THESIS AND DISSERTATION PREPARATION GUIDE

COLLEGE OF ENGINEERING GRADUATE PROGRAMS

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TABLE OF CONTENTS

INTRODUCTION

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There are three major sections in the dissertation:

1. **Cover Pages**

   Title Page

   Copyright Page

   Approval Page

   Statement by Author Page

   Dedication page (optional)

Acknowledgment Page (optional)

Table of Contents

List of Tables

List of Figures

Nomenclature

Abstract

2. **Body of Dissertation**

The body is organized into Chapters. The first Chapter is the Introduction and Motivation. The last Chapter is Conclusions and Recommendations.

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In

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ACKNOWLEDGEMENTS

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Many people who I cannot mention one by one deserve thanks and appreciation for their support in the preparation of my thesis. However, I should especially acknowledge Mr. Eric Stoltz Valley Forge Sewage Authority, the staff of Phoenixville Wastewater Treatment Plant and Mr. Don Cairns (Cairns Farm) for their assistance in sample collection.

DEDICATION

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I dedicate this thesis to my parents

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and

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TABLE OF CONTENTS

(Sample Thesis Table of Contents—Note, this is a two column table formatted so that the border is not visible. Do not change the table margins or format)

LIST OF TABLES

NOTE: Table 4.1 indicates chapter 4, figure 1. Table 4.9 indicates chapter 4, figure 9 etc.

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LIST OF FIGURES

NOTE: Figure 3.2 indicates chapter 3, figure 2. Figure 4.9 indicates chapter 4, figure 9 etc.

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NOMENCLATURE

(Lower Case symbols, followed by Upper Case symbols, followed by Greek Symbols, followed by Super and Subscripts)

a fin width (m)

d fin diameter (m)

A_{wet} channel wet area (m^2)

Bo boiling number

c_p specific heat of water (J/kg·K)

D_h hydraulic diameter of channel (m)

f friction factor

G mass flux (kg/m^2·s)

Greek symbols

ρ mass density (kg/m^3)

μ water dynamic viscosity at mean temperature (N·s/m^2)

α channel aspect ratio

σ liquid surface tension

ϕ bubble contact angle

η cost-effectiveness coefficient

Subscripts

CBD convective boiling domain

l liquid

NBD nucleate boiling domain

ABSTRACT

Liquid cooled small channel heat sinks have become a promising heat dissipation method for future high power electrical devices. Traditional mini and microchannel heat sinks consist of a single layer of low-aspect ratio rectangular channels. The alternative new heat sinks are fabricated by stacking many channels together to create multiple layer channels. These multilayer heat sinks can achieve high heat flux due to high heat transfer coefficients from small channels and large surface area from multilayer structure. In this research, multilayer copper and silicon carbide (SIC) minichannel heat sinks were tested in single-phase flow. It was shown that multilayer heat sinks have significant advantages over single-layer equivalents with reductions both in thermal resistance and pressure drop. A 3-D resistance network model for single and multilayered heat sinks was developed and validated. Parametric study and optimization on copper and SiC heat sinks with respect to channel geometries, number of layers, and heat sink conductivity were conducted by using the model.

Several boiling correlations combined with the resistance network model were used to compute the heat sink surface temperature distributions, which were compared with experimental results. It was found the classical boiling correlations for macro channels are not suitable for the minichannels, frequently overestimating the boiling heat transfer coefficient. Boiling correlations for small channels are more consistent with experimental data and the predictions of Yu's correlation match the experimental results best.

(Sample Thesis Abstract[1])

[1] Ning Lei. (2006). "The Thermal characteristics of Multilayer Minichannel heat Sinks in Single-Phase and Two-Phase Flow." PhD Thesis, The University of Arizona, AZ.

CHAPTER I

INTRODUCTION

The increasing power of electronic devices has pushed the traditional air cooling technology to its performance limit. With air as a working fluid, it is increasingly difficult to design cost-effective heat sinks that can dissipate over 100 W/cm^2 heat flux at the device level as shown by Ortega (2003). The increasing volume of air cooling heat sinks also prevents their application as miniaturization becomes the trend in the electronic industry. Liquid cooled heat sinks have emerged as the natural substitute for air cooled heat sinks because of better performance and smaller size. The most commonly used working fluid is water. Benefiting by its stable properties and high thermal capacity compared with other fluids, water has been extensively studied in liquid cooling systems for electronic cooling.

