2011

Pool boiling enhancement via micro ratchets

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POOL BOILING ENHANCEMENT VIA MICRO RATCHETS

A Thesis

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
Master of Science in Mechanical Engineering

In

The Department of Mechanical Engineering

by

Lance Austin Brumfield
B.S. Louisiana State University, 2009
May, 2011

This thesis is dedicated to:

My parents

Jon and Wendy,

For helping to 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.

To my Grandmothers,

For being my biggest fans.

And to my friends,

For showing me the lighter side of life.

Acknowledgements

I would like to offer sincere thanks, appreciation, and gratefulness to my advisor Dr. Sunggook Park for his consistent guidance and support throughout my Master's research and academic studies. This investigation was partially supported by the Center for Nanoscale Mechatronics & Manufacturing (CNMM), one of the 21st Century Frontier Research programs from the Ministry of Science and Technology, Korea and the National Science Foundation.

I would also like to thank my advisory committee members, Dr. Dimitris Nikitopoulos and Dr. Michael Murphy, 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 that have provided me with quality teaching instruction and support during my undergraduate and graduate studies.

Finally, I must thank my family, friends, and colleagues for their constant support and encouragement that has been vital to my success throughout my academic career.

Table of Contents

Acknowledgements.....	iii
List of Tables.....	viii
List of Figures.....	ix
List of Nomenclature	ix
Abstract	xi
Chapter 1: Introduction	1
1.1 Motivation	1
1.2 Outline of the Thesis	2
Chapter 2: Literature Survey	4
2.1 Pool Boiling Heat Transfer	4
2.1.1 Pool Boiling Curve.....	4
2.1.2 Nucleate Boiling Mechanisms	5
2.1.3 Nucleate Pool Boiling Correlations.....	7
2.1.4 Critical Heat Flux Correlations	9
2.2 Enhancing Pool Boiling Heat Transfer	12
2.3 Asymmetric Micro and Nano Ratchets	14
2.3.1 Flow Rectification	14
Chapter 3: Experimental Setup	18
3.1 Introduction	18
3.2 Ratchet Surface Fabrication	18
3.3 Experimental Apparatus for Pool Boiling.....	19
3.3.1 Area Enhancement	23
3.3.2 Thermocouple Calibration.....	23
3.4 Experimental Procedure for Pool Boiling Experiments	25
3.4.1 Preliminary Experiments.....	25
3.4.2 Concentration Dependence Experiments	27
3.4.3 Working Fluid	29
3.5 Uncertainty	29
3.6 Conclusions	30
Chapter 4: Pool Boiling on Micro Ratchets.....	31
4.1 Introduction	31
4.2 Characterization of Surfaces	31
4.3 Pool Boiling on Microratchets	33

4.4 Heat Transfer Analysis.....	34
4.5 Adjusted Heat Transfer Results.....	39
4.6 Location Dependent Heat Transfer	40
4.7 Reverse Flow Observations.....	43
4.8 Post Experimentation Surface Characterization.....	44
 Chapter 5: Effect of Nanoparticle Concentration on Pool Boiling on Microratchets.....	 50
5.1 Introduction	50
5.2 Characterization of Surfaces	50
5.3 Pool Boiling on Microratchets	52
5.4 Thermal Analysis	54
5.5 Adjusted Results.....	56
5.6 Post Experimentation Surface Characterization.....	58
5.7 Conclusions	62
 Chapter 6: Conclusions and Future Work.....	 64
6.1 Conclusions	64
6.2 Limitations and Recommendations	65
6.3 Future Work	66
 References.....	 68
 Appendix A: Test Apparatus Design Drawings	 73
 Appendix B: Material Suppliers	 76
 Vita.....	 77

List of Tables

Table 3-1: Area enhancement ratios for the various surfaces.....	23
Table 3-2: Table showing the nano particle solutions used in the second series of tests.....	27
Table 3-3: Table containing error values for the experiment.....	30
Table 4-1: Surface characterization results for the first series of experiments.....	33
Table 4-2: Contact angle measurements of the 150 μ m and polished surfaces before experimentation.....	34
Table 4-3: Maximum and average performance characteristics of the various surfaces and working fluids. The polished surface with DI water is used as the reference.....	36
Table 4-4: Maximum and average performance characteristics of the various surfaces and working fluids adjusting for thermal resistance of glued layer. The polished surface with DI water is used as the reference.....	40
Table 4-5: Surface characterization results for the first series of experiments.....	47
Table 4-6: Contact angle measurements for the polished and 150 μ m surfaces.....	48
Table 5-1: Surface characterization results for the first series of experiments.....	52
Table 5-2: Contact angle measurements of the 375 μ m, 150 μ m and polished surfaces before experimentation.....	52
Table 5-3: Maximum and average performance characteristics of the various surfaces and working fluids. The polished surface with DI water is used as the reference.....	54
Table 5-4: Maximum and average performance characteristics of the various surfaces and working fluids adjusting for thermal resistance of glued layer. The polished surface with DI water is used as the reference.....	54
Table 5-5: Surface characterization results for the experiments.....	61
Table 5-6: Contact angle measurements for the surfaces.....	62

List of Figures

Figure 2-1 Brief overview of mechanisms in nucleate boiling (adapted from Hsu and Graham [4]).....	6
Figure 2-2: Kandlikar correlation plotted for various receding contact angles on a copper surface using DI water.....	7
Figure 2-3: Heat transfer mechanisms during nucleate pool boiling, Kenning [8].....	8
Figure 2-4: Rohsenow correlation for nucleate pool boiling heat transfer for DI water at atmospheric pressure.....	9
Figure 2-5: Kandlikar correlation plotted for various receding contact angles on a copper surface using DI water.....	12
Figure 2-6: Cartoon drawing 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 [37].....	15
Figure 3-1: (a) Image of the process scheme for the fabrication of miniaturized ratchets in brass by micromilling and (b) definition of period and height of finished ratchets.....	19
Figure 3-2: Schematic of the arrays machined into the brass blocks.....	20
Figure 3-3: The polished brass block after thermocouple insertion and sealing.....	21
Figure 3-4: The completed test aquarium (post experimentation).....	22
Figure 3-5: Measured multimeter sensitivity.....	24
Figure 3-6: View of the experimental setup.....	26
Figure 4-1: Scanning electron micrograph of the 150 μm period ratchet and polished surfaces after fabrication. (a) 150 μm 50x, (b) 150 μm 250x, (c) polished 500x, (d) polished 500x.....	31
Figure 4-2: Results of optical profiler analysis showing the overall height and period of the ratchet after multiple cleanings. Note the rounded edges of the ratchets.....	33
Figure 4-3: Images of the 150 μm and polished surfaces at various set temperatures.....	35
Figure 4-4: Average vertical heat flux results for the various surfaces and working fluids.....	37
Figure 4-5: Average HTC results for the various surfaces and working fluids.....	38

Figure 4-6: Heat flux versus HTC for the various surfaces and working fluids.....	39
Figure 4-7: Image of the 150 μ m ratchet and the expected flow direction.....	41
Figure 4-8: Vertical heat flux dependence of the polished surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.....	42
Figure 4-9: Vertical heat flux of the 150 μ m ratchet surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.....	43
Figure 4-10: Examples of reversed flow on the 150 μ m ratchet at two hot plate set temperatures (a) 340°C (expected) and (b) 360°C (reverse).....	44
Figure 4-11: SEM images of the 150 μ m period ratchet and polished surfaces after experimentation. (a) 150 μ m 100x, (b) 150 μ m 500x, (c) polished 100x, (d) polished 500x.....	45
Figure 4-12: Images of the surfaces before and after experimentation (a) initial polished, (b) initial 375 μ m ratchet, (c) post 150 μ m, (d) post polished.....	46
Figure 5-1: Scanning electron micrograph of the 150 μ m period ratchet and polished surfaces after fabrication. (a) 150 μ m 50x, (b) 150 μ m 250x, (c) 375 μ m 50x, (d) 375 μ m 100x, (e) polished 500x, (f) polished 500x.....	50
Figure 5-2: Images of the 375 μ m and polished surfaces at 400°C set temperature with various concentrations of nanoparticles.....	53
Figure 5-3: Vertical heat flux of the 375 μ m ratchet surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.....	55
Figure 5-4: Alumina nano particle concentration dependence for the polished and 375 μ m ratchet surfaces.....	57
Figure 5-5: Adjusted average vertical heat flux for the polished and ratchet surfaces.....	58
Figure 5-6: SEM images of the 375 μ m period ratchets and polished surfaces after experimentation. (a) 375 μ m 50x, (b) 375 μ m 100x, (c) polished 100x, (d) polished 500x.....	59
Figure 5-7: Images of the surfaces before and after experimentation (a) initial polished, (b) initial 375 μ m ratchet, (c) post 150 μ m, (d) post polished, (e) post 375 μ m.....	60
Figure 6-1: The experimental test rig for future experiments.....	66

