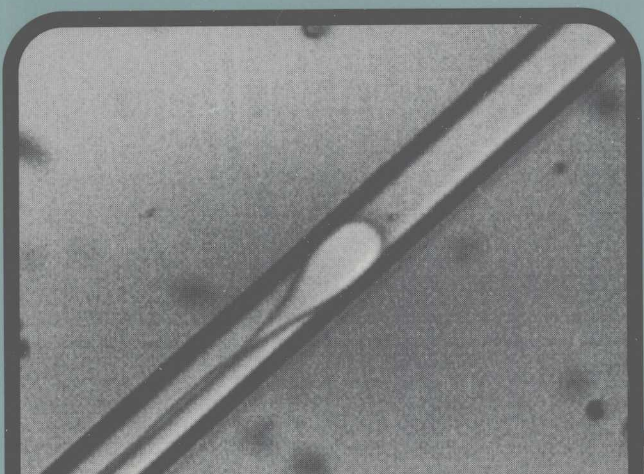
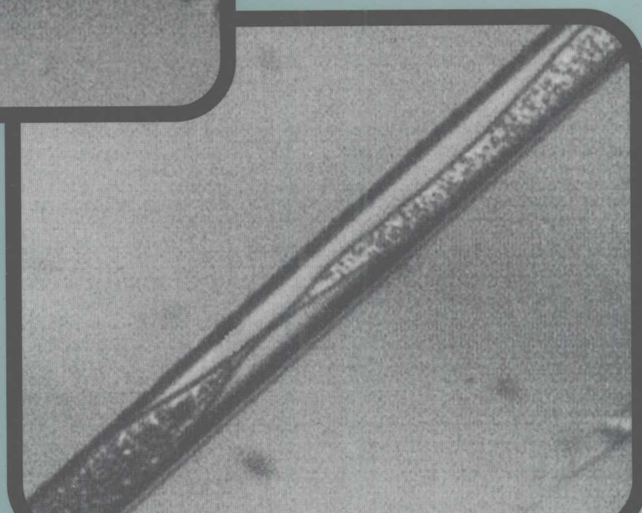
Heat Convection in Micro Ducts

Yitshak Zohar





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Foreword

Yitshak Zohar's book on *Microchannel Heat Sinks* is the second book in the Microsystems Series to focus on heat transfer in microsystems. The first, *Microscale Heat Conduction in Integrated Circuits and Their Constituent Films*, by Ju and Goodson, dealt with the problem of conduction in heterogeneous microstructures and presented new methods of characterizing the heat flow. This new volume addresses the coupling between heat conduction and fluid mechanics that is central to understanding convective heat transfer, and does so in the context of microfabricated structures.

Understanding the fundamentals of microchannel heat transfer is essential not only for the important task of heat removal in integrated circuits, but also for a growing family of microfluidic devices designed for chemical and biochemical analysis. Thus, the book includes both conventional pressure-driven fluid flow and electrokinetic transport along with applications appropriate to each type of flow. There is good balance between the fundamentals of the relevant theory and the approximations that are used to create tractable solutions to practical problems so that experimental behavior can be confronted on a sound footing.

Microchannel Heat Sinks will be a welcome addition to the microsystem engineer's bookshelf.

Stephen D. Senturia
Brookline, MA

Preface

Electronic cooling has been the technology driver for the developments of microcooling systems since the early 1980's. As electronic products become faster and incorporate greater functionality, they are also shrinking in size and weight, with continuing demand for cost reduction. Shrinking system sizes are resulting in increasing heat generation rates and surface heat fluxes leading to a significant interest in ultra-compact high heat removal devices. However, with the proliferation of microsystems to all aspects of our life, thermal control and management on a microscale is becoming a critical factor in a wide range of applications. The concept of lab-on-a-chip requires several thermal components and, ultimately, the technology is directed toward chemical and biochemical analysis tools based on the miniaturization and integration of many elements on a single chip. For commercial success, this new technology not only satisfies the need of a large demand but also promises enormous potential. This broad base application may become the prime technology driver for the development of thermal microsystems.

