**Series in Contemporary Perspectives in Emerging Technologies**
**Series Editor: Satish. G. Kandlikar**

# *Contemporary Perspectives on*
# *LIQUID COLD PLATE DESIGN:*
## *Design and Manufacturing Liquid Cooled Heat Sinks for Electronics Cooling*

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**Mark E. Steinke**
**Satish G. Kandlikar**

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New York • Connecticut

**SERIES IN CONTEMPORARY PERSPECTIVES IN EMERGING TECHNOLOGIES**
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**CONTEMPORARY PERSPECTIVES ON LIQUID COLD PLATE DESIGN, DESIGN AND MANUFACTURING LIQUID COOLED HEAT SINKS FOR ELECTRONICS COOLING**

CLIFFORD N. HAYNER II, MARK E. STEINKE, SATISH G. KANDLIKAR



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ISBN: 978-1-56700-281-2 Print
ISBN: 978-1-56700-285-0 Online

PRINTED IN THE UNITED STATES OF AMERICA 1 2 3 4 5 6 7 8 9 0

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**Library of Congress Cataloging-in-Publication Data**
Hayner, Clifford N., II, author.
Contemporary perspectives on liquid cold plate design, design and manufacturing liquid cooled heat sinks for electronics cooling / Clifford N. Hayner II, Mark E. Steinke, Satish G. Kandlikar.
pages cm. -- (Series in contemporary perspectives in emerging technologies)
Includes bibliographical references and index.
ISBN 978-1-56700-281-2 (hardcover : alk. paper)-ISBN 978-1-56700-285-0 (online) 1. Cold plates (Electronics)-Design and construction. 2. Heat-Transmission. 3. Electronic apparatus and appliances-Cooling. I. Steinke, Mark E., 1976- author. II. Kandlikar, S.G. (Satish G.), author. III. Title.
TK7872.H4H39 2014
621.3815'4--dc23
2014020006

**Direct inquires to Begell House, Inc., 50 North Street, Danbury, CT 06810**

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# Foreword

Liquid-cooled cold plates are becoming the workhorses of electronics cooling industry. They deliver an efficient solution that integrates well with a small-scale product such as a remote server as well as large-scale applications such as data centers.

I am very pleased to present this unique book that combines an in-depth thermal and fluid design perspective with practical manufacturing considerations. Oftentimes, these manufacturing details are difficult to find and each manufacturer has to develop such expertise in house. The combination of these two themes in a single source is seen as a major contribution in the area of liquid cooling of electronics component.

We have been very fortunate to gain the exhaustive manufacturing perspective from our coauthor, Clifford N. Hayer II. He brought over 30 years of practical experience and shared it generously prior to his sad demise in the summer of 2013. The book serves as a tribute of our appreciation for his contribution.

Mark Steinke has been a leading researcher at IBM and brings the combined perspective of theoretical design and the practical aspect of electronics cooling. He has been instrumental in presenting some of the solved examples in this book. I was able to present some of the theoretical design considerations and provide a platform for us to bring this book to fruition.

Once again, I would like to thank Begell House for their support in publishing through this contemporary perspective series. In particular, I am thankful to Yelena Shafeyeva, President of Begell House, for her encouragement and support in founding this series. I am also thankful to the Vice-President and Production Manager, Vicky Lipowski, who has been an efficient yet kind project manager, and helped us bring out the book in a timely manner. I would also like to extend my heartfelt thanks to Wendy Weitz, typesetter, for taking extra care in preparing the text. The support and tireless efforts by all Begell House staff is also gratefully acknowledged.

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# Preface

It is my pleasure, on behalf of the three authors, to write the preface for this book. The concept for this book was really born from Cliff and his vast industrial experience. He had a keen observation that most published works on cold plates mainly focused on the fundamental theory at play in the cold plates. It was the heat transfer and fluid mechanics involved that drove the discussion. After all, a liquid cold plate has the same appeal that heat exchangers do to those interested in thermodynamics, heat transfer, and fluid mechanics. It represents the perfect marriage of all three disciplines and the opportunity to apply all three.