List of Nomenclature

Greek Letters

β	deg	dynamic receding contact angle
μ_l	Ns/m ²	liquid absolute viscosity
ϕ	deg	horizontal surface angle
ρ_l	kg/m ³	liquid density
ρ_v	kg/m ³	vapor density
σ	N/m	fluid surface tension

Latin Letters

A	m ²	surface area
C	m/s	constant
cp _l	J/kgK	liquid specific heat
C _{s,l}	-	constant
g	m/s ²	local gravitational acceleration
g _s	m/s ²	standard gravitational acceleration
h	W/m ² K	heat transfer coefficient
h _{fg}	J/kg	heat of vaporization
K	-	constant
k	W/mK	thermal conductivity
Pr _l	-	liquid Prandtl number
n	-	constant
Ra	μm	average surface roughness
ΔT	K	temperature difference
T _A	K	temperature at point A

T_B	K	temperature at point B
T_S	K	surface temperature
T_{SAT}	K	liquid saturation temperature
Q	J/s	total heat transfer
q''	J/m^2s	heat flux
q''_{CHF}	J/m^2s	critical heat flux
w	-	uncertainty of dependent variable
w_R	-	uncertainty of function
Δx	m	distance between thermocouples
x	-	dependent variable

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 issues with implementing nucleate boiling as a cooling mechanism lies in the difficulty of quantifying the complex and numerous 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. Three brass surfaces were tested for comparison, one surface was manually polished, the second was composed of asymmetric ratchets with $30 \text{ }\mu\text{m}$ height and $150 \text{ }\mu\text{m}$ period and the third $75 \text{ }\mu\text{m}$ height and $375 \text{ }\mu\text{m}$ period asymmetric ratchets. Small test aquariums were fabricated and tested on a hot plate. Heat flux and heat transfer coefficient (HTC) were measured with thermocouple arrays and video and photographic images were taken at various set temperatures. Results show that $150 \text{ }\mu\text{m}$ ratchets can improve heat flux by 61 % using DI water and by 210 % using a 0.03 wt.% microparticle (MP) solution over a polished surface with DI water. Varying alumina nanoparticle

(NP) solution concentrations on 375 μm ratchets shows an increase in heat transfer performance over pure DI water.

The acquired data was used to show proof of theory and to design a more complex test apparatus which will allow for the testing of many surfaces and working fluids.

Chapter 1: Introduction

1.1 Motivation

Pool boiling is an efficient method for dissipating heat in industry settings due to the ability of the boiling fluid to achieve high heat fluxes while maintaining low wall superheat temperatures (ie. 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. However, continued heat dissipation will be required as computing power increases. 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 also 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 CHF is approached. These obstacles must be overcome in order to design robust and reliable cooling methods for circuits.

Typically, the working fluid proposed for immersion cooling has been a fluorinertTM liquid known as FC-72. FC-72 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 remain to be 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 heat flux and surface superheat.

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

This research on pool boiling heat transfer with micro ratchet and alumina particle enhancement began in May 2009 at Louisiana State University with the collaboration of the Center for Biomolecular Multi Scale Systems (CBMM). The objective of the research is to determine if asymmetric ratchet surfaces could enhance pool boiling heat transfer performance through preliminary experimentation. 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.

1.2 Outline of the Thesis

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 describes the experimental fabrication, setup, thermocouple calibration, uncertainty and procedure. The results and discussion are shown in Chapter 4 and 5. Chapter 4 discusses the experimental results of the pool boiling experiments on the 150 μm period ratchets and their implications. In Chapter 5 the experimental results of the boiling experiments on the 375 μm period ratchets with varying the alumina nanoparticle concentrations and their implications. For both cases, a polished surface was a control sample used for comparison. The conclusions and recommendations are discussed in chapter 6.

Chapter 2: Literature Survey

2.1 Pool Boiling Heat Transfer

2.1.1 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 tensions, surface geometries, etc. Newton's Law of cooling describes the process in the form of

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

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 and $\Delta T \equiv T_s - T_{sat}$ is defined as the superheat temperature. Nukiyama [2] was the first to identify the different regimes of pool boiling, as plotted on the boiling curve, using a heated Nicrome wire (due to its high melting temperature) in saturated water. However, the transition boiling region of the curve was not fully characterized until Drew and Mueller [3], 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 four regimes which are determined by the nature of the vapor formation: natural convection (I), nucleate boiling (II), transition boiling (III) and film boiling (IV). 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. Nucleate boiling, regime II, is characterized by a sharp increase in slope on the pool boiling curve. 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. As the surface temperature increases further, a maximum heat flux is reached, point C, which is typically referred to as the critical heat flux (CHF). 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 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, then surface temperature can fall suddenly and if the surface temperature is controlled then transition boiling, regime III, is reached.

2.1.2 Nucleate Boiling Mechanisms

Portions of this section have been adapted from Hutter [5]

Nucleate pool boiling provides high heat transfer while maintaining low surface superheats and is widely used in industrial processes such as heat exchangers. Nucleate boiling involves many processes by which heat is transferred which makes the modeling 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.

Figure 2-1: Typical pool boiling curve (Pool Boiling [4]).

Figure 2-2: Brief overview of mechanisms in nucleate boiling (adapted from Hsu and Graham [6]).

Three nucleate pool boiling mechanisms Micik and Rohsenow [7] 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 [8]. 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.

2.1.3 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[10].

Figure 2-3: Heat transfer mechanisms during nucleate pool boiling, Kenning [9].

$$q'' = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{pl} \Delta T}{C_{s,f} h_{fg} Pr_l^n} \right)^3 \quad (2.2)$$

where μ_l is the dynamic viscosity, h_{fg} is the heat of formation of the vapor, g is the local acceleration, ρ_l is the density of the liquid phase, ρ_v is the density of the vapor phase, σ is the liquid surface tension, c_{pl} is the specific heat of the liquid phase, Pr_l is the Prandtl number and the coefficients $C_{s,f}$ 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.

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

2.1.4 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 [11] postulated that critical heat flux was a hydrodynamic instability that resulted from the vapor phase velocity reaching a critical value. After performing dimensional analysis he proposed the following correlation.

$$q''_{CHF} = Kh_{fg}\rho_v^{1/2} [\sigma g(\rho_l - \rho_v)]^{1/4} \quad (2.3)$$

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

Borishanskii [12] 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 (μ_l) into account, but it does not play a significant role.

$$K = 0.13 + 4 \left\{ \frac{\rho_l \sigma^{3/2}}{\mu_l^2 [g(\rho_l - \rho_v)]^{1/2}} \right\}^{-0.4} \quad (2.4)$$

Rohsenow and Griffith [13] 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.

$$q''_{CHF} = Ch_{fg}\rho_v \left(\frac{g}{g_s} \right)^{1/4} \left[\frac{\rho_l - \rho_v}{\rho_v} \right]^{0.6} \quad (2.5)$$

Where the coefficient $C = 0.012 \text{ m/s}$, g is the local gravitational acceleration and g_s is the standard gravitational acceleration 9.81 m/s^2 .

Zuber [14] 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 Kutateladze [15], but $K = 0.131$.

