FALL 2018
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A THERMAL PERSPECTIVE ON HETEROGENOUS INTEGRATION FOR HARSH MIL/AERO ENVIRONMENT ELECTRONICS

THE EFFECT OF AMBIENT CONDITIONS ON LOCAL CLIMATE INSIDE A PUMP ELECTRONICS ENCLOSURE

TOWARDS GREEN TECHNOLOGY: MODELING OF A COMPACT PLATE HEAT EXCHANGER CONDENSER FOR THERMOSYPHON COOLING OF ENTIRE HIGH POWER DATACENTER RACKS

CALCULATION CORNER:
A Simple Method for Estimating Radiation Heat Transfer

TECHNICAL BRIEF:
Summary of the IEEE ITherm 2018 and Preview of ITherm 2019

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ITEM MEDIA

EDITORIAL

Ross Wilcoxon, Ph.D.
Principal Mechanical Engineer
Electronics Cooling®, Fall 2018 Issue
ross.wilcoxon@rockwellcollins.com

Over the past few weeks, I have had numerous (some might say excessive) opportunities to talk to my department head. He is slightly reorganizing his organization, which does research and development of electronic systems, and is trying to identify what role his mechanical engineers fit in the grand plan. Since it is R&D, of course a lot of attention is paid to being innovative. Therefore, many of his discussions with me have revolved around what are the best roles for mechanical engineers, and particularly thermal engineers, in the process of developing innovative electronics.

As part of my eternal quest to bound the expectations of senior leadership, I have reminded him of one of my favorite quotes from the industry, which I will now paraphrase and/or misquote here: "Thermal management is the garbage collection of the electronics industry" (Christian Belady). I generally follow up this statement with my own extension of it, which is "No one moves to a city because it has the best sanitation workers in the world, but they won't move there if it doesn't have any." From a system perspective, we need electronics cooling but don't necessarily need great electronics cooling. In most cases, it just needs to be adequate. If the cooling approach does not meet requirements, everyone cares; if the cooling exceeds requirements, not so much.

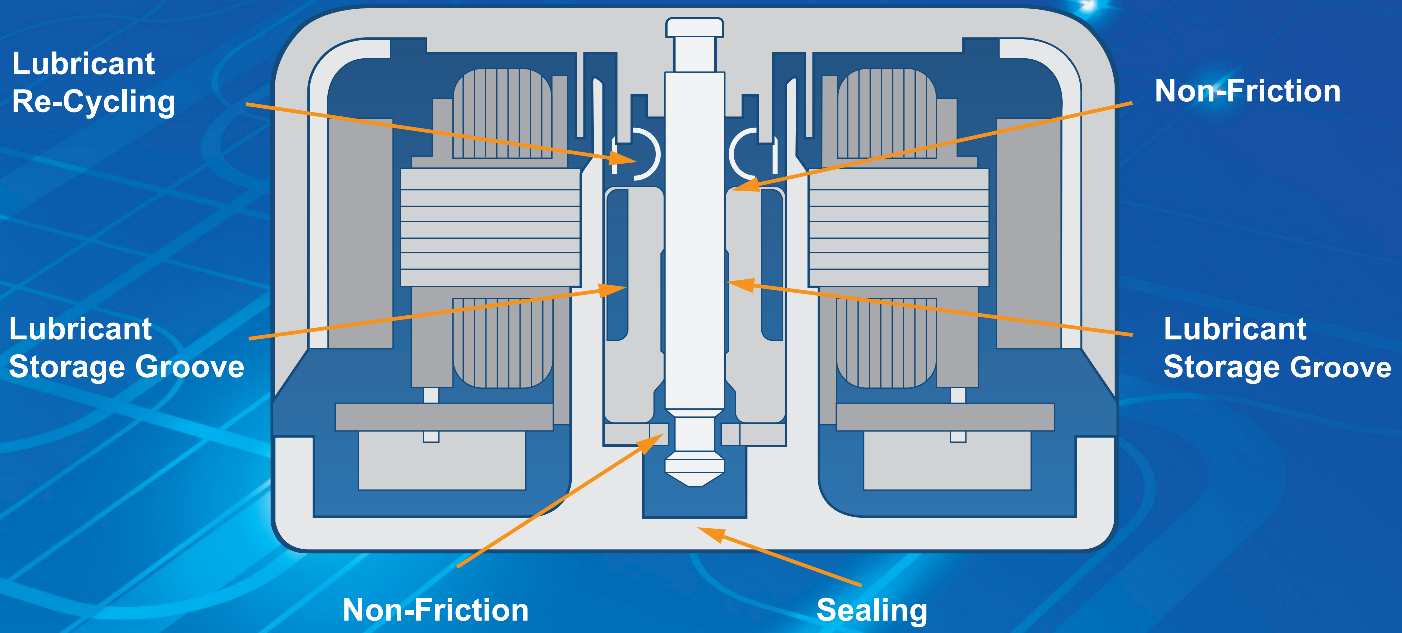
The discussions with my department head have been along the lines of how mechanical engineers should contribute to our department's innovation. Should I, for example, focus on being innovative in creating new thermal management solutions? Or should I instead focus on creating thermal management solutions that enable innovative electronic solutions? My vote is for the second choice, which may involve innovative thermal management, but also requires a good application of thermal design combined with a reasonable understanding of how it interacts with the overall system.