1.1 Motivation

The heat dissipation ability of liquid cooled heat sinks is determined by the heat conduction in solid and heat convection in fluid. Normally the convection is the dominant factor for reducing the thermal resistance when highly conductive material is used to fabricate the heat sinks. For a fully developed laminar flow in a square channel with constant wall temperature or constant wall heat flux, the Nusselt number is a constant. The heat transfer coefficient can be calculated by the following equation,

$$h = \frac{Nuk}{D_h} \Rightarrow h \propto \frac{1}{D_h} \tag{1.1}$$

The heat transfer coefficient is inversely proportional to the channel hydraulic diameter. By reducing the channel hydraulic diameter, a large heat transfer coefficient can be achieved. Since heat exchanger performance scale with the product hA_s for a single channel, where A_s is the surface area, then hA_s does not depend on D_h because the surface area scales as $A_s \propto D_h$. But for a confined geometry, there are more channels for small hydraulic diameter than large ones. So the heat sink with smaller hydraulic diameter has better overall thermal performance.

On the other hand the friction factor for a fully developed laminar flow in square channel is also a constant. The pressure drop across the channel is determined by the equation,

$$\Delta P = 4f\left(\frac{\rho u^2}{2}\right)\frac{L}{D_h} \tag{1.2}$$

The pressure drop is also inversely proportional to the channel hydraulic diameter at constant average flow velocity. The pumping power needed to drive the flow through the channel is defined by the equation,

$$W_p = Q \cdot \Delta P \tag{1.3}$$

For a constant volumetric flow rate, the pumping power can be calculated by the following equation.

$$W_p = Q \cdot 4f\left(\frac{\rho u^2}{2}\right)\frac{L}{D_h} = 2f\rho Q^3 L\frac{1}{D_h^5} \Rightarrow W_p \propto \frac{1}{D_h^5} \tag{1.4}$$

The pumping power needed increases dramatically if the channel hydraulic diameter decreases. There are two solutions to the above problem. One is to use high aspect ratio rectangular channel instead of square channel, which increases the wetted and channel cross-section area and keeps the channel hydraulic diameter reasonable small at the same time. The second solution is to stack many channels together to form multiple layers of channels. Compared with single-layer heat sinks, multilayer heat sinks keep the individual channel hydraulic diameter unchanged but increase the total wetted and cross-section area multiple times. By doing so the convective heat transfer is enhanced by increasing the contact area. Simultaneously, the average flow velocity in each channel decreases multiple times. The decrease of flow velocity causes the reduction of the pressure drop, which consequently decreases the required pumping power. However the multilayer structure makes the conduction in the solid matrix more complicated and increases the thermal resistance between the heated surface and the channels farthest away from the heated surface. Understanding the influences of the multilayer structure on the thermal and hydraulic performance of heat sinks in single-phase flow is the major goal of this research.

In recent years, boiling in small channels has been studied by many investigators, both on the topics of boiling heat transfer coefficient and flow pattern. Most of the experiments were conducted on single channel or single-layer channel heat sinks. The influences of the multilayer structure on the boiling in mini and microchannels have not been studied. The boiling heat transfer coefficient correlation for conventional size channels has been thoroughly studied and summarized by many researchers. The boiling correlations for small channel are sparse and mostly based on data from unique experiments, which are limited to certain working fluids and channel dimensions. Validating and choosing the best boiling correlations for modeling minichannel behavior is another important goal for this research.

1.2 Literature Review on Single-phase Flow in Small Channels

For the single-phase flow, single-layer microchannels which were etched directly into the back of silicon wafers were first shown to be effective cooling solutions by Tuckerman and Pease (1981). In their experiment a maximum of 790 W/cm^2 was rejected. While the cost of fabricating microchannel heat sinks currently prohibits their application in production level electronics, the study showed that microchannel structures are well suited to the task of cooling electronic devices.

