immediately upon contact with the sample surface even after creating a flat spot as a pilot.

Due to the difficulty drilling holes with the 50 μm bits, the same bits used for milling the samples were chosen to be used for drilling the artificial nucleation sites. The chosen bit was a 100 μm with a 0.31 mm flute length. The bits available only have a ~3:1 aspect ratio and therefore no bits satisfy the 11:1 aspect ratio needed. If a larger diameter bit is chosen then the hole may interfere with the bubble dynamics and choosing a smaller diameter bit would result in a flute length that may not successfully create a hole deeper than the ratchet height. This is particularly important in regards to the 750x75 μm sample with its large ratchet height. So it is believed that using a 100 μm bit is the optimal size.

The final hole dimensions were chosen to be at least 3 mm on center which is 23 % larger than the spacing needed to ensure the isolated bubble regime criterion. Once the 3 mm spacing is achieved, the next nearest ratchet trough will receive the artificial nucleation site. Three holes will be drilled on each sample assuring the above criterion 3 mm from the edge of the sample nearest the high speed camera.

Since the holes of the appropriate aspect ratio could not be fabricated, the artificial nucleation sites did not activate as designed. Therefore, significant bubble generation was observed making locating the artificial nucleation sites virtually impossible. This means that the
bubbles used for measurements may not be located at the artificial nucleation site, but bubbles chosen for measurement were believed to be in the isolated regime.

4.4 Heat Flux Data Acquisition

Heat flux can be simply measured by knowing the distance between two thermocouples, the thermal conductivity of the sample, and the temperatures at the thermocouples. The heat transfer coefficient can be measured after knowing the heat flux.

4.4.1 Thermocouple Calibration

Thermocouple calibration was performed in the same manner as discussed in chapter 3. Temperatures in the block were measured using an Extech ML 720 multimeter with a maximum temperature resolution of 1 °C and a base accuracy of ±0.3 %. The thermocouples were calibrated in an ice water bath and were found to have an error of ±2.6 %. Since the multimeter reads only to the nearest whole degree, a more precise method for temperature calculation had to be implemented. Therefore, using laboratory refrigerators and ovens, various temperatures and their corresponding voltages were measured (since voltages could be measured to the nearest hundredth of a millivolt). These values were then plotted to determine the multimeter sensitivity as shown in Figure 3-13.

The linear fit equation allows for temperature measurements to be calculated to the nearest hundredth of a degree by using an Excel spreadsheet. This is done during the experiment by measuring the voltage differential with the multimeter and inputting the values into Excel.

4.4.2 Uncertainty

The overall error for the experiment has been calculated using the method defined by Kline and McClintock [104] and is the same method used in chapter 3 according to equation 3.2. In order to calculate the heat flux and heat transfer coefficient the driving equations 3.3 and 3.4
were analyzed for the experiment. The results of the uncertainty analysis indicate that error for heat flux and heat transfer coefficient falls between 7 - 11 % in Table 4-2 which is typical for values found in the literature. The temporal uncertainty is limited by the frame rate of the high speed camera at ±1 ms.

Table 4-2: Uncertainty of the single bubble dynamics heat flux measurements.

<table>
<thead>
<tr>
<th>Sample (Period x Height)</th>
<th>Heat Flux and Heat Transfer Coefficient Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished</td>
<td>8.5</td>
</tr>
<tr>
<td>150x15 μm</td>
<td>7.4</td>
</tr>
<tr>
<td>750x75 μm</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Analyzing the data obtained from the bubble images via the analysis of variance method [105] reveals the error. The error shown is the range of uncertainty for the superheats studied and can be viewed in Table 4-3. The error is high (particularly bubble frequency) and makes it difficult to draw conclusions from the data. However, similar work has been performed by Hutter [106] and showed error for similar experiments as high as 25 % but the uncertainty in that case is based upon the standard deviation of three successive bubbles. So, it would be expected that uncertainty based upon the analysis of variance would be significantly higher.