The traditional air-cooling method of finned heat sink with an attached dc fan is clearly approaching its limits. Therefore, the first alternative is liquid cooling with or without phase change. Most of the proposed cooling techniques utilize, of course, the latent heat of phase change for enhanced heat transfer efficiency. As the area of micro fluid mechanics and heat transfer continues to grow, it becomes increasingly important to understand the fundamental mechanisms involved with single- and two-phase micro-scale heat convection. In particular, the subject of convective boiling in microchannels is relatively young, and most of the work has been done within the last decade. The goal of this book is, therefore, to summarize the findings of this early research stage of convection heat transfer in micro ducts. However, typical to any emerging field, the understanding of fundamental principles is often neglected in favour of discovering new applications. Thus, it is inevitable that some initial concepts and preliminary results are not mature yet. Indeed, the book was written as a stepping-stone with the hope of stimulating discussion and research among colleagues to enhance our knowledge for the benefit of all.

Yitshak Zohar

Acknowledgements

I would like to express my gratitude to Professors Chih-Ming Ho of UCLA and Yu-Chong Tai of Caltech, who introduced me to the micro world a decade ago, and Professor Man Wong of HKUST, who has been working with me shoulder-to-shoulder for a decade now. The interaction with them over the years has been the source of inspiration and guidance required for a sustained research work.

I'm particularly grateful to the colleagues and students who spent many pain-stacking hours fabricating devices, testing them, and analyzing the results. The bulk of the book material is based on their work. Prof. Yuelin Wang initiated the fabrication and testing methodology of integrated thermal microsystems. Dr. Linan Jiang continued in his footsteps, and her Ph.D. thesis is the main source for much of the book content; this includes the steady and unsteady, single- and two-phase microchannel heat sink as well as the thermistor studies. Finally, Mr. Man Lee, through his M.Phil. thesis on micro heat pipes, together with Mr. Yiu Yan Wong, working on a rectangular microchannel heat sink, contributed their fare share to the evolving research program.

Several other colleagues and students who indirectly contributed to this effort are Prof. Xinxin Li, Prof. Xin Zhang, Ms. Wing Yin Lee, and Mr. Sylvanus Yuk Kwan Lee.

The unsung heroes are perhaps the members of the technical support staff of the Micro Fabrication Facility at HKUST, who quietly and diligently provide efficient and highly professional service.

Last but certainly not least is the tremendous support of the Lab Scientific Officer Mr. Wan Lap Yeung. He humbly, behind the scenes, has been welcoming into the group every newcomer, and patiently provides the proper training critically needed in the initial stage of every research project.

Special thanks are due to Dr. Linan Jiang of Stanford, who read the draft, corrected some glaring errors, and made a few significant comments and suggestions. Her efforts, no doubt, enhanced the quality of the final product.

The funding by the Research Grants Council, through the Competitive Earmarked Research Grant program, is highly appreciated. It has been instrumental in enabling us to develop the MEMS program at HKUST.

Contents

Chapter 1

Introduction

The last decade of the twentieth century has witnessed an impressive progress in micromachining technology enabling the fabrication of micron-sized devices, which become more prevalent both in commercial applications and in scientific research. These microsystems have had a major impact on many disciplines, e.g. biology, chemistry, medicine, optics, aerospace, mechanical and electrical engineering. This emerging field not only provides miniature transducers for sensing and actuation in a domain that we could not examine in the past but also allows us to venture into a research area in which the surface effects dominate most of the physical phenomena [62]. Fundamental heat-transfer problems posed by the development and processing of advanced Integrated Circuits (ICs) and MicroElectroMechanical Systems (MEMS) are becoming a major consideration in the design and application of these microsystems. The demands on heat removal and temperature control in modern devices, with highly transient thermal loads, require new techniques for providing high cooling rates and uniform temperature distributions. Thus, thorough understanding of the physical mechanisms dominating microscale heat transfer is vital for continuous evolution and progress of microdevices and microsystems.

1.1 Electronic cooling

A fundamental requirement for the commercial success of any micro-fabrication technology is an application with a very large demand. These applications are essential technology drivers providing sufficient economic pull for the adequate recovery of facility costs, which sustain continued research into new and improved devices at very low unit cost.