While many of the subscribers to *Electronics Cooling*® Magazine do work for companies that develop innovative thermal management technologies, I suspect that the majority of them share my perspective. Effective electronics cooling design is often a combination of the novel and the mundane. Making a design that is 'good enough' and understanding requirements well enough to know exactly what defines 'good enough' are key. For years, *Electronics Cooling*® Magazine has helped me in this area. The combination of new technologies, descriptions of how various thermal technologies and analysis methods can be used to address design challenges, tutorials on fundamental analysis methods, and a sufficiently healthy dose of insight and cynicism provided by columns such as "Thermal Facts and Fairy Tales" has made me a better thermal engineer. I have been fortunate in my career to have the opportunity to work on innovative thermal solutions as well as innovative electronic systems that required "perfect", i.e. adequate, thermal management.

This issue of *Electronics Cooling*® Magazine once again provides this range of innovation and practical application of thermal management techniques, including novel packaging approaches for heterogeneous integration, design approaches for implementing thermosyphons for passive data center cooling, use of computational fluid dynamics for assessing the effects of humidity on an electronic system, an overview of the ITherm conference held last May and a methodology for doing a back-of-the-envelope assessment of radiation heat transfer. I hope that you enjoy this issue and I welcome your feedback.

- Ross

Superflo Fan Construction



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COOLING EVENTS

News of Upcoming Thermal Management Events

POWER ELECTRONICS UK: THERMAL MANAGEMENT WORKSHOP

September 21st, 2018
3M, Cain Road , Bracknell, RG12 8HT

Market requirements for power electronics and RF power devices are driver higher power densities and the need to operate in higher temperature environments. As a result, thermal management of devices and systems is a key design and manufacturing challenge.

The aim of this workshop is to bring together the power electronics and power RF communities to discuss trends and directions in device and systems thermal management to encourage best practice and the development of new supply chain collaborations in R&D.

► www.nmi.org.uk/event/powerelectronicsuk-thermal-management-workshop/

THERMINIC 2018 - 24TH INTERNATIONAL WORKSHOP

September 26th through September 28th, 2018
Scandic Victoria Tower, Stockholm, Arne Beurlings Torg 3, 164 40 Kista

THERMINIC is the major European Workshop related to thermal issues in electronic components and systems. For academics and industrialists involved in both micro and power electronics this annual event promises to be a very special occasion with a high quality technical program and exciting social events.

► www.therminic2018.eu/

IMAPS 2018 - PASADENA – 51st Symposium on Microelectronics

October 9th through October 11th, 2018
Pasadena Convention Center, CA

The 51st International Symposium on Microelectronics is being organized by the International Microelectronics Assembly and Packaging Society (IMAPS).

The IMAPS 2018 Technical Committee seeks original papers that present progress on technologies throughout the entire microelectronics/packaging supply chain. The Symposium will feature 5 technical tracks, plus our Interactive Poster Session, that span the three days of sessions.

► www.imaps2018.org

THERMAL MANAGEMENT SYSTEMS SYMPOSIUM

October 9th through October 11th, 2018
San Diego Marriott Mission Valley, 8757 Rio San Diego Dr, San Diego, CA 92108

With the start of new vehicle powertrains such as hybrid, electric, and fuel cell vehicles, all thermal management systems, including mobile air conditioning systems, require new concepts to provide passenger compartment heating and cooling, as well as heating and cooling of batteries and cooling vehicle fuel systems.