Table 4-3: Uncertainty of the single bubble dynamics heat flux measurements.

<table>
<thead>
<tr>
<th>Sample (Period x Height)</th>
<th>Bubble Departure Frequency Error (%)</th>
<th>Relative Bubble Departure Diameter Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished</td>
<td>±52</td>
<td>±9 – 36</td>
</tr>
<tr>
<td>150x15 μm</td>
<td>±65 – 180</td>
<td>±25</td>
</tr>
<tr>
<td>750x75 μm</td>
<td>±23 – 66</td>
<td>±17 – 23</td>
</tr>
</tbody>
</table>
4.5 Boiling Fluid

The working fluid for the boiling experiment was the same for that used in chapter 3, which is fluorinert FC-72 (perfluorohexane C₆F₁₄, 3M). FC-72 is a non-flammable, non-toxic, non-corrosive liquid that is commonly used in boiling experiments. It is also clear and colorless which allows for easy observation of bubble nucleation and departure. It has a low boiling temperature \(T_{\text{sat}} \approx 57 \, ^\circ\text{C}, \text{at} \, 1 \, \text{bar}\) and high dielectric strength which make it possible to completely immerse electrical components. More information on the fluid can be reviewed in chapter 3.5.

4.6 Single Bubble Dynamics Experimental Procedure

Prior to any testing, the system was assembled and tested for leaks. Once the system was assured to be leak fit tests could begin. Before the sample was installed the base of the sample was coated with a thin layer of thermally conductive grease. The hole for the thermocouple was liberally filled with grease. The vertical side walls near the heater surface were coated with a thin layer of RTV silicone to ensure sealing between the Teflon cap and the sample. The thermocouple spacing was checked and measured before installing the sample and screwing it to the heater block, being sure to align the gratings parallel with the high speed camera. The Teflon cap was then installed and screwed down. The countersink holes in the Teflon cap were then filled with RTV to ensure sealing around the screws. The system is then purged with compressed air for at least 30 minutes to allow the RTV to “skin” and partially harden. The continuous flow of gas ensures that the volatile acids that are released by the RTV as it cures can be diluted before being vented and alleviates corrosion issues. The interior of the chamber is then wiped down with ethanol to remove dust, oils, and other contaminants.
After the RTV has “skinned”, the boiling chamber is then filled with FC-72 to a predetermined fill line and a cursory leak check is performed. The chamber is checked with a digital level. A p-trap is formed in the vent line between the boiling chamber and the fume hood and is primed with water. The p-trap prevents the continuous flow of material from being pulled from the chamber by the fume hood. The cooling water to the condenser is turned on and checked for leaks. The chamber is then purged with argon at a flow rate of approximately 100 ml/min for one hour by connecting the argon to the lid side of the sight tube and plugging the sight tube connection at the chamber lid. One this process is complete, the sight tube is reconnected. It is at this point that chamber heating begins. The external heater is turned on to 45% power, the cartridge heaters are turned on to low power via the Variac, and the experiment is started as soon as steady state is reached. The degassing period is avoided in order to encourage activation of nucleation sites at lower superheats.

The HMI 575 back light (Cinemills) is setup with the viewport across from the Kodak Model HRC1000 High Speed Camera and a frosted glass diffuser is placed between the light and boiling chamber. The light is then turned on and allowed to warm. The high speed camera is turned on, setup (1000 FPS, 50 μs exposure, 25 mm lens spacer), aligned and focused on the sample.

The fluid is ensured to be at saturation by measuring the thermocouples and ensuring a fluid temperature between 56 – 58 °C. The heater block thermocouples are measured repeatedly until steady state operation is determined. The variable transformer power is then increased a few percent and the system is allowed to reach steady state. This process is repeated until boiling is observed on the heater surface and the thermocouple values are then recorded and high speed video recordings are taken. Once recordings and measurements are taken, the power to the
transformer is increased in 1% power increments and the data recording process is repeated until the range of superheat to be studied is traversed. The variable transformer, external heater, cameras, and light are turned off and the system is allowed to cool ensuring that the water to the condenser is not interrupted. Once the system is cooled to room temperature the FC-72 can be drained and the system can be prepared for the next sample.