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 [16] developed a model based on dynamic receding contact angle. Dynamic receding contact angle (β) is 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.

$$q''_{CHF} = 0.171 h_{fg} \rho_v^{1/2} [\sigma g (\rho_l - \rho_v)]^{1/4} \frac{(1 + 0.000324 \beta^2)^{1/4}}{(0.018 \beta)^{1/2}} \quad (2.6)$$

Diesselhorst [17] 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 [18] 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.

$$q''_{CHF} = h_{fg} \rho_v^{1/2} \left(\frac{1 + \cos \beta}{16} \right) \left[\frac{2}{\pi} + \frac{\pi}{4} (1 + \cos \beta) \cos \phi \right]^{1/2} [\sigma g (\rho_l - \rho_v)]^{1/4} \quad (2.7)$$

Where β is again defined as the dynamic receding contact angle and ϕ 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 2.6 has been plotted in Figure 2-5 for DI water using dynamic receding contact angles found by Kandlikar [19] by dropping liquid droplets at various surface temperatures, roughness and materials (typical values were found to be in the range of 45 - 80°).

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

2.2 Enhancing Pool Boiling Heat Transfer

Nucleate pool boiling has several system parameters as proposed by Dhiri [20] 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.

Surface properties such as increasing surface roughness lowers boiling incipience temperature and moves the boiling curve to the left (lower superheat) while surface wettability

shift the boiling curve to the right (higher superheat), but Takata [21] 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 [22] 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 HTC. Jeong et al. [23] 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 contact angle and surface tension. A discussion involving Kandlikar's [24] correlation concluded that surface wettability is far more important to CHF than surface tension.

Increasing 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 shown by Kim et al. [25] to increase CHF. Parker and El-Genk [26] 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. [27] and Wei and Honda [28] 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. [29] and You et al. [30] 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 [31] using stainless steel substrates. Even though Dhir [32] 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 [33] observed CHF enhancements of 200% for small additions of alumina nanoparticles using a platinum wire. Lee [34] showed substantial improvements in the thermal conductivity of water with small additions ($>5\%$ wt) of alumina or cupric oxide nanoparticles. Kim [35] 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. [36] showed improvements in heat transfer.

The methods by which the experiment 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.

2.3 Asymmetric Micro and Nano Ratchets

2.3.1 Flow Rectification

The use of topologically asymmetric ratchets as heat transfer surface was studied by Linke et al. [37] 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 [38].

Figure 2-6: Cartoon drawing 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 [39].

Ratchet pumping phenomena has been studied by Sedler [40] creating millimeter scale channels with 2 mm period 0.3 mm height ratchets making up the sidewalls with 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 achieve temperatures above the Leidenfrost temperature for water (~250°C) with the surface temperature being measured along the ratchet at several locations. Fluid reservoirs were designed so that a constant stream of DI water could be applied to the unit and flow rate could be calculated. Results show that a peak mass flow rate of 6.42g/min occurred at surface temperatures of 300°C which results in an estimated average liquid velocity of 0.56cm/s.

This work was furthered studied by Ok et al. [41] in which micro and nanoscale ratchets were used to propel fluid droplets near and above the Leidenfrost regime. He has shown that droplet motion on simple asymmetric structures can be improved with the use of hydrophobic coatings. Micro and nanoscale brass ratchets at a fix 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.

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 HTC. It is hypothesized that when a bubble is formed on the surface the liquid above the bubble will act in a similar matter to the liquid and vapor layer as the droplet experiments described above and be propelled along the surface due to the potential.

Chapter 3: Experimental Setup

3.1 Introduction

This chapter covers the design and fabrication of a test rig used for this experimental study. The main purpose of this setup was to provide the evidence that asymmetric ratchets can enhance pool boiling heat transfer. The setup also had to fulfill the requirement of be economical and easy to operate.

3.2 Ratchet Surface Fabrication

The 150 μm x 30 μm and 375 μm x 75 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. A review of the fabrication process can be viewed in Figure 3-1. The polished surface was fabricated by successive sandings of 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.

(a)

(b)

Figure 3-1: (a) Image of the process scheme for the fabrication of miniaturized ratchets in brass by micromilling and (b) definition of period and height of finished ratchets.

3.3 Experimental Apparatus for Pool Boiling

Two small aquariums were fabricated to compare the heat flux performance of the three surfaces. 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 3-2). The thermocouple arrays allowed for the measurement of heat flux and HTC

variations across the heated surfaces, as well as, allow for the calculation of averages for these values.

Figure 3-2: Schematic of the arrays machined into the brass blocks.

Since the ratchets were milled on a separate brass section, the block it was to be attached to was machined shorter by the thickness of the ratchet section (4.6 mm) so that the polished and ratchet blocks were of equal height. This simplifies aquarium fabrication and the recording of the experiments. After sanding and cleaning with acetone, isopropyl alcohol, DI water and dried, the ratchet section and brass block were fastened using Duralco 133 conductive adhesive (Cotronics Corporation, $k = 5.76 \text{ W/mK}$). 1/8" Extech High Temperature K type thermocouples (TP875,

Extech Instruments) were then liberally coated in Omegatherm 201 conductive paste (Omega Engineering Ltd., $k = 2.31 \text{ W/mK}$), the thermocouple connections were labeled with its corresponding hole and inserted into the block. Excess paste was removed and the wires were then routed to one corner of the block and sealed in place using the Duralco adhesive. Any excess adhesive was removed with sand paper after curing as seen in Figure 3-3. The experiments using the $150 \text{ }\mu\text{m}$ ratchets was run first and upon completion the ratchets were removed and the $375 \text{ }\mu\text{m}$ was glued in place following the same procedures used to adhere the $150 \text{ }\mu\text{m}$ ratchets.

Figure 3-3: The polished brass block after thermocouple insertion and sealing.

The walls of the aquariums were made by cutting 6.35 mm thick ceramic plate glass (McMaster-Carr) that was cut 1.65 mm oversized to the brass blocks and to a height of 152.4 mm. The gap between the block and glass allowed for sealing the glass to the brass with high temperature room temperature vulcanization (RTV) silicone (Permatex). The edges of the aquariums were attached using Waleset high temperature adhesive (Wale Apparatus Co.) and

sealed with RTV and allowed to cure. The finished 150 μm ratchet aquarium can be view in Figure 3-4.

Figure 3-4: The completed test aquarium (post experimentation).

After completing fabrication of the experimental setup, the aquariums were checked for leaks at room temperature with DI water and again on a Torrey Pines Scientific digital hot plate at set temperature of 200°C. If a leak was present, the water was poured out and the aquarium would be left on the hot plate set at 100°C for four hours until the water had evaporated. Then RTV would be applied near the leak and left to cure. This was repeated until the units were leak free.

3.3.1 Area Enhancement

In order to calculate heat flux, the total amount of heat input is divided by the surface area over which it was transferred. Determining the area of the polished surface is straightforward enough (simply the product of the length times the width of the surface). But, the ratchets add to the surface area and this addition must be considered in order to accurately calculate heat flux. To do this, a single 150 μm and 375 μm period ratchet of a unit width were sketched and the lengths of the upper surfaces of the triangle form were measured. This length was then divided by the ratchet period to get an area enhancement ratio. The average heat flux recorded during the experimentation was divided by its corresponding area enhancement ratio. The area enhancement ratios can be viewed in Table 3-1.

Table 3-1: Area enhancement ratios for the various surface.

Table 3-2	Polished	150 μm x 30 μm	375 μm x 75 μm
$A_{\text{ratchet}}/A_{\text{flat}}$	1.000	1.065	1.180

3.3.2 Thermocouple Calibration

Temperatures in the block were measured using an Extech ML 720 Multimeter with a maximum temperature resolution of 1 $^{\circ}\text{C}$ and a base accuracy of $\pm 0.3\%$. The thermocouples were calibrated in an ice water bath and were found to have an error of $\pm 2.6\%$. 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 3-5.

Figure 3-5: 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 Experimental Procedure for Pool Boiling Experiments

3.4.1 Preliminary Experiments

Two series of tests were run on each surface. During the first series of tests, pure DI water and DI water with 0.1 g of deagglomerated gamma alumina microparticle powder with diameters of 12.5 μm or 25 μm (Buehler) were used as boiling fluids. The inclusion of microparticles was to aid in flow visualization and to observe the combine effects of the surfaces and alumina (measured with a Mettler AE 100 digital scale)). This resulted in an alumina concentration of 0.296 g/l (0.03 wt%).