For 2018, the Thermal Management Systems Symposium will focus on the latest and most pertinent topics in the field of thermal systems technology today. This event will serve as the meeting ground for thermal systems professionals from around the globe to discuss the latest regulatory changes and their impacts on the thermal management systems industry. This symposium represents the perfect opportunity to interact and network with other industry professionals from OEMs, academia, chemical companies, regulatory bodies, and more.

► www.sae.org/attend/thermal/

THERMAL LIVE™ 2018

October 23rd through October 24th, 2018
Online

Thermal Live™ is an innovative concept in education and networking in thermal management – a FREE 2-day online event for electronics and mechanical engineers to learn the latest in thermal management techniques and topics. Produced by *Electronics-Cooling* magazine, Thermal Live™ features webinars, whitepapers, and live product demos, all with no cost to attend.

► www.thermal.live

THERMAL DESIGN & COOLING OF ELECTRONICS WORKSHOP

November 12th through November 14th, 2018
Eindhoven

Industry trends towards ever increasing functionality, performance, miniaturization, and less cost result in higher heat density and corresponding higher temperatures. Unfortunately, these have a negative impact on the performance, reliability and lifetime of electronic products, and make thermal design more challenging than ever.

Two very experienced lecturers, Wendy Luiten (winner of the prestigious Harvey Rosten Award 2014) and Clemens Lasance

COOLING EVENTS

News of Upcoming Thermal Management Events

(a.o. SEMI-THERM THERMI Award winner in 2001), teach the participants how to solve the thermal problems inherent in electronics thermal management today. Based on a combined 75-plus years of industrial thermal design experience they present a balanced mix of theory and practice. The course focusses on recognition and prevention of thermal problems through optimal thermal design and architecture choices in all stages of the industrial product creation process – avoiding re-design, delayed time-to-market and associated costs in time and resources. On the third day, participants practice the acquired thermal know-how by solving a real life case of the current or previous participants.

► www.hightechinstitute.nl/en/training/electronics/thermal_design_and_cooling_of_electronics_workshop/?utm_source=ElectronicsCoolingWebsite&utm_medium=Agenda-item&utm_campaign=Electronics-Cooling-Agenda-item

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5TH AUTOMOTIVE THERMAL MANAGEMENT FORUM
November 19th through November 20th, 2018
Crewe, UK

Don't miss the opportunity to join the only International Automotive Event on the topic which perfectly combines high-quality presentations, exclusive participation of top-level experts at decision-making level with smart and innovative networking opportunities. Join us and gain insight into the latest case studies on smart powertrain thermal management, advanced HVAC and climate control solutions, efficient waste-heat recovery applications, thermal modelling as well as holistic approaches and integrated thermal management among many other topics.

► www.internect.co.uk/content/262/international-forum-automotive-thermal-management-2018-/

SEMINAR: THERMAL MANAGEMENT OF ELECTRONIC SYSTEMS
November 27th, 2018
ÅF, Grafiska vägen 2a, Gothenburg, Sweden

This single day seminar will give you insights to best practices and latest development in different industry domains such as automotive, data centers and telecom. It will also give you results from state of the art research. Take the change for networking with specialists and international experts in this field!

A small exhibition will take place in the venue during the seminar. The seminar is free of charge. Lunch and mingle food will be served.

► www.afconsult.com/en/get-to-know-us/events-seminars--fairs/thermal-management-of-electronic-systems2/

SEMI-THERM 2019 – 35th Annual Semiconductor Thermal Measurement, Modeling and Management Symposium
March 18th through March 22nd, 2019
DoubleTree by Hilton, San Jose, CA USA

SEMI-THERM is an international symposium dedicated to the thermal management and characterization of electronic components and systems. The symposium fosters the exchange of knowledge between thermal engineers, professionals and leading experts from industry as well as the exchange of information on the latest acedemic and industrial advances in electronicsthermal management.

