Series in Contemporary Perspectives in Emerging Technologies
Series Editor: S. G. Kandlikar

Contemporary Perspectives
on
Air Cooling of Electronic Components

Mark E. Steinke
IBM

begell house, inc

SERIES IN CONTEMPORARY PERSPECTIVES IN EMERGING TECHNOLOGIES
SERIES EDITOR: S. G. KANDLIKAR

CONTEMPORARY PERSPECTIVES ON AIR COOLING OF ELECTRONIC COMPONENTS
MARK E. STEINKE

Copyright ©2012 by Begell House, Inc. All rights reserved. This book, or any parts thereof, may not be reproduced or distributed in any form or by any means, or stored in a data base retrieval system, without prior written consent from the publisher.

This book represents information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Every reasonable effort has been made to give reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials for the consequences of their use.

ISBN: 978-1-56700-304-8

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

Library of Congress Cataloging-in-Publication Data

Steinke, Mark E., 1976-
Contemporary perspectives on air cooling of electronic components / Mark E. Steinke.
p. cm. -- (Series in contemporary perspectives in emerging technologies)
ISBN 978-1-56700-304-8 (hardcover : alk. paper)
1. Electronic apparatus and appliances--Cooling. I. Title.
TK7870.25.S734 2012
621.381--dc23
2012022131

Direct inquires to Begell House, Inc., 50 Cross Highway, Redding, CT 06896.

TABLE OF CONTENTS

FOREWORD

It gives me great pleasure to present one of the first of two books in the *Series in Perspectives in Emerging Technologies*. The series was started to promote dissemination of the latest technological developments by leading researchers in fields related to thermal and fluids aspects of the engineering and biological sciences. It is expected to cover broader topics as further interest in the series develops.

Air cooling of electronics components is an extremely important technique, forming the backbone of the electronics cooling industry, an area facing increasing demands with regard to higher dissipation rates, higher effective heat-transfer coefficients, compact size, lower noise, and higher efficiencies. Extending air cooling limits is very attractive in terms of avoiding the significant cost increases associated with the liquid cooling option.

Dr. Mark Steinke has been the main driver in developments in air cooling systems at IBM for the last six years. He brings extensive breadth and depth through this experience in furthering the art and science of air cooling. This book is intended as an indispensable and comprehensive resource for designers and researchers in the field of air cooling of electronics components.

The vision and foresight of our great friend William Begell in founding Begell House Publications to promote research in the fields of engineering and medicine have been the main driving force behind this effort. The impetus provided by him is further amplified by Yelena Shafeyeva, president of Begell House. Her encouragement and support in founding this series is gratefully acknowledged. I am also thankful to Vice President and Production Manager Vicky Lipowski, who has been extremely patient and supportive in the entire process leading to publication of this book. The support and tireless efforts by all Begell House staff is also gratefully acknowledged.

Satish Kandlikar
Chief and Founding Editor
Series in Perspectives in Emerging Technologies
Begell House, Inc.
Gleason Professor of Mechanical Engineering
Rochester Institute of Technology,
Rochester, NY

PREFACE

I was first approached by Dr. Kandlikar for the *Series in Contemporary Perspectives in Emerging Technologies* in 2011. We discussed recent advances in air cooling technology that have allowed the computer industry to hold off conversion to liquid cooling. In the early 2000s, the microprocessor roadmaps available showed an increase in heat flux, again reaching the critical mass which requires liquid cooling. This was a foregone conclusion. Right away I could think of a few specific reasons why a transition to a liquid cooling paradigm has not come to fruition.

A vast number of researchers, including myself, were lured to the challenge of providing high heat-transfer capacities to small areas. Much research emerged which centered on liquid cooling in microchannels, presenting obvious heat-transfer enhancement and a capability to meet impending industry challenges. There are examples today of extremely large-scale computing (IBM P7IH) that require liquid cooling. However, the vast majority of servers are still air cooled.

The desire to extend air cooling for as long as possible was clear. The vast majority of research for air cooling shifted to the suppliers and venders to improve processes, efficiencies, and performance to meet industrial requirements in the near term. A great number of advances went under-represented. The research developed by suppliers turned into a competitive advantage versus their peers, and not much public disclosure occurred.