It is envisioned that, sooner or later, billions of people, places and systems could be all connected to each other and to useful services through the Internet. Then, scalable and cost-effective information technology capabilities will need to be provisioned, delivered, metered, managed and purchased as a service [44]. Consequently, processing and storage will be accessible via a utility. In this model, planetary-scale computing, customers will pay for services based on the amount they use, similar to other public utilities such as electricity and water. Some of the technical challenges facing the designers are thermal and mechanical issues of future integrated circuits, densely packaged racks of servers, and large scale data centres. It is estimated that a planetary-scale data centre will require 50MW of power for the computing infrastructure, and the cooling of this centre will consume an additional 25MW.

There is no denying that the prime technology driver for thermal microsystems has been electronic cooling. The picture of a modern microprocessor under a finned heat sink with an attached dc fan, like the example shown in Figure 1, is by now a household recognized image. This picture demonstrates both the problem of heat generation during the operation of microelectronic devices, and the traditional solution of heat removal using forced convection air-cooling through a network of fins. However, it is well known that this cooling technology is approaching its limits.

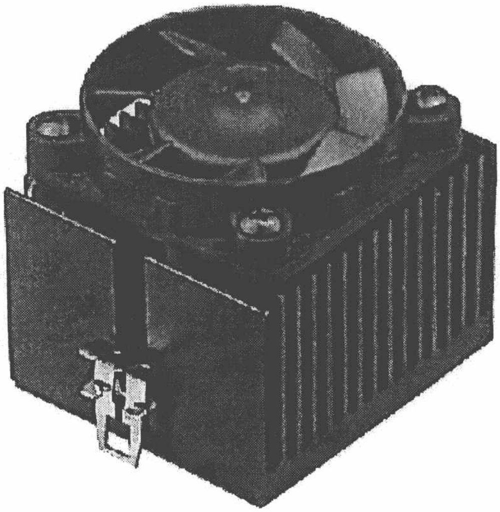

Figure 1.1: A picture of a modern CPU cooling system featuring a finned heat sink with an attached DC fan.

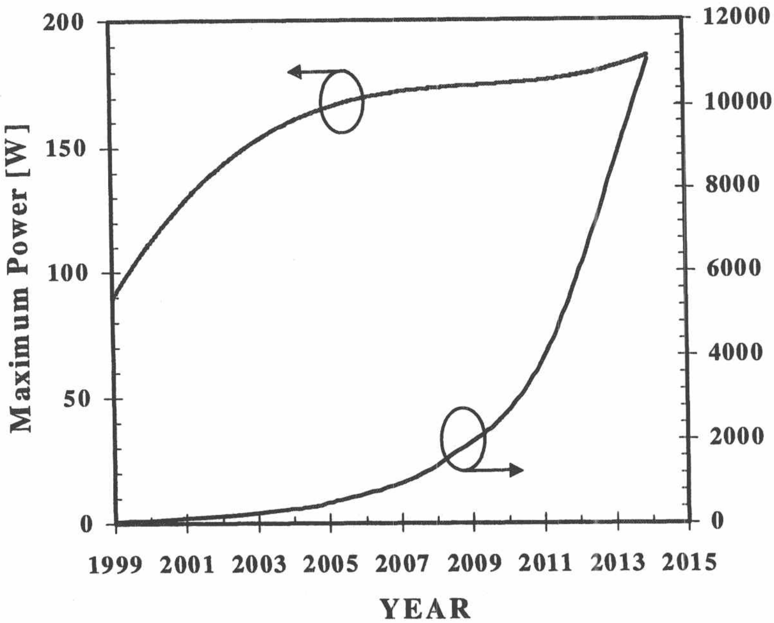

Figure 1.2: The projected number of transistors and corresponding heat generation according to the roadmap.

Indeed, the role of thermal and mechanical architecture is critical to ensure efficient power management, cooling and physical data centre design. These trends motivate a variety of thermo-mechanical research topics related to innovative thermo-mechanical designs that are required for the next generation of chips, the total energy costs over the lifetime of a product, and techniques that allow using and re-using energy more efficiently. To meet this challenge, The Defence Advanced Research Project Agency (DARPA) launched the Heat Removal By Thermo-Integrated Circuits (HERETIC) program, and a project summary is now available [35]. For the immediate future of the high-performance chip market, it is projected that by the year 2003 the microprocessor frequency will reach 3.5GHz, the device feature size will decrease to 0.1μm, the number of transistors per chip will increase to 200 million and the number of I/O connections per chip will increase to 4000. In the International Technology Roadmap for Semiconductors (2000 Update) [72], it is predicted that within a decade the number of transistors per device will reach 12×10^9 with heat generation of close to 200W as shown in Figure 1.2. Currently, all the advanced technologies have demonstrated cooling capability of less than to $100W/cm^2$.