The test began by coating the base of the aquarium with conductive paste then filling the aquarium the aquarium with DI water to a predetermined height and placed on the plate. The appropriate amount of alumina is added (if it is to be used) at this time and gently stirred. A beaker of DI water was also placed on the hot plate which was used to replenish water as it boiled off. The hot plate was then set to 100°C and allowed to heat for one hour (Figure 3-6). A bubble level is then used to ensure that the surface of the hot plate is level. Remaining pieces of ceramic plate glass was stacked around the aquarium to make recording experimental data safer and allow for the hot plate to operate at lower power levels to maintain surface temperature.

Steady state was determined by checking that the temperature variation of the upper centerline thermocouple was within 0.2 °C. Once steady state 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 reach steady state for at least 10 minutes. This process was repeated from 100 – 400°C which was the maximum working

Figure 3-6: View of the experimental setup.

temperature of the hot plate. The array of thermocouples allowed for the calculation of an average heat flux and HTC for the surface, as well as, allowing for analysis of location dependence of heat flux and HTC of the three surfaces. This allowed for the working fluid to degas, the aquarium to heat up slowly and to determine the boiling point of the system.

Upon completion of the experiment, the set temperature was returned to room temperature and the aquarium was monitored until boiling ceased. It was then covered with a

paper bag and allowed to cool slowly overnight. This reduced the risk of the glass cracking or separating due to thermal stresses.

3.4.2 Concentration Dependence Experiments

Two series of tests were run on each surface. During the first series of tests, pure DI water and DI water with 50 nm deagglomerated gamma alumina MP (Buehler) to observe the combine effects of the surfaces and alumina. The various alumina concentrations used in the experiment can be viewed in Table 3-2.

Table 3-2: Table showing the nano particle solutions used in the second series of tests.

Nano Particle Concentration (mg/liter)	Weight Percent (wt %)
Pure DI water	n/a
1.0 $\pm$ 0.095	0.0001
5.0 $\pm$ 0.48	0.0005
10.0 $\pm$ 0.95	0.0010
25.0 $\pm$ 2.38	0.0025
50.0 $\pm$ 4.75	0.0050
75.0 $\pm$ 7.13	0.0075

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 placing on the hot plate. To expedite experimentation, the second series of experiments started at a set temperature of 200 °C, since it was found in the first series of experiments that boiling does not begin until a set temperature of nearly 280 °C. The aquarium was allowed to heat and degas and reach equilibrium for one hour. The process of data acquisition was the same as above. Remaining pieces of ceramic plate glass was stacked around the aquarium to make recording experimental data safer and allow for the hot plate to operate at lower power levels to maintain to same surface temperature.

Steady state was determined by checking that the temperature variation of the upper centerline thermocouple was within 0.2 °C. Once steady state was assured, the six thermocouples were measured as well as, the water temperature near the surface. 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 placed was increased by 20 °C, DI water was slowly added to replenish boil off and the system was allowed reach steady state for at least 10 minutes.

The 375 μm ratchet surface was tested using DI water from 200 – 400 °C and upon reaching the maximum set temperature various amounts of alumina were added to achieve the concentrations in Table 3-2 in steps with at least 10 minutes in between steps to allow the system to reach equilibrium and measurements were taken just as in the preliminary experiment.

The polished surface was heated in steps of 100 °C over the course of several hours allowing degassing and equilibrium to be reached. Upon reaching 400 °C, alumina, which was weighted using a Mettler AE 100 digital scale with a resolution of 0.01 mg, was added again in steps as with the 375 μm to achieve the appropriate concentrations. The system was allowed to reach equilibrium for at least 10 minutes in between steps to allow the system to reach equilibrium and measurements were taken.

Upon completion of the experiment, the set temperature was returned to room temperature and the aquarium was monitored until boiling ceased. It was then covered with a paper bag and allowed to cool slowly overnight. This reduced the risk of the glass cracking or separating due to thermal stresses.

3.4.3 Working Fluid

Deionized (DI) water was used during the experiments. It is typically used during heat transfer situations and is readily available and non toxic. It does have a rather high boiling point which makes it a possible safety hazard. The water also has the possibility of corroding surfaces in contact with it. Initially, microparticles were used for flow visualization with the knowledge that the particles would alter the heat transfer performance as You et al. [42] has shown. Once proof of microparticle enhancement with ratchets was observed, various concentrations of alumina nanoparticles following the concentrations used by You et al. [43] were used and the experiments were repeated for both surfaces.

3.5 Uncertainty

The overall error for the experiment has been calculated using the method defined by Kline and McClintock [44]

$$w_R = \pm \left(\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \left(\frac{\partial R}{\partial x_3} w_3 \right)^2 + \dots \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right)^{1/2} \quad (3.1)$$

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

$$q'' = \frac{k(T_B - T_A)}{\Delta x} \quad (3.2)$$

The variables in equation 3.2 are defined as: q'' is the heat flux, k is the thermal conductivity of the brass, Δx is the distance between row A and Row B (as seen in Figure 3-2) in the array and

T_A and T_B are the temperatures measured at A and B. The percent uncertainties were found to be $\pm 5\%$ for k , 12.5% for Δx , and 2.6% for temperature measurements.

$$h = \frac{q''}{T_A - T_{SAT}} \quad (3.3)$$

The remaining undefined variables in Equation 3.3 are defined as: h is the HTC and T_{SAT} is the saturation temperature of the working fluid. The results of the uncertainty analysis can be viewed in Table 3-3.

Table 3-3: Table containing error values for the experiment.

% Error	HF	HTC
Polished	13.79	14.12
Ratchet	15.79	16.08

3.6 Conclusions

Two experimental setups were fabricated to investigate pool boiling on two different surfaces at atmospheric pressure. One setup was used as a proof of concept and the second to determine how ratchets perform in the presence of various concentrations of alumina nanoparticles. The accuracy of the setup, as well as, pertinent properties of the working fluid was covered. This section also covers the experimental procedure and conducting the experiments.

Chapter 4: Pool Boiling on Micro Ratchets

4.1 Introduction

This chapter discusses the results of the pool boiling experiments that were performed with the 150 μm brass ratchet. The results were compared with those with the polished brass surface. Heat transfer coefficients and heat fluxes were calculated and the results are presented graphically. Post experimentation surface characterization will also be covered in the current chapter.

4.2 Characterization of Surfaces

The as fabricated surfaces were examined with a Hitachi S-3600 Scanning Electron Microscope (Figure 4-1). The white particles observed on the polished surface were confirmed to be alumina using energy-dispersive X-ray spectroscopy (EDX) which was imbedded during polishing.

Figure 4-1: Scanning electron micrograph of the 150 μm period ratchet and polished surfaces after fabrication. (a) 150 μm 50x, (b) 150 μm 250x, (c) polished 500x, (d) polished 500x.

(c)

(d)

The dimensions of the 150 μm ratchet were confirmed using a Nanovea CR750 Optical Profilometer. However, the 150 μm ratchet sample was used for multiple experiments and required repeated manual polishing to remove corrosion. Therefore, the height of the ratchets was $\sim 20\text{--}24\text{ }\mu\text{m}$ and the sharp edges of the ratchets had become rounded, as was discovered by an optical profiler examination (Figure 4-2). The polished surface was prepared by manually polishing with multiple metal polishing compounds and pads. Unlike the 150 μm ratchet, the 375 μm ratchet was not used for previous experimentation. Therefore, the surface did not require multiple cleanings and maintained the sharp edges as were designed and machined.

The 150 μm and polished surfaces were found to have an overall average surface roughness of 5.42 μm and 0.18 μm respectively as shown in Table 4-1. The contact angles for the two surfaces were measured with the static sessile drop method using a First Ten Angstrom 125 with DI water using 5 μl drops. Nine points on all surfaces were taken in a 3 x 3 array and an average was calculated. The 150 μm ratchet and polished surfaces had a contact angle of 110.19 and 85.51° respectively. Results for surface roughness and contact angle when fabricated can be observed in Table 4-2.

Figure 4-2: Results of optical profiler analysis showing the overall height and period of the ratchet after multiple cleanings. Note the rounded edges of the ratchets.

Table 4-1: Surface characterization results for the first series of experiments.