In this book I will discuss the roots of electronics cooling and how air cooling is still dominant over water cooling and will remain so for the near term. For over a century now, this area has been ripe with active research in many disciplines spanning heat transfer, thermodynamics, materials science, and structural engineering. Perhaps the most appealing feature of the electronics cooling field is the very multidisciplinary nature of the challenges being overcome. Unlike some other areas, the electronics cooling system designer must have knowledge of several disciplines to design and deliver the most optimal electronics cooling solution. In the future there will be a new roadmap laid out before us and there may be a time liquid cooling is required in mainstream computing. However, I see many current years where air cooling will play a critical role and must be improved to meet future needs.

I would like to take the opportunity to thank Dr. Kandlikar for inspiring me to put these thoughts to paper. Most importantly, I thank my wife for her support, understanding, and inspiration. Long days, late nights, and seemingly endless effort would have not been possible without her encouragement. Finally, I would like to thank my children, who continually remind me of the importance of learning new things every day. Life should be filled with the joy of discovery, and I am fortunate to experience that again through their eyes.

Mark E. Steinke
March 21, 2012

NOMENCLATURE

Roman Symbols

A	heat-transfer area, m^2 Chapters 3, 5
A_f	fin area, m^2, Chapter 3
C	capacitance, F, Chapter 1
C_p	specific heat at constant pressure, kJ kg^{-1} °C^{-1}, Chapter 3
D	diameter, m, Chapter 4
f	frequency, Hz, Chapter 1
g	acceleration of gravity, kg m s^{-2}, Chapter 4
h	heat-transfer coefficient, W m^{-2} K^{-1}, Chapters 3, 5; height, m, Chapter 3; head, m, Chapter 4
$\bar{h}$	average heat-transfer coefficient, W m^{-2} K^{-1}, Chapter 3
H	total head, m, Chapter 4
k	thermal conductivity, W m^{-1} K^{-1}, Chapters 1, 3, 5
K	degrees Kelvin, Chapter 4
L	length, m, Chapters 3, 5
m	parameter used in fin analysis, Chapter 3
M	parameter used in fin analysis, Chapter 3
$\dot{m}$	mass flow rate, kg s^{-1}, Chapter 3
n	rotational speed, revolutions min^{-1}, Chapter 4
p	pressure, kPa, Chapter 4
p_o	total pressure, kPa, Chapter 4
P	power, W, Chapters 1, 3, 4; perimeter, m, Chapter 3
PUE	power usage effectiveness, Chapter 6
q	power, W, Chapters 1, 3, 5
q''	heat flux, W cm^{-2}, Chapter 3
Q	volumetric flow rate, m^3 s^{-1}, Chapter 4
R	thermal resistance per unit area or insulance, cm^2 °C W^{-1}, Chapter 3
t	thickness, m, Chapter 3
T	temperature, °C, Chapters 1, 3, 5
U	thermal conductance, W °C^{-1}, Chapter 3
v	velocity, m s^{-1}, Chapter 4
V	volts, V, Chapter 1
w	width, m, Chapter 3
x	distance, m, Chapter 3
z	height, m, Chapter 4

Greek Symbols

∇	dell operator, Chapter 3
ΔT	delta temperature, °C, Chapters 3, 5

ε	fin effectiveness, Chapter 3
η	fin efficiency, Chapters 3, 4
θ	thermal resistance, °C W^{-1}, Chapters 3, 5
Π	nondimensional parameter, Chapter 4
ρ	density, kg m^{-3}, Chapter 4

Subscripts

1	first, Chapters 1, 3
2	second, Chapters 1, 3
AMB	ambient, Chapter 3
b	base, Chapter 3
BGA	Chapter 3
Board	Chapter 3
BottomPath	Chapter 3
c	corrected length, m, Chapter 3
C	case, Chapter 3
Carrier	Chapter 3
Case	Chapter 3
Conductive	Chapter 5
Convective	Chapter 5
dynamic	Chapter 4
f	fin, Chapter 3
head	Chapter 4
inlet	Chapter 3
J	junction, Chapter 3
JA	junction to air, Chapter 3
JB	junction to base, Chapter 3
JC	junction to case, Chapter 3
JS	junction to heat sink, Chapter 3
Junction	Chapter 3
max	Chapter 3
outlet	Chapter 3
TIM1	Chapter 3
TIM2	Chapter 3
TopPath	Chapter 3
s	surface, Chapter 3
SA	sink to air, Chapter 3
Substrate	Chapter 3
SurfaceA	Chapter 3
SurfaceB	Chapter 3
∞	infinity, Chapter 3

Superscripts

$''$	flux, Chapter 3

Chapter 1

Historical Perspective of Electronics Cooling

1.1 Early History of Electronics Cooling

The need to cool electronic components developed over a century ago with the advent of high-power electronics equipment. Originally, each industrial site locally produced electricity for its own consumption. These generators were horribly inefficient by today's standards. The heat generated by the power components was roughly managed with large metal plates and fans. This low efficiency did not matter because the cost of fuel was insignificant versus the demand and reliability of local generation, and the resulting energy converting to heat was relatively easily handled.