As early as two decades ago, Tuckerman and Pease [208] pioneered the use of microchannels for the cooling of planar integrated circuits. They demonstrated that by flowing water through small cooling channels etched in a silicon substrate; heat transfer rates of about $10^5 W/m^2K$ could be achieved. This rate is about two orders of magnitude higher than that in the state-of-the-art commercial technologies for cooling arrays of ICs. Since then heat transfer performance of flows in microchannels has been experimentally and theoretically analysed by a number of researchers. Most of the early studies dealt with single-phase flow of either liquid or gas through microchannels, as it proved to be complicated enough. However, it is clear that utilizing the latent heat associated with phase-change can dramatically enhance the performance of microchannel heat sinks.

1.2 Thermal issues in microsystems

Although electronic cooling is recognized as the current technology driver for thermal management solutions, similar problems exist in other microsystems. Microsystem technology generally involves coupled-field behaviour, combining two or more energy domains such as mechanical, electrical, chemical or thermal [36]. The electrical and thermal domains are probably the most prevalent in microdevices, either by design or as a by-product. Unlike thermal management in electronic packaging, concerned mainly with efficient heat removal, thermal challenges in microsystems encompass a large number of issues; ranging from harnessing thermal energy for driving microactuators to the ultimate sensor noise limits imposed by inherent thermo-mechanical coupling in microsensors.

One of the earliest and most successful applications of thermal microsystems is the microfabricated for thermal inkjet print heads [143]. Microsystem technology has been a major enabler in this field since the mid-1970s, allowing significant reduction in cost while increasing the performance of printers. The operating principles are based on a combination of thermodynamics and fluid dynamics using silicon micromachined components. In these devices, a vapour bubble is thermally generated and expanded within a silicon chamber using an integrated microheater, forcing ink to be expelled from an exit nozzle. A similar technique was applied to micro-machined fuel injectors for automotive applications, and a novel design using multiple thermal elements for rapid droplet generation was also demonstrated [204].

Bulk silicon has been extensively applied to thermal isolation of passive and active on-chip components. Isolation to remove heat sources or sinks in the proximity of a thermal element is typically achieved through etching of either the bulk substrate or a thin film sacrificial layer underneath the thermal element. Thermal isolation structures can be found in high performance thermal sensors. For example, thermoelectric infrared detector arrays have been fabricated using a commercial 1μm-linewidth CMOS process, with the polysilicon/aluminium interface acting as a thermopile detector and backside bulk micromachining providing thermal isolation [135]. Beyond passive thermal isolation, active thermal control has also been used for applications such as frequency tuning for microresonators, which often exhibit high temperature sensitivity that can limit their performance [174]. Active thermal control has been used to perform direct mechanical actuation through thermal expansion. With relatively low voltage requirements and high force output, electrothermal actuation has important advantages over traditional electrostatic actuation. Both in-plane and out-of-plane actuators have been developed that rely on resistive heating and thermal expansion of various materials [142,168].

Thermal expansion for controlled mechanical work has been applied to realize micropumps and microvalves for gas and liquid manipulation. Rather than using bubble expansion to expel fluid from the micromachined chip, as in the case of inkjet print head, a bubble pump for fluid mixing in a stationary micromachined chamber has been demonstrated [41]. Due to high surface tension forces, thermally generated microscale bubbles tend to be highly stable and useful for generating mechanical work. An extension of fluid displacement via thermally generated bubbles has also been used to generate bulk pumping in microchannel networks [233]. A valveless micropump was demonstrated by combining a series of addressable microheaters to create a travelling sequence of bubbles capable of precise fluid pumping with a 0.5nL/min flow rate [103]. A larger scale thermal bubble micropump capable of delivering a 6.5mL/min flow rate [203], and thermal bubble micropumps for drug dispensing from a micro-needle [234] have also been fabricated. Other micropumps utilize alternate thermal actuation methods such as bimetallic and thermopneumatic elements [241], or TiNi shape memory alloy actuators with integrated thermal control [121].