Following the pioneering work of Tuckerman and Pease, considerable research has been conducted on mini- and micro-scale heat sinks. Many of these studies have been focused on single-layer heat sinks fabricated from some highly thermally conductive materials, such as copper, aluminum, or silicon, with rows of small channels fabricated into the surface by precision machining or chemical etching. A thorough review of single-layer mini and microchannel heat sinks was presented by Sobhan and Garimella (2001).

Multilayer or stacked heat sinks consist of repeating arrays of single-layer channels. High thermal conductivity is particularly important in multilayer structures where heat can be conducted into lower layers and thereby reducing the surface temperature.

Kern and Kraus (1972) analyzed single and double stack cold plates using a finite element formulation where both symmetrical and asymmetrical heat loadings were analyzed.

By using a finite element method, Pieper and Kraus (1998) showed that double-stacked cold plates had a better performance compared with a single stack design for a fixed flow volume. Their analysis also included the coverage of all regimes of asymmetric heat loadings.

Vafai and Zhu (1999) showed that a two-layer microchannel structure with counter flow reduced the streamwise temperature rise along the device surface compared with that of an equivalent single-layer heat sink. There was also a subsequent reduction in the pressure drop for the two-layer heat sink. The thermal performance was examined numerically using a finite element method and an optimization of the design parameters was also performed.

Beh et al. (2003) analyzed the transient performance of single, double and triple stack cold plates using the finite element method where the triple stack cold plate showed the best performance. The results were reproduced in dimensionless form so that the analysis can be used for other stack dimensions.

Wei and Joshi (2003, 2004) evaluated the thermal performance of stacked high-aspect ratio microchannel heat sinks using a simple thermal resistance network. The solution procedure was iterative in nature. A thorough parametric study was performed for optimal channel aspect ratios, conductivities, number of layers, pumping power per unit area and channel length.

Experimental and numerical characterization of two-layer silicon microchannel heat sinks in parallel and counter flow configurations were investigated by Patterson et al. (2004). They concluded that the counter flow configuration resulted in more uniform surface temperature while the parallel flow configuration showed a lower maximum surface temperature.

Skandakumaran et al. (2004) proposed a two dimensional closed-form analytical resistance network model on single and multilayer SiC heat sinks using a constant heat flux formulation by assuming an average constant surface temperature. The predictions of the analytical model was compared with Bower’s (2005) data and shown to match with experimental data only at high flow rates.

1.3 Literature Review on Two-phase Flow in Small Channels

Due to its broad application in boiler, power plant, and refrigerant systems, the boiling in conventional size plain tubes has been extensively investigated by many researchers. In the past twenty years, the boiling process and two-phase flow in small channels have attracted growing interest due to the needs for high heat flux dissipation and miniaturization of electronic device. Because of insufficient knowledge of flow patterns and poor boiling correlations, two-phase flow in small channels is difficult to predict and therefore difficult to implement in practical technologies such as for electronic devices.

For two-phase flow, the distribution and structure of the liquid and gas phase inside the flow is an important characteristic of their description. The two-phase flow patterns are the description of certain flow structures which have particular identifying characteristics. Local boiling heat transfer coefficient and pressure drop are closely related to the local flow pattern. Correct prediction of two-phase flow pattern, which depends on channel geometry, local flow conditions, and wall heat flux, is an important aspect of investigating and modeling boiling and two-phase flow in channels.

Predicting the local boiling heat transfer coefficient is the key issue of two-phase flow research. There are two important heat transfer mechanisms normally considered to model the boiling in channels: nucleate boiling heat transfer and convective boiling heat transfer. Nucleate boiling in channels is similar to nucleate pool boiling except the effect of bulk flow and the influence of the channel size and geometry. The bulk flow affects the growth and departure of the bubbles and bubble induced convection. The channel size affects the flow pattern which influences which heat transfer mechanism is dominant. The convective boiling refers to the interaction between the channel wall and the liquid-gas mixture. In the conventional size channels, the nucleate boiling strongly depends on local heat flux and it tends to be dominant at low vapor quality and high heat flux conditions. On the other hand, the convective boiling is mainly dependent on local vapor quality and mass flux and it dominates on high vapor quality and low heat flux conditions. For mini and microchannels, the surface tension, which is normally negligible in large size channels, begins to play important role in two-phase flow. This makes the boiling in small channels more complicated than that in conventional size channels.