There is little information available in literature about the design and manufacturing of these cold plates, despite the interest from academia and industry alike. As a result, we have an entire industry that has no common knowledge base, no vernacular, and no shared learning of the best practices in manufacturing cold plates at an industrial scale. Each cold plate designer is forced to learn the painful lessons that producing cold plates has to offer. Corrosion, erosion, high pressure drops, and contact voiding are but a few obstacles that one must overcome along the journey to produce a cold plate product.

Cliff's desire was to share the lessons he learned and establish a common knowledge on cold plate manufacturing. He approached Satish with the concept for the book. Together, they began to form the content of the book. The fundamental theory and some of the manufacturing issues were identified. Finally, I was approached to add the nascent industrial aspects of cold plates, specifically, microchannel based. I had worked with Cliff on a few projects during my grad school days and saw his industrial expertise first hand. Naturally, I jumped at the chance to be involved.

All of the pieces finally fell into place. As I read through a few of the preliminary concepts and ideas, I recognized almost every issue I had faced in bringing my first liquid cold plate to production at IBM. There they were—the obstacles I had spent months discovering, working around, and working through while designing and developing the product! I thought to myself that I would have loved to read this before I began my design work.

The book describes the fundamental theories involved in cold plate design as well as issues involved with the manufacturing of cold plates. Obviously, every manufacturer will have their special trade secrets and methods. However, one will find that there are more common issues than there are special ones. This is a wide field in terms of theory, technology, and application. Microchannels and microfabrication have added a recent twist to the age-old cold plates, but the fundamentals remain unchanged. One needs to produce an efficient, quality part at a reasonable cost. As this application of thermodynamics, heat transfer, and fluid mechanics continues to evolve into the future, it is our collective hope that this serves as a base of shared knowledge to improve upon.

*Mark E. Steinke*

On behalf of Clifford J. Hayner II, Mark Steinke and Satish G. Kandlikar

# Chapter 1

# *Introduction*

## 1.1 Introduction

Electronics cooling is a unique industry whose roots began when the first electronic component was built more than half a century ago, and yet, it is still a very active area for researchers and engineers alike. With each successive generation of electronics equipment, the package density and resulting power consumption has increased. The physical volume of these devices is staying constant or even shrinking. The heat fluxes encountered in these systems can range from the trivial to the ultradense. With stringent limits on temperature, there are a great deal of cooling challenges that need to be addressed through the knowledge of heat transfer, fluid mechanics, structural mechanics, materials science, and manufacturing technology.

In the first several decades of electronics products, the use of air cooling did a perfectly fine job of cooling the low-power-density components. Eventually, the heat flux would reach a point at which the low heat capacity and high specific volume of air would not provide adequate cooling to maintain reasonable component temperatures. Liquid cooling was the next logical step to achieve the desired cooling. With many working liquids having several orders of magnitude higher heat capacity than air, even small flow rates of cooling fluid would provide superior heat transfer performance.

The field of liquid cooling of electronics can basically be broken down into two general areas: high-power electronics and microelectronics. The two classifications are mainly separated by power dissipation and scale.

High-power-consumption products can dissipate from a few hundred watts to a few thousand watts. They tend to have much larger component sizes and thus larger heat transfer areas. Despite the larger heat transfer area, the heat flux in a high-power electronics component can be quite high. In most cases, the junction temperature (temperature of the device) can be increased to a higher level to facilitate cooling solutions.

The microelectronics components tend to be lower in power consumption as compared to the high-power-consumption devices. The microelectronics components tend to range between tens of watts to a few hundred watts. The smaller package size can vary between less than 1 $cm^2$ to 4 $cm^2$ in surface area. The resulting heat flux, however, can be quite high on these devices when a small package size and a high power state are utilized. Unlike several of the high-power electronic components, the junction temperature of these devices tends to be much lower. This is mainly done to ascertain reliable operation as well as increased manufacturing yield. The emerging field of 3D integrated circuits (ICs) is in its infancy and is not covered in this book.