Another widely used application of thermal microsystems is the sensing of bulk fluid flow in microdomains. A variety of micromachined thermal sensors for measuring liquid flow rates and wall shear stress have been demonstrated, such as microscale hotwire anemometers fabricated from polysilicon elements [67,79], and anemometers based on p/n polysilicon thermopiles with integrated heating elements [129]. The heaters in these devices function as classical hotwire anemometers, with a feedback loop to maintain the temperature of the element as heat is removed by the flow. The sensors have demonstrated a flow rate resolution of 0.4nL/min. [225]. Such resistive Joule heating elements for anemometry can be readily formed using resistive metal or selectively doped bulk silicon.

An important application for thermally actuated pumping, valving, and flow sensing is lab-on-a-chip microsystems. The development of lab-on-a-chip technology is ultimately directed toward chemical and biochemical analysis tools based on the miniaturization and integration of liquid handling, sample processing, and sample analysis in a single chip. In addition to flow control applications, other issues in lab-on-a-chip concept are directly related to thermal phenomena. For example, microdevices for polymearase chain reaction (PCR) amplification of DNA have been developed by a number of groups. The PCR process involves sequential heating and cooling, with 30s at 95°C for denaturation of double-stranded DNA molecules, and 1-2min each for annealing and extension at 72°C to form a new set of double-stranded molecules. With 25-40 cycles per reaction, a traditional cycler requires about 90min for amplification. In contrast, micro heaters integrated in a micro reaction chamber for PCR amplification have been reported with a cycle time of 60s/cycle and heating rate of 15°C/s, for a total amplification time of approximately 22min [137]. More recently, an integrated device that accomplishes cell lysis, PCR, and capillary electrophoresis on monolithic microchips has been demonstrated using bacterial samples [216]. Rapid PCR thermal cycling rates as fast as 17 s/cycle have been demonstrated in silicon microchambers [10]. The short cycle times are made possible by the relatively small thermal mass of the microstructures. This technology is based on temporal control over the temperature field within a single reaction chamber. Similarly, spatial temperature control has been used for continuous flow PCR, based on a glass chip with a single microchannel that meanders the sample across three zones of constant temperature to provide 20 amplification cycles in times ranging from 1.5 to 18.5 min [101].

Genetic tests have an enormous scope of applications in biotechnology and medicine, ranging from agriculture and farming to genetic diagnostics on human subjects. Currently, about 400 diseases are diagnosable by molecular analysis of nucleic acids, and the number is continuously increasing. Many of these assays have been developed as part of a major thrust aimed at making medicine a more quantitative science. Furthermore, many more assays will follow as more genetic information is discovered by major research efforts such as the Human Genome project. Humans have approximately 100,000 genes that could be potentially tested for defects or the propensity for diseases. Essentially with the same procedure, the contents of every gene on any form of life could be examined. This new development of microsystem technology not only satisfies the requirement for a huge demand but also promises enormous potential for growth. Such a broad base application may indeed prove to be the ultimate technology driver of all time.

1.3 Case studies

As the limit for air-cooling (finned heat sink with a dc fan) is reached, the first alternative is liquid cooling with or without phase change. So far, liquid-cooled electronics has not penetrated the market, with the exception of heat pipes used in laptop computers. Intense activities are currently taking place, such as arrays of micro impinging jets with the advantage of single-phase operation [227]. The majority of the proposed cooling techniques, though, utilize the latent heat of phase change for enhanced efficiency. The electrokinetic microcooler incorporates an electro-osmotic pump in conjunction with a microchannel heat sink for a continuous, closed-loop operation [78]. A micro capillary pumped loop, comprising an evaporator, condenser, reservoir and fluid lines, is capable of carrying a much greater heat load due to its single directional flow [165]. A compact thermosyphon loop includes an array of channels and pores fabricated inside the evaporator section to enhance the boiling performance [172]. Other techniques such as cross-flow micro heat exchangers [57], spray cooling [139] or thermoelectric microcoolers [232] have also been studied in association with thermal management of microsystems. Indeed, a diversity of ideas.