1.3.1 Boiling Heat Transfer Coefficient Correlations

Chen (1966) proposed the first flow boiling correction for evaporation in conventional vertical tubes. He suggested the local two-phase boiling heat transfer coefficient h_{tp} to be superposition of the nucleate boiling coefficient h_{nb} and the convective boiling coefficient h_{cb} with proper factors.

$$h_{tp} = Sh_{nb} + Eh_l \qquad (1.5)$$

The nucleate pool boiling coefficient h_{nb} is given by Forster-Zuber (1955),

$$h_{nb} = 0.00122\left[\frac{k_l^{0.79} c_{p,l}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{\lg}^{0.24} \rho_g^{0.24}}\right]\Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} \qquad (1.6)$$

The single-phase convective heat transfer coefficient h_l is given by Dittus-Boelter (1930), which is commonly used for turbulent flow and for the fraction of liquid flow only

[IN THIS STYLE, THE TABLES AND FIGURES ARE PLACED AT THE END OF THE CHAPTER TEXT, WITH TABLES FIRST, FOLLOWED BY FIGURES]

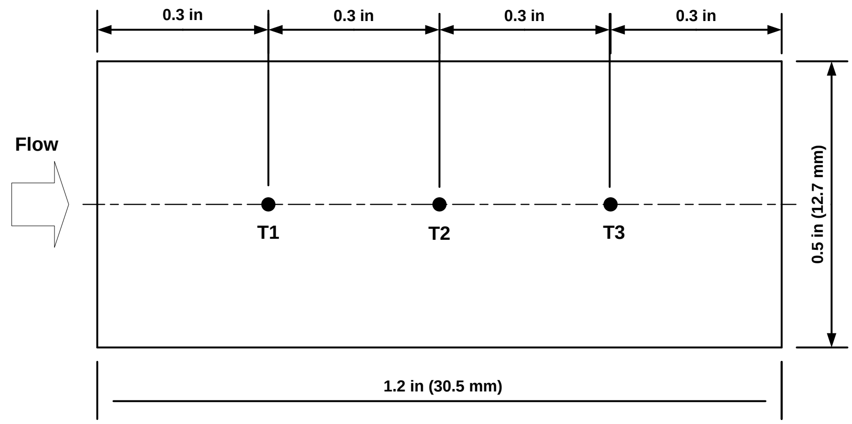

Figure 2.7a Thermocouple position for SiC heat sinks

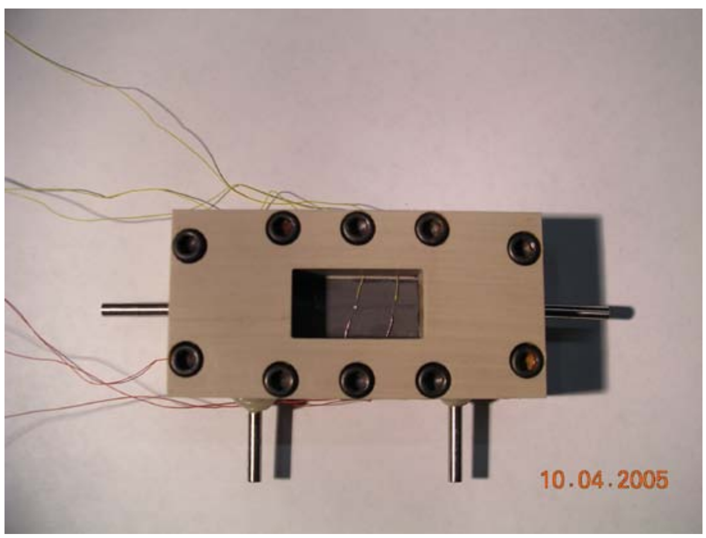

Figure 2.7b Top view of a SiC heat sink with thermocouples inside heat sinks manifold

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[2] Ning Lei. (2006). "The Thermal characteristics of Multilayer Minichannel heat Sinks in Single-Phase and Two-Phase Flow." PhD Thesis, The University of Arizona, AZ.