There are more similarities than differences between these two seemingly separate electronics cooling areas. With the establishment that the fundamental theories of fluid mechanics and heat transfer are still valid in the microscale, the scale difference between these two areas is no longer a barrier and what benefits one will benefit the other.

## 1.2 High-Power Electronics Cooling

Electronic devices are at the heart of almost all major industrial and military equipment. Some of these are power drives, insulated-gate bipolar transistor (IGBT) controllers, radio-frequency (RF) generators, magnetic resonance imaging (MRI) machines, traction devices for locomotives, battery chargers, UPS (uninterrupted power systems), DC-AC converters, AC-DC inverters, and army tanks (using transmission fluid already at a high temperature). The high-power, high-heat-flux demands on the cooling system cannot be met with air cooling, and advanced liquid cooling solutions are necessary.

Today it is common to find a 7000 hp motor being driven by multiple 2500 W IGBTs in pumping or traction (railroad) devices, which may not be adequately cooled with air. Multiple silicon-controlled rectifiers (SCRs), commonly called “hockey pucks” of 63 mm diameter, each dissipating over 2000 W, are also used to drive electric motors. The shape of these devices makes them difficult to cool with air. This is often due to the large volumetric displacement, fan power needed, and the noise generated that makes air cooling an undesirable choice from cost and space considerations.

There are many other devices that are shifting to liquid cooling as their power levels increase. Liquid cooling may be found in RF generators, industrial battery chargers, printing press humidity and thermal control equipment, vacuum chambers, oil extraction equipment, mining devices, magnetic resonate imaging equipment, mobile military equipment, shipboard launch systems, submarine systems, railroad engines, large motor drives, and even beer coolers used in microbreweries. Multi-thousand horse power motors which convey ore from mining locations experience large power fluctuations due to the nature of their loads. If driven by efficient motor drives, the power they consume will match the variable loads with greatly reduced costs. Likewise in oil extraction, powering these large motors with efficient motor drives, to match the loads presented, results in least-cost operation.

The IGBT and the SCR are both minority carrier devices whose ultimate high-temperature limit of operation is governed by intrinsic carrier generation. In other words, at any given temperature there is a steady creation of thermally activated electrons and holes. When the density of these thermally generated carriers becomes comparable to the engineered doping levels, the desired characteristics of the semiconductor layers break down. The limit of this phenomenon is the intrinsic temperature, Ti, at which the intrinsic carrier concentration equals the doping level of the most lightly doped layer. At this point, rectification of the p–n junction ceases and the device cannot function. In many silicon devices the intrinsic temperature is about 280°C. However, since all of the fundamental physical parameters of semiconductors are functions of temperature to a data on cold plate manufacturing, the fundamental heat transfer theory of cold plates, the manufacturing details, and the design of cold plates.

The open literature is reviewed and several of the available papers that describe liquid cold plates are listed in Chapter 2. Some of the details about these works are also presented. In addition, several of the known cold plate manufacturers are listed, although the list is certainly not a comprehensive one.

The fundamental heat transfer and fluid mechanics theory utilized in cold plate design and manufacture is presented in Chapter 3. The mechanisms and formulations of heat transfer, including conduction and convection, are presented. Then, the fluid mechanics and microfluidics theory of the cold plate and its system are discussed. Finally, the energy efficiency gains of a liquid-cooled cold plate are discussed.

Chapter 4 presents several details on the design and manufacture of cold plates. Several of the critical manufacturing issues and pitfalls are described. In addition, several of the design challenges are discussed. Some of these problems include material selection, machining, and surface finishing.

The intent of this book is to introduce the reader to the design, manufacture, and application of liquid cold plates. The modern liquid cold plate can serve in a variety of applications under different fluid flow and pressure drop constraints in meeting the desired thermal load. In addition, the internal geometry of the modern cold plate can span multiple scales, from traditionally sized pipes to the micro-sized channels. This is a surprisingly wide field, and it is very difficult to capture the entirety of the manufacturers of liquid cold plates and the variations thereof. However, this book is rather a combination of the fundamental design principles, design and manufacturing techniques, and a jumping-off point to investigate this very broad application of heat transfer and fluid mechanics.

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