The bubble diameters were measured by importing the relevant frames into computer aided design software (Solidworks) and manually measuring the bubble diameters at the surface. Without some method of scaling the CAD images, the results only give a relative diameter. One of the main goals of the experiments was to determine if ratcheted surfaces alter the bubble diameter, absolute bubble diameter is unnecessary. Also, these measurements have been performed by numerous authors and finding the absolute bubble diameter was felt to be repetitive.

4.7 Results

The experiment is limited because as superheat increases bubble generation subsequently increases as well. The end result is that observing bubble generation, growth, and departure at the surface becomes impossible even at moderate superheats. The highest superheat that still allowed for bubble generation was 19 °C with the average superheat being 13 °C. When it was observed via the high speed camera that bubble observation was impossible the shutdown procedure is then initiated. Therefore, the data reported for all cases is the first two data points at which boiling was observed.

It is difficult to study any bubbles on the surface and the bubbles that were able to be studied were limited. This leads to high uncertainties as discussed in chapter 4.4.2. Adding to this difficulty was the fact that the low aspect ratio of the artificial nucleation sites resulted in
them not activating at low superheats which resulted in a field of bubbles in the images. This field of bubbles makes it difficult to track an individual bubble during its ebullition period and make it difficult to accept that the bubble growth is not being affected by nearby bubbles, which would result in altering the nature of individual bubble growth.

All data was normalized by dividing by the bubble diameter and bubble frequency of the polished surface at the lowest superheat. In Figure 4-1 the bubble growth on the polished surface with a wall superheat of 10.3 °C and 11.5 °C and applied heat flux of 9.3 kW/m² and 15.9 kW/m² respectively are presented. The relative departure diameters are approximately 1.0 for both superheats which is expected given the normalization. The lower superheat shows the typical exponential growth trend. The initial bubble growth is rapid and begins to saturate before the bubble detaches. The higher wall superheat shows the bubble reached departure diameter and detaches soon after.

In Figure 4-2 the bubble growth on the 150x15 μm surface with a wall superheat of 15.9 °C and 19.1 °C and applied heat flux of 19.0 kW/m² and 27.9 kW/m² respectively are presented. The relative departure diameters are approximately 0.92 and 1.15 respectively. The lower wall superheat shows the bubble has a relatively linear growth profile before detachment. The higher superheat shows the initial bubble growth is rapid and begins to saturate before the bubble detaches. Also, the bubble diameter oscillates as the departure diameter is reached which may be indicative of the “pumping” phenomena discussed in chapter 3.12.

In Figure 4-3 the bubble growth on the 750x75 μm surface with a wall superheat of 9.2 °C and 19.0 °C and applied heat flux of 14.2 kW/m² and 15.6 kW/m² respectively are presented. The relative departure diameters are approximately 0.86 and 1.12 respectively. The lower wall
Figure 4-1: The results for the single bubble dynamics experiments with the polished surface. Superheat shows the bubble has a relatively linear growth profile before detachment. The higher superheat shows the initial bubble growth is rapid and begins to saturate before the bubble detaches. Also, the bubble diameter oscillates as the departure diameter is reached. In a similar manner to the 150x15 μm sample. The 750x75 μm sample shows a reduction in departure diameter and bubble departure frequency with increasing superheat which is a trend reversal when compared to the previously discussed samples.

Plotting the relative bubble departure diameter versus superheat for the samples in this study makes it less difficult to compare the samples due to the fact that the measurements
occurred at various superheats. This is an unavoidable side effect of having a power controlled heater. Due to the fact that only two data points could be resolved, only a linear trend can be assumed. Hutter [107] performed similar experiments using FC-72 and showed a linear relationship between relative bubble departure diameter and superheat so a linear regression is satisfactory. This data can be studied in Figure 4-4 and the trend for relative bubble departure diameter agrees with Hutter in that relative bubble diameter increases linearly with increasing superheat.