► www.semi-therm.org

thermal LIVE 2018

October 23 & 24, 2018

Presented by Electronics Cooling®: Thermal Live™ is the electronics and mechanical engineer's free, online resource for education and networking in thermal management. Learn the latest techniques and topics directly from thermal management thought leaders without leaving your seat. Join us for one full day of interactive webinars, product demonstrations, roundtables, whitepapers, and more. Produced by Electronics Cooling® magazine

Technical Program: Tuesday, October 23, 2018

Nolato

9:00 – 9:45 am ET

What Thermal Management Means for Your Business, and What TIM's Mean for Thermal Management

Overview: Thermal management technology is, without exaggeration, fast becoming the primary key enabling technology for the future development of the electronics industry. Current development trends drive thermal issues at an exponential rate. This webinar examines the physical mechanisms underlying the importance of effective thermal management in electronics applications, and then delves deeper into how thermal interface materials affect the bigger picture of thermal management, and how different types of materials answer different needs.

Speaker: Jussi Myllyluoma, Senior Electronics Thermal Management Specialist

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INDIUM CORPORATION®

10:00 – 10:45 am ET

Innovative Metal Thermal Interface Materials to Maximize Heat Dissipation

Overview: Metal-based thermal interface materials (TIMs) are proving to be an attractive option in electronics assembly because of their high z-direction thermal conductivity. Because of many recent innovations, there have been great strides made in improving interfacial resistance, heat dissipation and longer life during power cycling. This presentation will review these innovations and why they make metal TIMs the most attractive option for high-reliability applications such as TIM 1, TIM 2, IGBT, LED and other applications.

Speaker: Tim Jensen, Sr. Product Manager for Engineered Solder Materials

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thermal LIVE 2018

October 23 & 24, 2018

New presentations are still being added.
Please visit **www.thermal.live** for the most up-to-date schedule.

Technical Program: Tuesday, October 23, 2018

AAVID THERMAL DIVISION OF BOYD CORPORATION

11:00 – 11:45 am ET

Advanced Heat Pipe Modeling with Swept Geometries for Transporting Heat

Overview: Utilizing CFD software, this webinar explores best practices for faster, more accurate modeling of heat pipes and swept geometries for transport heat assemblies. Best practices will include how to create faster design cycles utilizing rapid modeling and the benefits of swept geometries for design flexibility and heat transport. The webinar will also briefly touch on modeling and simulating embedded heat pipes and heat pipe fin stacks.

Speaker: Michael Beliveau

CPC A DOVER COMPANY

12:15 – 1:00 pm ET

The Case of Thermoplastic Quick Disconnects in Liquid Cooling

Overview: Liquid cooling system components must meet requirements for chemical compatibility, flow rates, and temperature and pressure exposures. Ease of use and reliability over long periods of time are desirable attributes as well. To avoid potential damage to expensive electronic equipment due to leaks, secure drip-free connections are also essential for any liquid cooling system.

Quick disconnects (QDs) designed and built specifically for thermal management applications are now available, simplifying connector selection. However, questions surface around component materials – metal or thermoplastics and their ability to meet HPC thermal requirements. Intended use, ease of installation and maintenance, operating conditions, durability, and potential for leakage all have bearing on the selection process.

This presentation describes the performance and reliability factors of highly-engineered thermoplastics for fluid handling. The differences between thermoplastic and metal fluid connectors are discussed. Special focus is given to sealability, integrity over time, condensation and corrosion, chemical compatibility and weight.

Speaker: Kristin Anderson

thermal LIVE 2018

October 23 & 24, 2018

New presentations are still being added.
Please visit **www.thermal.live** for the most up-to-date schedule.

Technical Program: Tuesday, October 23, 2018

Henkel

1:30 – 2:15 pm ET

How e-Mobility is Fueling the Need for Innovation in Thermally Conductive Materials

With significant near-term growth expected in battery powered electric vehicles (EV) and plug-in-hybrids (PHEV), Henkel continues to lead the industry with innovative thermal material solutions designed for use in electronics battery cooling and packaging. Our extensive global design teams provides close collaborative customer engagement enabling faster identification and validation of critical parameters needed to ensure improved product performance, safety and cost for the consumer. These challenges require a high level of innovation in materials, process, and supply chain to ensure on-time delivery to customer needs.