As time progressed, motor designs became more advanced and the demand for higher power consumption increased. At this time, business began to consider shifting from locally generated power to remotely generated power. Some of the various reasons that electrical generation switched to off-site production could have included care and maintenance of aging equipment, increased electrical demand for additional equipment, or the cost of investing capital not related to their main product. The newly formed electric utility companies were able to apply the economy of scale to remain profitable. The scale of equipment leads to even more increased power densities and thereby increased cooling requirements. A very complete reference for more details regarding the early days of electronics cooling is given by a review published by the Department of Energy[1] on electronics cooling.

Air cooling these large power components was important not only for component function but also for increasing the energy efficiency. Greater understanding of the nature of electrical energy efficiency leads to better and better power generation, because less of the electrical *product* escapes to waste heat and more of it goes into billable goods. All the while, air cooling these components continues to be the mainstay for cooling. There was little demand to switch to anything else. Provide enough air flow rate and surface area, and the solution scaled very nicely for the majority of applications. The cooling medium, air, is abundant, inexpensive, and readily available to everyone. No special containment or treatment was really required.

Air cooling continues to be the main cooling technique used in the vast majority of cases for power generation. Simply observe any transfer station, substation, or remote power facility and you will find the large metal heat sinks and larger fans providing cooling. When the heat flux increases to a much higher value, such as in the case of steam generators in nuclear facilities, the cooling fluid medium is switched to liquid. The increased thermal capacitance of liquid versus gas is utilized. However, there is another underlying reason to switch to liquid—contamination is a major issue. The thought of whirling contaminates throughout the plant is not a pleasant one and is certainly unacceptable from an environmental standpoint.

The late 1950s and early 1960s saw the dawn of early computing. It was only natural to translate the use of air cooling to this new heat-transfer application. This worked and scaled for a period of time. However, no one ever says they want a slower computer. The demand for more transactions per second and more functionality drove higher frequencies. The power efficiency of the devices was largely fixed and as more transistors were added, more power was required. The processor package size increased to accommodate the increased number and size of components and the volumetric space of the computer system decreased. There was a desire not to allocate an entire building floor for the computer and condense these super-sized computer systems to smaller and smaller footprints. The resulting heat flux increased to an uncomfortable level. One had to maintain the functionality and reliability of these very expensive systems. Thus the specific application of electronics cooling presented the largest challenge. A great deal of attention has been paid to microprocessor cooling and the remainder of this book will follow suit.

The electronics cooling roadmap looked promising for several years. Scaling air cooling methods provided a few generations of computer systems. The overall volumetric densities were still relatively large. More metal in the heat sink and spinning the fans faster provided the answers. In the mid-1970s, International Business Machines (IBM) introduced liquid cooling to bipolar devices in an effort to cool increasing processor powers. The thermal conduction modules (TCMs) were able to contact a multitude of chips to bring the cooling fluid as close to the power-generating silicon chip as possible. The liquid thermal capacitance dominated the energy balance and the main advantage was obvious.

The performance of the chip was directly proportional to the number of transistors. At this time in history, the physical size of the transistor was large and it was difficult to fit many of these components into one chip. This fact worked as an advantage for the thermal designer. The available area for heat transfer increased along with the increased number of transistors. Despite the overall power increase, the added heat-transfer area allowed the heat flux to remain manageable.

The transistor's large volumetric space requirement began to be a roadblock to further performance advances. Fortunately, microprocessor designers drew upon the decades-old work of a colleague. Jack Kilby's patent[2] and work with Gallium to produce a small planer transistor with a very small footprint was the next evolutionary step in microprocessor packaging. The transistor density could greatly increase without having to increase the platform area. In the early days of the complementary-symmetry metal-oxide semiconductor (CMOS), the power requirements were greatly reduced over their bipolar cousins. The switch in technology was obvious and swift.

The quick change in process technology, from bipolar to CMOS, was the largest reason that the breaks had been applied to liquid cooling microprocessors. There simply was no longer any need to maintain the cooling complexity for these new microprocessors. It was far more cost effective to utilize air cooling for next-generation microprocessors. The electronics roadmap again looked very promising, after several years of requiring liquid cooling to deliver on increasing performance. However, there was a problem lurking on the horizon.