Figure 4-4 shows that the relative bubble departure diameter on the polished surface has the weakest relationship with superheat. The 150x15 μm and 750x75 μm surfaces have 4.2 and
Figure 4-3: The results for the single bubble dynamics experiments with the 750x75 μm ratchet surface.

8.3 times higher slopes respectively. The figure also suggests that the relative bubble departure diameters for the polished and 750x75 μm samples are similar at a superheat between 10 -12 ºC, but the 750 x75 μm sample relative bubble departure diameter quickly grows larger than the polished surface as superheat is further increased.

For the superheat range studied, the relative bubble departure diameter for the 150x15 μm sample is smaller than both remaining samples. However, at a superheat of approximately 19 ºC the relative bubble departure diameter of the polished and 150x15 μm samples is roughly 1.2. The trend suggests that at higher superheats the 150x15 μm would have a larger relative bubble departure diameter than the polished surface as superheat is increased past this point.
Figure 4-4: The relative bubble diameter versus superheat for the three samples used in this study.

Performing a similar exercise as above, comparing the relative bubble departure frequency versus superheat reveals a similar linear trend as shown in Figure 4-4. Again, only two data points could be resolved meaning only a linear trend can be assumed. The results again agree with those found by Hutter so a linear regression is satisfactory. This data can be studied in Figure 4-5 and the trend for relative bubble diameter agrees with Hutter in that relative bubble departure frequency increases linearly with increasing superheat except for the 750x75 μm sample.
Figure 4-5 shows that the relative bubble departure frequency on the polished surface has the strongest relationship with superheat. The 150×15 μm surface has an approximately 3.5 times smaller slope than the polished surface. The 750×75 μm surface has a negative slope that is -1.93 times smaller than the polished surface and means that the relative departure frequency decreases as superheat increases which is the opposite trend one would expect. This may be the result of variations in nucleation site activation as the superheat is changed which can alter bubble dynamics. The figure also suggests that the relative bubble departure frequencies for the polished and 750×75 μm samples are similar at a superheat of 10 °C, but the 750×75 μm sample relative bubble departure frequency quickly grows smaller than the polished surface as superheat is further increased. Similarly, at a superheat between 11-12 °C the 750×75 μm and 150×15 μm samples share the same relative bubble departure frequency. For most of the superheat range studied, the relative bubble departure frequency for the polished sample is larger than both remaining samples. Given the slope of the polished surface it is expected that the relative bubble departure frequency would remain higher than the other samples.

In order to grasp the overall effect of the bubble departure diameter and frequency on the evaporative heat flux, a basic energy balance is implemented. The removal of heat by latent heat transfer as a result of vapor generation (i.e. evaporation) is estimated from the product of the measured bubble frequency and the volume of the generated bubble, modeled as a sphere, which is calculated from the bubble departure diameter. The value is then divided by the area of the bubble to obtain the heat flux. The evaporative heat flux can be expressed as:

\[
q_e^* = \frac{\pi}{6} f D_b \rho_g h_{fg}
\]

(4.3)

where \(q_e^*\) is the evaporative heat flux, \(f\) is the bubble departure frequency, \(D_b\) is the bubble departure diameter, \(\rho_g\) is the saturated vapor density, and \(h_{fg}\) is the heat of vaporization. The
bubble departure frequency is the sum of the bubble growth time and the bubble waiting time (time between one bubble detaching and the next bubble nucleating), but the bubble waiting time is negligible beginning at superheat around 10 °C [108].

From Equation 4.3 it is quickly seen that the evaporative heat flux is equally weighted between the bubble departure diameter and frequency. Plotting these values shows that at the same superheat one would expect the polished surface to have the highest evaporative heat flux, but the 150x15 μm has the highest overall heat flux. This suggests that the 150x15 μm sample has enhanced sensible heat transfer as a result of the surface structure. This can be studied in Figure 4-6.
Figure 4-6: The relative evaporative heat flux versus superheat for the three samples used in this study.