Table 4-1	Polished	150 μm
Overall Ra (μm)	¹ 0.178	¹ 5.42
Ratchet Ra (μm)	n/a	¹ 0.73
RMS Roughness (μm)	¹ 20.20	¹ 26.01
Ratchet Height (μm)	n/a	¹ 322

¹Data obtained via optical profiler, ²RMS value estimated, ³Estimated average ratchet height

Table 4-2: Contact angle measurements of the 150 μm and polished surfaces before experimentation.

Table 4-2	Polished	150 μm
Average Contact angle ($^{\circ}$)	86	110
Standard Deviation ($^{\circ}$)	2.8	5.0

4.3 Pool Boiling on Microratchets

Figure 4-3 shows captured images of bulk fluid motion induced by boiling on the 150 μm ratchets and polished surfaces at different hot plate set temperatures. Working fluids are DI water with 0.03 wt % MPs and pure DI water. For pure DI water, as the hot plate set temperature

increases, the frequency of the bubble formation also increases. The bubbles detached from the surface move almost vertically or at a low departure angle, the behavior similar to that of the polished surface. A significant difference can be seen with the addition of MPs. First, bubble formation with MPs is so much more frequent that at higher heat fluxes viewing the heated surface becomes practically impossible, clearly indicating an enhanced heat transfer at the liquid/ratchet interface. Second, the convectonal flow of detached bubbles and liquid circulates in the aquarium unidirectionally. In Figure 4-2, the fluid moves right along the ratchet surface, upward along the right wall, left along the liquid/air interface, and downward along the right wall. This suggests that the enhanced heat transfer is caused by enhanced convection and increased vapor formation (phase change). This is the expected fluid motion; however, instances of reverse flow were observed for various set temperatures on the ratchet surface.

While the polished surface produced bubbles that were carried to the surface, the bubbles produce on the ratchet surface with and without alumina were typically smaller. The motion of the fluid of the ratchet with alumina was so energetic that a head of bubbles was created at the top of the aquarium.

4.4 Heat Transfer Analysis

The initial experimentation was to determine if asymmetric ratchets could influence pool boiling heat transfer performance. The first series of experiments involved both surfaces with pure DI water and 0.296 g/l solution of micro sized alumina particles as described in Chapter 3.

The heat flux and HTC are given in Figures 4-4 and 4-5 respectively as a function of surface superheat with the polished surface with DI water being used as the reference. The

Figure 4-3: Images of the 150 μ m and polished surfaces at various set temperature: (a) ratchet with DI water and MPs, (b) ratchet with DI water, (c) polished with DI water with MPs, and (d) polished with DI water.

maximum and average values for heat flux and HTC for the various experiments are summarized in Table 4-3.

Table 4-3: Maximum and average performance characteristics of the various surfaces and working fluids. The polished surface with DI water is used as the reference. The percentage values with respect to the polished surface with DI water are also included in the parenthesis.

Maximum Performance Comparison			Average Performance Comparison		
Heat Flux (kW/m ²)	DI	MP	Heat Flux (kW/m ²)	DI	MP
Polished	34.165	56.030 (64%)	Polished	26.785	40.607 (52%)
150 μ m Ratchet	54.915 (61%)	105.998 (210%)	150 μ m Ratchet	43.208 (61%)	73.341 (174%)

HTC (W/m ² K)	DI	MP	HTC (W/m ² K)	DI	MP
Polished	3,024	4,835 (60%)	Polished	2,422	3,695 (53%)
150 μ m Ratchet	2,881 (-5%)	5,763 (91%)	150 μ m Ratchet	2,460 (9%)	4,650 (92%)

The ratchet showed improvement over the polished surface of 61% for the maximum heat flux from 34.17 kW/m² to 54.912 kW/m² with DI water. The addition of alumina MPs to the polished surface had nearly the same effect of the ratchets with DI water.

The alumina improved the heat transfer of both systems. The most significant performance discrepancy between the two surfaces occurred with the addition of the alumina and ratchet combination showing a 210 % improvement over the polished surface at the maximum heat flux with values of 106.00 kW/m² and 34.17 kW/m² respectively. Analysis of data shows that the ratchet and alumina have a significant combined effect on heat flux. No system reached CHF due to the limitations of the experimental setup.

The heat transfer coefficients of the ratchet systems were generally higher than the polished surface. Therefore, increased HTC can be attributed to the surface structure of the ratchets and alumina particle interaction. The peak HTC occurred with the ratchets with alumina at 5,386 W/m²K versus 3,024 W/m²K for the polished with DI water which is a 91 % increase. It was observed after the completion of the ratchet experiment with the alumina that the particles

were embedded into the brass surface. The maximum HTC for the ratchet with DI was 2,693 $\text{W/m}^2\text{K}$ which is an 5 % decrease when compared to the baseline.

Figure 4-4: Average vertical heat flux results for the various surfaces and working fluids.

Figure 4-5: Average HTC results for the various surfaces and working fluids.

When heat flux is plotted against HTC, as in Figure 4-6, the performance the improvement in the ratchet performance becomes even more apparent. The ratchet surface with MP has notably better heat flux and HTC with the polished surface with MP. The two surfaces with DI water fall well below which indicates how significant the addition of MP can alter the performance of the surfaces.

Figure 4-6: Heat flux versus HTC for the various surfaces and working fluids.

4.5 Adjusted Heat Transfer Results

It is important to note that the fabrication of the ratchet aquarium required gluing a separate brass section with the ratchets milled into it onto a brass block containing the thermocouple array. This glued layer creates an additional thermal resistance which can influence measured surface temperature and measured HTC. Analysis performed via the thermal resistance method [45] allows for thermal conduction to be modeled in a manner analogous to electrical resistances based upon thermal properties of the system. By assuming 1-D conduction and steady state conditions, temperature drops across the brass and glued layers can be calculated. The thermal resistance method reveals that superheat temperatures can be lower than

measured by nearly 11 °K. This results in a maximum HTC of 410 % over the reference value. A summary of estimated values can be viewed in Table 4-4. Heat flux values would remain unchanged; however, wall superheat temperatures would be decreased.

Table 4-4: Maximum and average performance characteristics of the various surfaces and working fluids adjusting for thermal resistance of glued layer. The polished surface with DI water is used as the reference.

Maximum Performance Comparison			Average Performance Comparison		
Heat Flux (kW/m ²)	DI	MP	Heat Flux (kW/m ²)	DI	MP
Polished	34.165	56.030 (64%)	Polished	26.785	40.607 (52%)
150µm Ratchet	54.915 (61%)	105.998 (210%)	150µm Ratchet	43.208 (61%)	73.341 (174%)

HTC (W/m ² K)	DI	MP	HTC (W/m ² K)	DI	MP
Polished	3,024	4,835 (60%)	Polished	2,422	3,695 (53%)
150µm Ratchet	4,195 (39%)	15,428 (410%)	150µm Ratchet	3,712 (53%)	10,081 (316%)

4.6 Location Dependent Heat Transfer

It is important to recall that the ratchets have shown rectified motion during droplet experiments and therefore, during pool boiling situations rectified flow is again expected. The expected flow direction can be viewed in Figure 4.7.

The use of a thermocouple array allowed not only for the ability to calculate an average heat flux and HTC across the surface, but also allow for the calculation of heat flux and HTC at threes individual points along the surface centerline. Figure 4-8 shows the heat flux as a function of surface superheat at different locations along the surface centerline for the polished brass

Figure 4-7: Image of the 150 μ m ratchet and the expected flow direction.

surface and DI water with MPs as working fluid. The maximum heat flux occurred at the center of the aquarium. The heat flux at different locations of the 150 μ m ratchet is shown in Figure 4-9, where the maximum heat flux occurs at one edge with the minimum heat flux occurring at the opposite end of the surface. This can be explained by the directional motion induced by the ratchets forming a single convective cell while the polished surface formed two convective cells which is indicative of natural convection.

Figure 4-8: Vertical heat flux dependence of the polished surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.

Figure 4-9: Vertical heat flux of the 150 μ m ratchet surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.