CHAPTER IV

GOOSE CREEK WATERSHED DATA

[NOTE: ALTERNATIVELY, THE TABLES AND FIGURES CAN BE PLACED WITHIN THE CHAPTER TEXT. THEY SHOULD BE PLACED AFTER THE TEXT THAT FIRST CITES THE TABLE OR FIGURE. EXAMPLE BELOW]

4.1 Goose Creek Watershed Area

One of the primary aims of this study was to assess sources of indicator microorganisms using FAME profiles as an MST method in the Goose Creek located 20 miles southwest of Villanova University in the Chester Creek Watershed area (See Figure 3.1 for the Location of Goose Creek in Delaware River Basin, Chester County, Pennsylvania).

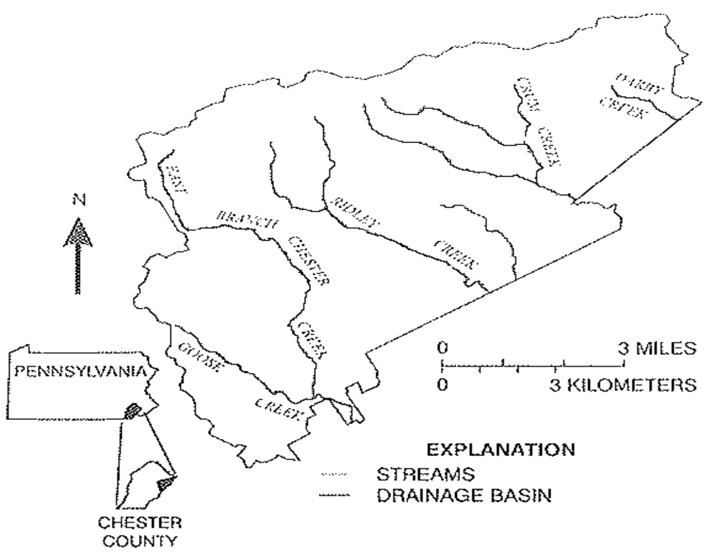

Figure 3.1 Location of Goose Creek in Delaware River Basin, Chester County, PA
(Adopted from USGS Fact Sheet FS-116-02, December 2002)

(Sample Continuation Page with Figure[3])

[3] Unlu C. (2009). "Microbial Water Quality and Sources of Indicator Microorganisms in Goose Creek." MS Thesis, Villanova University, PA.

According to water flow direction of Goose Creek, sampling sites can be ordered as site 10, 1, 4, 6, 7, and 9 from upstream to downstream. US Route 202 and 322, which follow North to South orientations, are the major transportation routes in the vicinity of Goose Creek watershed area. Figure 3 shows the main transportation routes in the Chester and Goose Creek watershed area. Sites 1 (close to US Route 202), 7 and 9 are in the residential parts of the Goose Creek watershed area, additionally Site 7 is next to the West Bourne Middle School. West Goshen WWTP and West Chester Borough WWTP discharge points are close to Site 4 and Site 6, respectively. Moreover, there are two horse farms next to Site 6. Site 10 is located adjacent to the Ridley State Park and Chester County Government Building. Features of the sampling locations are summarized in Table 4.1.

Table 4.1. Locations of Goose Creek sampling sites

Site #	Location	Feature of the location
Site 1	Lacey Street	Densely populated residential area
Site 4	Hagerty Blvd.	Downstream of West Goshen WWTP
Site 6	Oakburne Rd.	Downstream of West Chester Borough WWTP
Site 7	West Bourne Rd.	Next to the West Bourne Middle School
Site 9	Westtown Thornton Rd.	Residential area
Site 10	Westtown Rd.	Next to the Chester County Government Building

(Sample Continuation Page with Table[4])

[4] Unlu C. (2009). "Microbial Water Quality and Sources of Indicator Microorganisms in Goose Creek." MS Thesis, Villanova University, PA.