4.8 Conclusions

Three brass samples, two micro ratchet and one polished control, were fabricated in order to study the effects of ratcheted surfaces on single bubble dynamics. Holes were drilled in the sample in an attempt to create artificial nucleation sites to aid in the image capture of the bubbles nucleating and growing on the surface. Images of the bubbles growing on the surface were captured with a high speed camera. These images were used to calculate the relative bubble departure diameter and departure frequency of the bubbles on the various samples.

The boiling chamber discussed in Chapter 3 was employed and the various fabricated samples were tested using the low boiling point organic liquid FC-72 as the working fluid. Heat
transfer data and images were taken until bubble ebullition became so vigorous that observation of the bubbles on the surface became impossible, at which point the experiment was ended.

Studying the bubble growth over an ebullition period corresponds well to the literature. Bubbles diameter initially grows rapidly and saturates. For the ratcheted samples, the saturation period of the bubble growth cycle shows an oscillation which could be indicative of bubble “pumping” as hypothesized in the previous chapter.

Results compare well with the literature showing linear trends in regards to bubble departure diameter and departure frequency versus superheat. However, the limited number of bubbles that were clear enough to characterize resulted in undesirable uncertainties. The results indicate that ratchets have a large effect on bubble departure diameter and increase its sensitivity to superheat. Analyzing bubble departure frequency shows that the polished surface is more sensitive to superheat with the 750x75 μm showing an unexpected decrease in departure frequency with increasing superheat. This trend reversal may be indicative of variations in nucleation site activity during the experiment.

Acquiring the bubble departure diameter and frequency allows for the use of a simplified model to estimate the evaporative heat flux. This is the portion of the overall heat flux that results from the generation of vapor bubbles on the surface. This analysis shows that the polished surface has the highest evaporative heat flux over the superheat regime, but the fact that the 150x15 μm sample has the highest overall heat flux suggests that the 150x15 μm sample must have enhanced sensible heat transfer as a result of the surface structure. This observation coupled with the fact that the bubble departure diameter of the 150x15 μm sample overtakes the polished surface at higher superheats supports the enhancement theories developed at the end of chapter 3.
Chapter 5: Conclusions and Recommendations

5.1 Conclusions

This research was performed in order to understand the effects of asymmetric micro ratchets on pool boiling heat transfer, attempt to enhance the heat transfer over polished surfaces using FC-72, and begin simulating the results in order to understand the underlying enhancement mechanism. After designing and fabricating a boiling chamber and performing detailed surface characterization, experimental results indicate that asymmetric ratchets improve pool boiling heat transfer significantly over the polished surface. This enhancement significantly outperforms other surfaces found in the literature and is currently underpredicted by several models.

Single bubble dynamics experiments were performed in order to get a better glimpse of bubble/surface interaction. Bubble growth on the ratcheted surface seems to confirm the “pumping” phenomena which may be a possible explanation for enhanced heat transfer. Studying the relative bubble departure diameter and frequency on the surfaces shows that the ratchets can increase bubble departure size and enhance overall sensible and latent heat transfer.

5.2 Future Work

Simulation work is ongoing. Experience is being gained using ANSYS FLUENT and more complex models will be developed that include dynamic contact angle effects which allow for a moving triple point. This will more accurately model the system. Also, preliminary experiments studying the effects of asymmetric micro ratchets on condensation have begun and are showing promise of enhancing that mode of heat transfer also.

5.3 Recommendations

As with many complex ventures, hindsight and recommendations from other experts reveal alternative and/or improved methods for accomplishing the research that would have
enhanced or eased the completed research. Several recommendations for the sample fabrication, experimental apparatus, and experimental method will be discussed.