4.7 Reverse Flow Observations

Instances were observed throughout experimentation on the 150 μ m ratchet surface of bulk fluid motion that was counter to what was expected as shown in Figure 3.2. The reasons for this are not fully understood and have been shown to occur in the research performed by Sedler [46]. The most simple explanation would be that during the addition of DI water to replace what was lost through evaporation the fluid motion was disturbed. It is interesting to note that the

direction never corrected itself and no measurable changes in heat transfer were noticed between normal and reverse flow situations.

When comparing the various hot plate set temperature to instances with reverse flow it appears that the addition of MPs may induce a convective instability as shown in Figure 4-9. Interesting still, during reverse flow situations the heat flux and HTC at the various locations and average heat flux seem virtually independent of the flow direction. An explanation for the alternating nature between normal and reverse flow may be that during the addition of DI water after readings. A sealed experimental chamber with a condenser would need to be used to eliminate the need to replenish water.

(a)

(b)

Figure 4-10: Examples of reversed flow on the 150 μ m ratchet at two hot plate set temperatures (a) 340°C (expected) and (b) 360°C (reverse).

4.8 Post Experimentation Surface Characterization

Literature has indicated that pool boiling can damage the heated surface especially if abrasive nano or microparticles are introduced to the system in an attempt to enhance heat

transfer performance [47]. Also, the high temperature used in pool boiling experiments accelerates oxidation of brass surfaces. Therefore, it was important to perform surface characterization to access any degradation that has occurred due to experimentation. SEM images of the 150 μm ratchets and the polished surface can be viewed in Figure 4-11 and it is apparent that significant surface deterioration has occurred on the ratchets and the polished surface reveals damage consistent with alumina particle abrasion.

Figure 4-11: SEM images of the 150 μm period ratchet and polished surfaces after experimentation. (a) 150 μm 100x, (b) 150 μm 500x, (c) polished 100x, (d) polished 500x.

All surfaces also show significant oxidation on all surfaces has occurred during the course of the experiments as seen in Figure 4-12. This was expected, but unavoidable with the use of brass as heating surface material. The red material in the edges of the samples is remnants of the RTV that were not removed in order not to risk damaging the surface. The white material on the ratchet is embedded alumina. Attempts were made to clean the surface, but this alumina could not be removed.

Figure 4-12: Images of the surfaces before and after experimentation (a) initial polished, (b) post 150µm, (c) post 150µm.

Surface profiling was performed in order to quantify the deterioration with a Tencor P11 Surface Profiler. The overall average roughness (R_a) of the 150 µm surface decreased from 5.4 µm to 4.638 µm which is a reduction of 15.74% and the ratchet height has decreased from an average of 22 µm to 20.12 µm which is a decrease of 9.34%. Profiling along the individual ratchets shows that the ratchet average roughness has increased from 0.73 µm to 1.519 µm an increase of 51.94%. The root mean square (RMS) roughness of the ratchet surface increased but by 7.86% which is approximately half of the increase of the average roughness.

The polished surface underwent significant changes in roughness. Overall roughness has increased by 85.90 % from 0.178 μm to 1.277 μm and the RMS roughness increased on a similar scale. It is important to note that the initial measurements of the polished surface were taken using an optical profilometer which has limited data processing options and higher uncertainty. The RMS roughness was estimated from industry observations that the RMS roughness is typically 11% higher than average roughness [48].

These results indicate that the alumina has begun to polish the ratchet surface reducing the overall roughness but simultaneously increasing the micro scale roughness. However, the polished surface overall roughness increased. This correlates well with observations made by Narayan et al. [49] Further experimentation using the ratchet for pool boiling experiments resulted in heat transfer data that was significantly lower than the original experimentation and it was therefore determined to discontinue experimentation with the 150 μm ratchet. Surface profiling results can be viewed in Table 4-5. The ratchet average roughness is defined as the roughness along the ratchet back; it gives a surface roughness which can be compared its polished counterpart.

Table 4-5: Surface characterization results for the first series of experiments.

Table 4-5	Polished		150 μm	
	Initial	Final	Initial	Final
Overall Ra (μm)	¹ 0.178	1.277	¹ 5.42	4.683
Ratchet Ra (μm)	n/a	n/a	¹ 0.73	1.519
RMS Roughness (μm)	¹ ² 0.20	1.690	¹ ² 6.01	5.572
Ratchet Height (μm)	n/a	n/a	¹ ³ 22	20.12

¹Data obtained via optical profiler, ²RMS value estimated, ³Average ratchet height

Contact angle measurements were also repeated to determine changes in surface wettability due to changes in roughness and surface corrosion/oxidation. The measurements for the 150 μm ratchet show that the average contact angle has decreased by 29 % from 110° to 77.76°. The standard deviation of the measurements has increased by 673 % from 5.0° to 38°. This data indicates that significant changes in surface properties have occurred causing the wettability of the ratchet surface to become erratic. Similar results for the polished surface were observed although the wettability of the surface showed less variation than the ratchet, but the change is significant. The results can be viewed in Table 4-6.

Table 4-6: Contact angle measurements for the polished and 150 μm surfaces.

Table 4-6	Polished		150μm	
	Initial	Final	Initial	Final
Average Contact angle (°)	86	54	110	78
Standard Deviation (°)	3.0	5.1	5.0	38.0

The trend of these results compares well to those found by Hong et al. [50], where contact angle measurements on aluminum and copper surfaces of various roughness in the oxidized and non oxidized states were performed. His results indicated that increasing surface roughness and oxidation (which increases surface roughness) decreases the contact angle and would theoretically increase CHF. However, this contradicts the degraded performance that was observed upon continued use of the 150 μm ratchet. This hypothesis is corroborated by Coursey et al. [51] who studied pool boiling on copper surfaces and suggested that surface fouling may be the cause for similar experimental observations.

4.9 Conclusions

A pool boiling apparatus was fabricated to test 150 μm asymmetric ratchets and polished surfaces using DI water and a DI water alumina MP solution. By varying hot plate set temperatures the heat flux could be varied and measured via thermocouples arrays. Results show that with DI water the ratchets have a dramatic effect on heat transfer over the polished surface in the estimated range of 5 - 10 % of CHF using the Zuber correlation (Equation 2.3, $K = 0.131$). The addition of alumina MPs improved the performance of both surfaces with the improvement of the ratchets being more than the sum effects of the ratchet and MPs. Monitoring the heat flux distribution across the two surfaces indicated that the ratchets induced rectified flow resulting in a single convective cell, while the polished surface formed two counter rotating convective cells.

Inspection of the surfaces after experimentation indicated that significant surface degradation and oxidation had occurred. The contact angle for both surfaces decreased which is a result of the higher surface energy resulting from surface oxidation. The roughness of each surface changed with an overall increase in roughness on the polished surface and an overall decrease in roughness on the 150 μm ratchet surface.

Chapter 5: Effect of Nanoparticle Concentration on Pool Boiling on Microratchets

5.1 Introduction

In order to determine how varying the concentration of alumina in the working fluid a second series of tests were run. The second series of tests used the same alumina concentrations as You et. al. [52] with 50 nm alumina particles as shown in Table 3-2. The concentrations of particles can be found in Table 3-2 (see above). The results are compared with those from the 150 μm ratchets with DI water.

5.2 Characterization of Surfaces

As with the 150 μm and polished surfaces, the 375 μm surface was examined with a Hitachi S-3600 Scanning Electron Microscope and all three surfaces can be examined in Figure 5-1.

Figure 5-1: Scanning electron micrograph of the 150 μm period ratchet and polished surfaces after fabrication. (a) 150 μm 50x, (b) 150 μm 250x, (c) 375 μm 50x, (d) 375 μm 100x, (e) polished 500x, (f) polished 500x.

(c)

(d)

(e)

(f)

The dimensions of the 375 μm ratchets were confirmed using a Tencor P11 Surface Profiler. Unlike the 150 μm ratchets, the 375 μm ratchets were not used for previous experimentation. Therefore, the surface did not require multiple cleanings and maintained the sharp edges as were designed and machined.

The 375 μm ratchets were found to have an overall average surface roughness of 17.135 μm as shown in Table 5-1. The contact angle for the surface was again measured with the static sessile drop method using a First Ten Angstrom 125 with DI water using 5 μl drops. Nine points

were taken in a 3 x 3 pattern and an average was calculated. The 375 μm ratchets had a contact angle of 106.18°. Results contact angle when fabricated can be observed in Table 5-2.