4.2 Subsection Title

The channel heat flux has a maximum value at the inlet region due to high local heat transfers coefficients in entrance regions, low bulk flow temperature, and axial conduction. In the resistance network model, the local heat transfer coefficient is obtained by applying the empirical correlation for constant wall heat flux conditions, which is certainly not true at the inlet region. For low flow rates, the heat sink surface temperature is higher and the temperature gradient is larger than those of high flow rate, so the absolute error of predicted temperature is expected to be larger than that of high flow rate, which is also shown in Figure 4.8

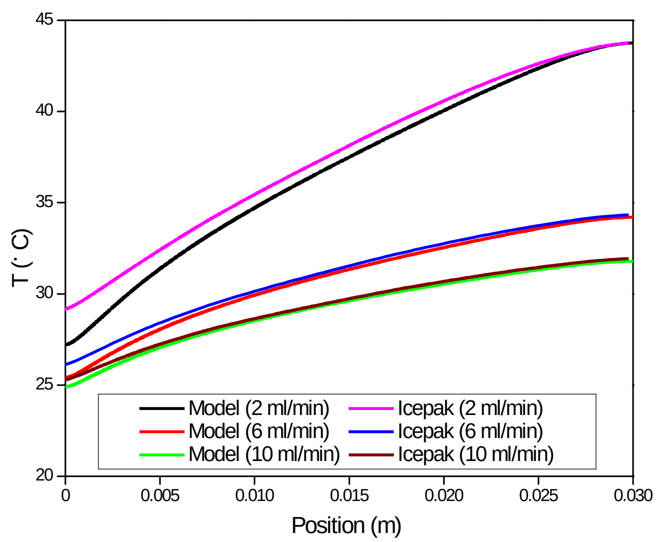

Figure 4.8 Temperature distribution comparison for single-layer copper heat sink

(Sample Continuation Page with Plot[5])

[5] Ning Lei. (2006). "The Thermal characteristics of Multilayer Minichannel heat Sinks in Single-Phase and Two-Phase Flow." PhD Thesis, The University of Arizona, AZ.

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(Sample Thesis References Page[6])

[6] Unlu C. (2009). "Microbial Water Quality and Sources of Indicator Microorganisms in Goose Creek." MS Thesis, Villanova University, PA.

APPENDIX A. Microbial Quality Results of Goose Creek Samples[7]

Sampling Time	Indicator Microorganism	CFU/100 ml					
		Site#1	Site#4	Site#6	Site#7	Site#9	Site#10
Oct-2006	FC	270	310	7200	1070	340	240
	Enterecoccus	240	TMC	1200	290	170	330
Nov-2006	FC	570	210	1000	30	30	160
	Enterecoccus	210	810	390	170	160	150
Dec-2006	FC	570	210	1000	30	30	160
	Enterecoccus	210	810	390	170	160	150
Jan-2007	FC	770	86	51	13	23	44
	Enterecoccus	120	160	148	30	24	9
Mar-2007	FC	940	390	230	110	250	50
	Enterecoccus	96	70	52	38	60	102
May-2007	FC	510	120	100	110	120	710
	Enterecoccus	130	460	TMC	160	100	480
Jun-2007	FC	TMC	450	540	470	890	TMC
	Enterecoccus	TMC	420	260	260	450	TMC
Jul-2007	FC	13400	270	360	200	160	1100
	Enterecoccus	2000	590	150	290	530	4900
Sep-2007	FC	210	4600	380	480	100	240
	Enterecoccus	750	1130	250	150	300	800
Oct-2007	FC	5000	150	70	70	60	480
	Enterecoccus	500	200	120	110	280	730
Nov-2007	FC	2400	150	100	80	80	130
	Enterecoccus	800	100	20	50	60	180

[7] Unlu C. (2009). "Microbial Water Quality and Sources of Indicator Microorganisms in Goose Creek." MS Thesis, Villanova University, PA.