5.3.1 Sample Fabrication

When the samples were first fabricated the available facilities did not have the cooling system connected to the KERN milling machine. As a result, machining staff would only mill high lead brass and would not allow for the milling of less sensitive materials such as stainless steel. Since the completion of the experimental work, a cooling system has been connected to the milling machine and new materials are now able to be machined. Using stainless steel would eliminate the variation in surface wettability due to surface oxidation. This may also reduce the importance of the argon purge prior to boiling the working fluid which necessarily removes a large amount of the volatile and expensive FC-72. Free machining 303 stainless steel would be a good material for future ratchet fabrication via milling. However, care will need to be taken to recalculate the heat flux, heat transfer coefficient, and experimental uncertainty as they are related to the thermal conductivity of the material.

The addition of the coolant spray to the milling machine will improve the machining tolerances by better controlling the sample temperature during machining. Temperature fluctuations in the room and as a result of the milling process can cause thermal expansions on the order of the height of the ratchets. For example, a 3 °C variation in sample temperature results in approximately a 2 μm change in height. This would make it nearly impossible to machine small period ratchet samples and would significantly alter ratchets with small heights.

The final recommendation is to have the pocket milled around the heated surface on all samples. This is far safer to do before the ratchets are milled in place without running the risk of
damaging them and easier to have them milled via computer control. This will aid in experimental accuracy and ensure all samples are the same.

5.3.2 Experimental Method

In order to better measure the heat flux, it is recommended that smaller diameter thermocouples be used. This would allow for the use of additional thermocouples which would improve the estimation of the temperature gradient in the sample.

Since the boiling chamber is a modified vacuum chamber it may be possible to study the effects of the ratchets on nucleation site density. By reducing the pressure, boiling can be initiated at reduced temperatures. This would allow the bubbles on the surface to nucleate slowly and an estimate of the nucleation site density to be obtained. However, additional seals may need to be incorporated into the chamber in order to seal against vacuum.

Thermocouples have an uncertainty of about 1 °C while thermistors and RTDs have much better uncertainties. This would help reduce experimental uncertainty. However, thermistors and RTDs are not as easy to use as thermocouples.

An effort to remove some of the material from the heater block would help expedite the experimental process. When the power to the heaters is changed, the heater block and sample have to be heated to steady state. The mass of the heater block is significantly larger than the block so the time spent waiting for steady state to be reached is a result of the thermal capacitance of the heater block. Clever machining could be implemented so that mass from the heater block could be removed and simultaneously reduce the radial heat loss. These combined actions could significantly reduce overall experimental run time.

In a similar fashion, the manner in which the heater block bolts to the lower chamber flange sandwiches a ceramic insulator, but heat transfer from the base of the heater block through
the lower flange causes boiling on inside surface of the flange during operation. This bubble generation inhibits viewing of the heated surface and requires the heaters to operate at a higher load. By simply removing some of the material on the heater block and lower flange surfaces that sandwich the ceramic plate, the heat transferred to the liquid and therefore bubble generation from the lower flange will be reduced. A new heater block was designed and could possibly reduce experiment run time by 18%.

Bubbles generated from the boiling chamber itself as a result from the external heater tape interfere with the ability to observe the heated surface with the high speed camera. A small baffle plate could be attached to bottom side of the viewport nipple to deflect bubbles around the plate and allowing for better study of the heated surface.

The single bubble dynamics study was plagued by the difficulty with observing the bubbles on the sample surface. This is the result of several factors. The magnification of the high speed camera was limited by the ability to focus on the nucleating bubbles. If the magnification was increased, by installing additional spacers, then focusing becomes impossible. One possible solution is to find alternative objectives that may be able to increase magnification while maintaining a clear image. The inability to drill the appropriate aspect ratio sized hole resulted in the artificial nucleation sites not becoming active until the surface was relatively inundated with bubbles making image capturing difficult and tedious. Laser drilling is one, albeit expensive, solution to drilling the hole. Finally, the frame rate of the camera was limited to 1000 FPS and it is believed that if a higher frame rate camera were available the image resolution and temporal accuracy could be improved.