Table 5-1: Surface characterization results for the first series of experiments.

Table 5-1	Polished	150μm	375μm
Overall Ra (μm)	¹ 0.178	¹ 5.42	17.135
Ratchet Ra (μm)	n/a	¹ 0.73	0.205
RMS Roughness (μm)	¹ 20.20	¹ 26.01	20.211
Ratchet Height (μm)	n/a	¹ 322	72.345

¹Data obtained via optical profiler, ²RMS value estimated, ³Estimated average ratchet height

Table 5-2: Contact angle measurements of the 375 μm , 150 μm and polished surfaces before experimentation.

Table 5-2	Polished	150μm	375μm
Average Contact angle (°)	86	110	106
Standard Deviation (°)	3.0	5.0	11.0

5.3 Pool Boiling on Microratchets

Figure 5-1 shows captured images of bulk fluid motion induced by boiling on the 375 μm ratchets and polished surfaces a set temperature of 400 °C using various alumina nanoparticle solutions. An improvement can be seen with the addition of NPs. Bubble formation with NPs is more frequent and the bulk fluid motion appears to be more energetic.

Figure 5-2: Images of the 375 μ m and polished surfaces at 400°C set temperature with various concentrations of nanoparticles.

5.4 Thermal Analysis

The maximum and average values for heat flux and HTC for the various experiments are summarized in Table 5-3 with the adjusted values being shown in Table 5-4.

Table 5-3: Maximum and average performance characteristics of the various surfaces and working fluids. The polished surface with DI water is used as the reference.

Maximum Performance Comparison		Average Performance Comparison	
Heat Flux (kW/m ²)	DI	Heat Flux (kW/m ²)	DI
Polished	34.165	Polished	26.785
150µm Ratchet	54.915 (61%)	150µm Ratchet	43.208 (61%)
375µm Ratchet	35.596 (4%)	375µm Ratchet	29.913 (12%)

HTC (W/m ² K)	DI	HTC (W/m ² K)	DI
Polished	3,024	Polished	2,422
150µm Ratchet	2,881 (-5%)	150µm Ratchet	2,460 (9%)
375µm Ratchet	1,501 (-50%)	375µm Ratchet	1,432 (-41%)

Table 5-4: Maximum and average performance characteristics of the various surfaces and working fluids adjusting for thermal resistance of glued layer. The polished surface with DI water is used as the reference.

Maximum Performance Comparison		Average Performance Comparison	
Heat Flux (kW/m ²)	DI	Heat Flux (kW/m ²)	DI
Polished	34.165	Polished	26.785
150µm Ratchet	54.915 (61%)	150µm Ratchet	43.208 (61%)
375µm Ratchet	35.596 (4%)	375µm Ratchet	29.913 (12%)

HTC (W/m ² K)	DI	HTC (W/m ² K)	DI
Polished	3,024	Polished	2,422
150µm Ratchet	4,195 (39%)	150µm Ratchet	3,712 (39%)
375µm Ratchet	1,794 (-41%)	375µm Ratchet	1,744 (-28%)

The heat flux of the 375 µm ratchets did not show distinguishable performance increase over the polished surface. This may indicate that if the ratchets are larger than a certain scale the

ratchet effect is lost. Studying the heat flux variation across the 375 μm surface shows that the centerline of the surface had the highest heat transfer performance. This indicates that the larger ratchets may not induce rectified flow and implies that a critical ratchet size may exist, since the aspect ratio was constant, where the only enhancement that occurs is due to enhanced surface roughness. The heat flux results for the 375 μm ratchets using DI water can be viewed in Figure 5-3.

Figure 5-3: Vertical heat flux of the 375 μm ratchet surface with micro particles. q_1'' and q_3'' represent the heat flux of the left and right side of the aquarium while q_2'' represents the centerline heat flux.

The addition of alumina nanoparticles has been shown to improve the performance of the ratchets. Small concentrations of alumina, up to 0.25 g/l, when added to the polished surface resulted in a 12 % increase in performance over pure DI water. Further increase in alumina concentration did not increase heat transfer performance. The trend of this data is consistent with the results of You et al [53].

When the experiment was repeated for the 375 μm ratchet, the data was initially very similar, but at 0.25 g/l the enhancement was well below the polished surface, but as alumina was added the enhancement became higher than the polished surface and a constant level of enhancement was not observed. Due to the anomaly that occurred on the polished surface at the 0.01 g/l alumina concentration, attempts were made to repeat the experiment, but it is believed that surface oxidation reduced the heat transfer performance to the point that repeatable results were not achieved. Results for the concentration dependent experiments can be observed in Figure 5-4.

5.5 Adjusted Results

As with the experimentation on the 150 μm ratchet, the temperature drop across the glue layer needs to be considered in order to get a more accurate superheat temperature. The temperature drop across the layer on the 375 μm ratchets was measured to be almost 4 °K. The reason the temperature drop is not as severe as the 150 μm ratchet is because it is a function of the heat flux and since the heat flux on the 375 μm ratchet was much lower. The results for the heat flux can be viewed in Figure 5-5 and show a clear reduction in performance when compared to the 150 μm over the entire range of superheat measured.

Figure 5-4: Alumina nanoparticle concentration dependence for the polished and 375 μm ratchet surfaces.

Figure 5-5: Adjusted average vertical heat flux for the polished and ratchet surfaces.

5.6 Post Experimentation Surface Characterization

Literature has indicated that pool boiling can damage the heated surface especially if abrasive nano or microparticles are introduced to the system in an attempt to enhance heat transfer performance. Therefore, it was important to perform surface characterization to assess any degradation that has occurred due to experimentation. SEM images of the 375 μm ratchets and the polished surface can be viewed in Figure 5-6 and it is apparent that the deterioration on the 375 μm surface was not as severe as the 150 μm surface.

(a)

(b)

(c)

(d)

Figure 5-6: SEM images of the 375 μ m period ratchets and polished surfaces after experimentation. (a) 375 μ m 50x, (b) 375 μ m 100x, (c) polished 100x, (d) polished 500x.

All surfaces also show significant oxidation has occurred during the course of the experiments as seen in Figure 5-7. This was expected, but unavoidable. The red material in the figure is remnants of the RTV that were not removed in order not to risk damaging the surface. The white material on the ratchet is embedded alumina. Attempts were made to clean the surface, but this alumina could not be removed.

(b)

(b)

(c)

(d)

Figure 5-7: Images of the surfaces before and after experimentation (a) initial polished, (b) initial 375 μ m ratchet, (c) post polished, (d) post 375 μ m.

Surface profiling was performed in order to quantify the deterioration with a Tencor P11 Surface Profiler. The overall average roughness (Ra) of the surface increased from 17.135 μ m to 17.956 μ m which is an increase of 4.79 % and the ratchet height has increased from an average of 72.345 μ m to 73.547 μ m which is an increase of 1.66 %. Profiling along the individual ratchets shows that the ratchet average roughness has increased from 0.205 μ m to 0.213 μ m a

change of 3.90 %. The RMS roughness of the ratchet surface increased but by 4.22 % which is approximately equal to the increase of the average roughness. The 375 μm ratchet did not show any appreciable degradation in surface profile. Differences between the surface profiles of the two ratchets are most likely due to the growth of the oxide layer and since the ratchet was not in service for extended periods the removal of this layer via particle erosion did not occur.

These results indicate that the alumina has begun to polish the ratchet surface reducing the overall roughness but simultaneously increasing the micro scale roughness. Again, this correlates well with observations made by Narayan et al. [54] Surface profiling results can be viewed in Table 5-5.

Table 5-5: Surface characterization results for the experiments.