However, as the area of micro fluid mechanics and micro heat transfer continues to grow, it becomes increasingly important to understand the mechanisms and fundamental differences involved with heat transfer in single- and two-phase flows in micro ducts. The subject of two-phase forced convection heat transfer in microchannels is relatively young, and most of the work has been carried out within the last decade. By far, the majority of the reported research work in this area has been empirical in nature [86]. Only recently, efforts to derive analytical models from basic principles rather than empirical correlations have been reported [146].

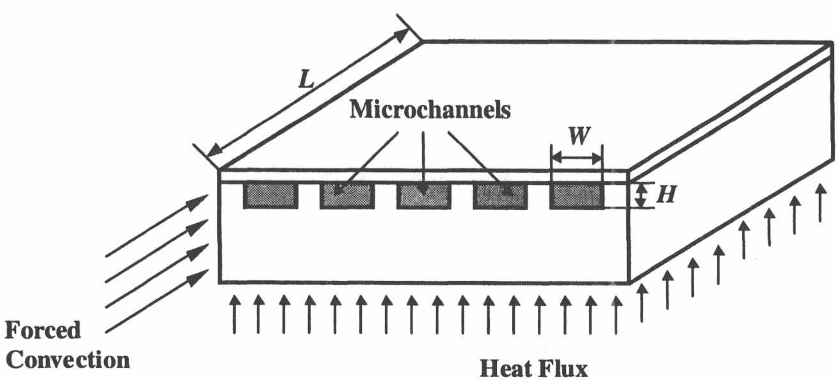

Figure 1.3: A schematic illustration of a microchannel heat sink showing the heat flux from the source and the microchannel forced convection for heat removal.

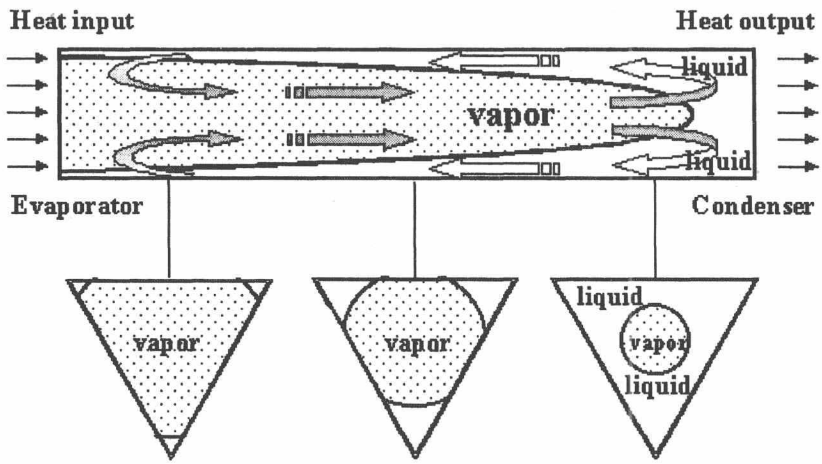

Figure 1.4: A schematic illustration of a micro heat pipe showing the evaporator where heat enters and the condenser where heat is rejected from the system together with the flow pattern and the corresponding cross-sections.

Two examples of thermal microsystems have been selected as case studies for a detailed discussion throughout the book: (i) microchannel heat sink, and (ii) micro heat pipe. The two microsystems are fundamentally different, yet both feature phase change and consequently two-phase flows. The microchannel heat sink, schematically illustrated in Figure 1.3, is an open system. Liquid is forced through the microchannel under pressure gradient, which is imposed by an external power source such as a pump. Even if all the control parameters are constant in time, the developing flow could be highly irregular. Although very promising, due to its complexity, this approach is yet to make in roads into the commercial world. On the other hand, the micro heat pipe illustrated in Figure 1.4 is a closed system. Once fabricated, it is self-contained and self-started. The heat source itself provides the driving force. Under steady-state operation, within the system limitations, the flow is highly stable. Due to its simplicity, the concept of a micro heat pipe has found some commercial applications already.

1.4 Book overview

Following the Introduction, Chapter 2 reviews fundamental aspects of convective heat transfer. Since this topic has been discussed in detail in many text-, reference- and hand-books, the emphasis has been put on size effects that may result in a different behaviour of scaled-down microsystems compared to their macosystems counterparts.