1.2 Processor Transistor Density and Power Consumption

The manufacturing process for silicon-based microprocessors allowed for great scaling of transistor density. This effect was defined by Moore[3] in his definitive work on this topic. Figure 1.1 shows the transistor count doubling every two years. The number of transistors that can be produced on a chip is directly related to the feature size of the transistor gate that can be produced. Lithography technology has moved from micrometers of feature size down to 32 nm in current technology. The number of transistors grew from a few thousand to now numbering in the billions.

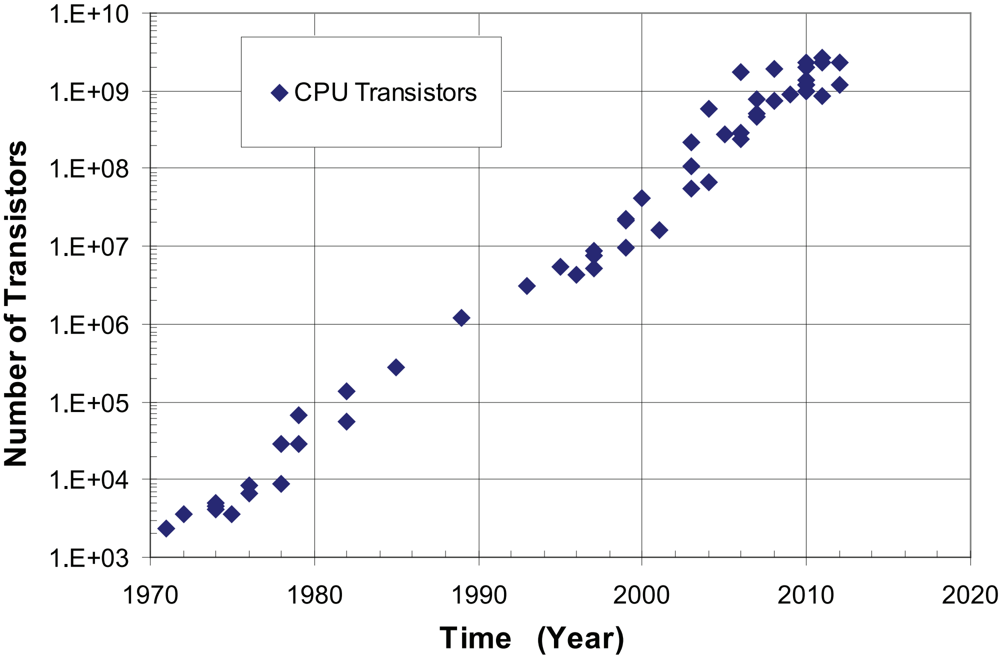

FIG. 1.1: Actual processor transistor count over time

One aspect that Moore's law did not address but is commonly understood is the increase in heat flux of the microprocessor devices. The power consumption increases proportionately with transistor count. Figure 1.2 shows the thermal design power of microprocessors.

It is easy to see an alarming trend in the processing power that will need to be dissipated over time. The heat fluxes in the future would require liquid cooling to maintain any reasonable junction temperatures, assuming a fixed volumetric space and air flow rate.

tions on microprocessors. The need to shift to liquid cooling as a requirement to manage future microprocessors is unclear. Keep in mind that history tends to repeat itself and we must learn from it. Will there be another microprocessing fabrication technology that shifts the paradigm and a return to air cooling? There are several promising technologies, such as polymer-based transistors, optical processing and storage, and organic-based transistors, in the research and early development stages that might facilitate just that paradigm shift. This time around, let us not quickly abandon all air cooling enhancement research and development. There is still a great deal of fundamental physics that remains to be discovered, and a strong need to extend cost-effective air cooling methods for the electronics industry.

References

1. *The Changing Structure of the Electric Power Industry: An Update*, Energy Information Administration, 1996.
2. Kilby, J.S., Plug-In Circuits, USPTO, Ed., J.S. Kilby, USA, 1959.
3. Moore, G.E., Cramming more components onto integrated circuits (Reprinted from Electronics, pp. 114–117, April 19, 1965), *Proc. IEEE*, vol. **86**(1), pp. 82–85, 1998.
4. Intel, *Enhanced Intel SpeedStep Technology for the Intel Pentium M Processor*, Intel Corporation White Paper, 2004.