Finally, it may be prudent for future experiments to change the working fluid. FC-72 is rather expensive and alternatives exist. Due to the fact that the decision to use FC-72 was made
and experiments had already begun before the knowledge of a similar replacement was known, its cost had to be borne. If a new set of experiments is to be run and comparison to this work is not necessary, it is recommended that a switch to Novec 7100 produced by 3M be made.

If the decision is to continue the use of FC-72 for experimental perpetuation, it is recommended that the liquid be kept refrigerated. This will reduce the vapor pressure by approximately 60%. Thus, during long term storage and initial filling and purging of the chamber the amount of liquid lost will be reduced significantly, helping reduce experimental costs and material waste.
References

Portions of this work have been adapted from Hutter (2009) and Sajid (2010).


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Appendix A: Heat Flux Hysteresis Curves

Polished Boiling Hysteresis Curve

Figure A.1: The hysteresis of the polished sample.

75x7.5 Boiling Hysteresis Curve
Figure A.2: The hysteresis of the 75x7.5 sample.

Figure A.3: The hysteresis of the 100x10 sample.

Figure A.4: The hysteresis of the 150x15 sample.
Figure A.5: The hysteresis of the 150x30 sample.

Figure A.6: The hysteresis of the 150S sample.
Figure A.6: The hysteresis of the 750x75 sample.
Appendix B: Test Apparatus Design Drawings

Figure A.7: The stainless steel six way cross vacuum chamber drawing.
Figure A.8: Chamber top flange drawing.
Figure A.9: Chamber bottom flange atmospheric side drawing.
Figure A.10: Chamber bottom flange fluid side drawing.
Figure A.11: Teflon sleeve drawing.
Figure A.12: Teflon sleeve and sample cap drawing.
Figure A.13: Teflon cap insulation plate drawing.
Figure A.14: Brass sample drawing.
Figure A.15: Heater block drawing.
Figure A.16: Chill plate drawing.
Figure A.17: Chill plate holder drawing.
Figure A.18: Updated heater block drawing.
Figure A.19: Updated heater block flange drawing (page 1).
Figure A.20: Updated heater block flange drawing (page 2).
Figure A.21: Updated heater block assembly.
Appendix C: Material Suppliers

Allied Electronics, Inc.
7151 Jack Newell Blvd. S.
Fort Worth, Texas 76118 U.S.A.
(866) 433-5722

Aremco Products Inc.
707 Executive Blvd.
Valley Cottage, NY 10989
1 (845) 268-0039
http://www.aremco.com

Cinemills
2021 North Lincoln Street
Burbank, CA, 91504
(818) 843-4560
http://cinemills.com

Cotronics Corporation
131 47th Street,
Brooklyn, NY 11232
(718) 788-5533
http://www.cotronics.com

Kinetic Systems, Inc.
20 Arboretum Road
Boston, MA  02131
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McMaster-Carr
6100 Fulton Industrial Blvd. SW
Atlanta, GA 30336-2853
(404) 346-7000
http://www.mcmaster.com

Harvey Tool Company, LLC
428 Newburypoint Turnpike
Rowley, MA 01969-1729
(978) 948-8555
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Omega Engineering
One Omega Drive
P.O. Box 4047
(888) 826 6342
http://www.omega.com

OnlineMetals.com
1138 W. Ewing Street
Seattle, WA 98119
(800) 704-2157
http://www.onlinemetals.com

Permatex
10 Columbus Boulevard
Hartford, Connecticut 06106
(860) 543-7500
http://www.permatex.com

Performance Micro Tool
4280 Kennedy Road
Janesville, WI 53547
1-866-737-3676
http://www.pmtnow.com/

Regal Plastics Supply Company
11776 S Choctaw Dr
Baton Rouge, LA 70815
(800) 749-3240

Specac
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Swedesboro, NJ 08085, USA
(800) 447 2558
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TFS Technologies
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Vita

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