	Polished		150 μm		375 μm	
	Initial	Final	Initial	Final	Initial	Final
Overall Ra (μm)	¹ 0.178	1.277	¹ 5.42	4.683	17.135	17.956
Ratchet Ra (μm)	n/a	n/a	¹ 0.73	1.519	0.205	0.213
RMS Roughness (μm)	¹ 20.20	1.690	¹ 26.01	5.572	20.211	21.063
Ratchet Height (μm)	n/a	n/a	¹ 322	20.12	72.345	73.547

¹Data obtained via optical profiler, ²RMS value estimated, ³Average ratchet height

Contact angle measurements were also repeated to determine changes in surface wettability due to changes in roughness and surface corrosion/oxidation. The measurements for the 150 μm ratchet show that the average contact angle has decreased by 29 % from 110.19° to 77.76°. The standard deviation of the measurements has increased by 673 % from 4.91° to 37.93°. The 375 μm ratchet showed a reduction in contact angle of 21 % and an increase in standard deviation of 13 %. The fact that the 375 μm ratchet was not used as much as the 150 μm

ratchet probably explains the lesser decrease in post experimentation contact angle. This data indicates that significant changes in surface properties have occurred causing the wettability of the ratchet surface to become erratic. Similar results for the polished surface were observed although the wettability of the surface showed less variation than the ratchet, but the change is significant. The results can be viewed in Table 5-6.

Table 5-6: Contact angle measurements for the surfaces.

Table 5-6	Polished		150μm		375μm	
	Initial	Final	Initial	Final	Initial	Final
Average Contact Angle (°)	86	54	110	78	106	84
Standard Deviation (°)	2.7	5.1	5.0	38	11	13

The trend of these results compare well to those found by Hong et al. [55] who performed contact angle measurements on aluminum and copper surfaces of various roughness in the oxidized and non oxidized states. His results indicated that increasing surface roughness and oxidation (which increases surface roughness) decreases the contact angle and would theoretically increase CHF. However, this contradicts the degraded performance that was observed upon continued use of the 150 μ m ratchet. These observations are corroborated by Coursey et al. [56] who studied pool boiling on copper surfaces and suggested that surface fouling may be the cause for similar experimental observations.

5.7 Conclusions

A pool boiling apparatus was fabricated to test 375 μ m asymmetric ratchets and polished surfaces using DI water and various DI water alumina nanoparticle solutions. By operating the

hot plate at the maximum set temperature of the hot plate, the peak heat flux of the systems could be measured via thermocouples arrays. Results show that with increasing concentrations of alumina nanoparticles heat flux on both surfaces is improved. However, the improvement of heat flux on the polished surface increases up to a constant, but in the concentration range tested the 375 μm ratchets showed continuous heat flux improvement with increasing alumina concentration. Monitoring the heat flux distribution across the two surfaces indicated that the 375 μm ratchets form two counter rotating convective cells like the polished surface and do not induce rectified flow.

Inspection of the 375 μm ratchets after experimentation indicated that significant surface oxidation had occurred. The contact angle for ratchets decreased which is a result of the higher surface energy resulting from surface oxidation. The roughness of 375 μm ratchets increased slightly which was most likely due to surface oxidation. The limited use of the 375 μm ratchets did allow for the alumina to erode the surface as in the case of the 150 μm ratchets.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

Preliminary pool boiling heat transfer experiments using asymmetric micro ratchets using DI water and various concentrations of micro and nano particle alumina have been studied. By fabricating small aquariums and placing them on hot plates, heat flux and heat transfer coefficients were measured. Surface characterization was performed prior to and post experimentation to quantify the nature of the surfaces used.

For the 150 μm ratchets, significant improvement in heat flux was seen over the polished surface especially with the use of micro particles. Strong rectified flow was also observed with the 150 μm ratchets as evidenced by the single convective cell formed while testing. This results in higher heat transfer coefficients when adjusting for the adhesive layer.

The 375 μm ratchet did not show significant heat transfer improvement over the polished surface. However, upon the addition of nanoparticle alumina, performance continuously increased for the concentrations tested over its baseline while the enhancement polished surface initially increased, but quickly reached a constant value.

It is interesting to note that for all surfaces, surface oxidation increased the surface wettability, but degraded heat transfer performance. The reason for this is not fully understood, but it is believed that a combination of the reduced thermal conductivity of the metal oxides formed on the surface and surface fouling are responsible. The overall surface roughness of the surfaces tested increases due to the erosion caused by the alumina and the formation of the oxide layer on the surface.

The results of the experiments performed indicated that ratchets may be an innovative method for enhancing pool boiling heat transfer and suggest self pumping pool boiling may be a

reality. Further testing is required to determine the CHF using asymmetric ratchets using various fluids and ratchet scales in order to compare ratchets to current attempts to improve CHF.

6.2 Limitations and Recommendations

The heat transfer data gathered was achieved using a preliminary experimental setup designed to show proof of theory that asymmetric micro ratchets can improve pool boiling heat transfer. There are several limitations discovered while data was being gathered. The first realization discovered, but was for all practical purposes unavoidable, was the adhesive layer which altered the measured wall superheat. The second limitation was caused by the proximity of the thermocouple pairs. Had the thermocouples been spaced farther apart, the uncertainty in the measured values would have been reduced. This relates to the fact that the thermocouples were run on the inside of the aquarium which could alter the temperature distribution in the heated surface near them as well as alter nearby fluid motion. The use of brass led to issues of oxidation during use; surface oxidation alters surface wettability and thus heat transfer performance. This made repeating experiments nearly impossible, but machining the ratchets from more stable materials or testing using fluids with lower boiling points. The hot plate had an upper temperature limit of 400°C which limited the heat flux range being measured. It is estimated that only 5-10 % of CHF was studied. The final limitation of the preliminary setup was the fact that the free liquid surface was exposed to atmosphere without any means of containing, condensing and returning the vapor back to the unit.

6.3 Future Work

The data acquired from the preliminary experiments were used to design a more sophisticated test apparatus (Figure 6-1) that would be adequate in serving multiple experimental roles. Not only would the unit allow for the study of different surface treatments during boiling, it would also allow for the study of surface treatments during condensation. A high speed camera will be able to record the formation of vapor or liquid droplets and their motion on the surface. Pool boiling experiments will be repeated for different ratchet periods and the design of the test apparatus will allow for the observation and study of CHF.

Figure 6-1: The experimental test rig for future experiments.

Various ratchet dimensions and aspect ratios will be studied, as well as, various surface treatments such as silane coatings and reactive ion etching (RIE). Silane coatings have

hydrophobic properties which will alter the surface wettability of the surface. RIE treatments alter the nano scale surface roughness which alters the surface wettability. These variables can give better insight into pool boiling performance, as well as, allow for the study of ratchets under various conditions.

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Appendix A: Test Apparatus Design Drawings

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UNLESS OTHERWISE SPECIFIED:		NAME		DATE	
DIMENSIONS ARE IN INCHES		DRAWN			
TOLERANCES UNLESS OTHERWISE SPECIFIED:		CHECKED			
FRACTIONAL ±		ENG APPR.			
ANGULAR, MACRO ±		MFG APPR.			
TWO PLACE DECIMAL ±		G.A.			
THREE PLACE DECIMAL ±		COMMENTS			
INTERPRET GEOMETRIC TOLERANCING PER:					
MATERIAL					
Ceramic Glass					
FINISH					
DO NOT SCALE DRAWING					
APPLICATION					
NEXT ASSY					
USED ON					
TITLE: Glass 2					
SIZE DWG. NO.					
A					
glass2					
REV					
SCALE: 1:2					
WEIGHT:					
SHEET 1 OF 1					

Appendix B: Material Suppliers

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

McMaster-Carr
6100 Fulton Industrial Blvd. SW
Atlanta, GA 30336-2853
(404) 346-7000
<http://www.mcmaster.com>

Omega Engineering
One Omega Drive
P.O. Box 4047
Stamford, Connecticut 06907-0047
(800)-848-4286 or (203)-359-1660
<http://www.omega.com/>

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

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

Wale Apparatus Co., Inc.
400 Front Street
Hellertown, PA 18055
(610) 838-7047
<http://www.waleapparatus.c>

Vita

Lance Brumfield is a master's candidate in the Department of Mechanical Engineering at Louisiana State University. He has been a graduate research assistant since 2007 when he began experimental work for Dr. Sunggook Park. He received his Bachelor of Science in Mechanical Engineering from Louisiana State University in May 2009. He grew up in Baton Rouge, Louisiana, and currently resides there. He is the second of three children. He will continue his research at LSU where he will pursue his doctorate.