While much has been published about extreme temperatures and inherent impact on battery performance and longevity, liquid cooled "cold plates" appear to be a preferred method used by EV designers to regulate battery temperatures. Regardless of cooling method selected, thermal interface materials (TIMs) offer a significant improvement in long-term performance and reliability to EV battery systems. The purpose of this summary to provide technical guidance to design engineers and scientists who often overlook features and trade-offs available in TIMs which impact the overall performance, cost, and reliability of EV batteries and associated electronic systems.

Speaker: Terry Solberg, Global Technology Head (GTH)

Fujipoly®

2:45 – 3:30 pm ET

Fundamentals of Heat Transfer in Thermal Interface Gap Fillers Materials

Overview: Thermal gap fillers are some of the most commonly used thermal interface materials in the electronic thermal solutions industry. They are available in varying levels of performance and cost. Hence, it is important to understand how to interpret data sheet information and to calculate the ideal temperature gradient across a volume of thermal gap filler.

This presentation will cover those details, while also examining what other factors impact thermal gap filler heat transfer and what factors impact the actual vs. ideal heat transfer. Lastly, various tools and resources available to help an engineer develop an accurate understanding of thermal solutions using thermal gap fillers will be covered.

Speaker: Christian Miraglia, Applications Engineering Manager

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thermal LIVE 2018

October 23 & 24, 2018

New presentations are still being added.
Please visit **www.thermal.live** for the most up-to-date schedule.

Technical Program: Wednesday, October 24, 2018

t-global TECHNOLOGY

10:00 – 10:45 am ET

How to Determine the K-Value of the Heat Pipe, Vapor Chamber or Graphite Sheet

In general, the thermal conductivity K value of the Z-axis of the material is measured by the TIM instrument. For pure substances such as pure copper, pure aluminum, or homogeneous substance such as a thermal pad, it is of course no problem to measure the K-value by Fourier's law. However, in the case of non-uniform substances such as heat pipes, vapor chamber or when the heating area and the heat dissipating area are different, the thermal diffusion occurs. In this condition, the K value measured from the TIM measuring instrument can't be assumed equivalent to the effective Keff value. This course introduces how to quickly and accurately measure the thermal diffusivity α of non-uniform materials such as heat pipes, vapor chambers or fragile materials such as Graphite sheets, graphene etc. In addition, If the material can also measure specific heat and density, by using these three parameters, one may obtain effective Keff value of the material.

Speaker: Professor William Lin Wei-Keng, Chief Technology Officer of T-Global Technology

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SIMSCALE

11:00 – 11:45 am ET – More info coming soon!

Mentor® A Siemens Business

12:15 – 1:00 pm ET

Improving Accuracy and Reducing Thermal Design Time by Modelling PCBs with Substitute Layer Analysis

Historically and even today, volume based calculations for in-plane and through-plane have been used to represent the PCB material both early in the design phase, before the PCB layout has been completed, and later in the design process when the PCB has been routed. Modeling PCBs with effective material properties is an appealing approach since the model creation process is quicker and the simulation time is faster. The downside with the use of effective thermal properties for PCB thermal modeling is reduced accuracy. Even worse, typical analytical calculations for PCB material properties result in under-predicting operating temperatures for the IC components relying on the PCB for heat removal. Thermal Engineers continue to use this approach because there was no better alternative that was easily accessible.

A new approach, Substitute Layer Analysis, for calculating the effective material properties for PCBs has recently been developed. The method, which is based on empirically deriving material properties, offers increased PCB thermal modeling accuracy while maintaining all of the benefits of a volume based calculation. In this presentation, PCB modeling approaches will be reviewed and the Substitute Layer Analysis approach will be introduced. Validation examples will be shown that illustrate the benefits of this modeling approach.

Speaker: John Wilson

► Register Now | **thermal.live**

A Simple Method for Estimating Radiation Heat Transfer

Ross Wilcoxon, Ph.D.
Principal Mechanical Engineer
ross.wilcoxon@rockwellcollins.com

SUMMARY

This article describes a semi-empirical equation that can be used to assess radiation heat transfer in terms of an effective convection coefficient.

The effective convection coefficient due to radiation is shown to be:

$$h_{rad} \approx \varepsilon \left(4 + \frac{(T_H + T_C)}{25}\right) \text{ W/m}^2\text{K}$$

Where temperatures are in °C and ε is the emissivity of the radiating surface. This equation is accurate to within ~10% over a temperature range of 0 - 130°C.

EQUATION DERIVATION

The relative effects of heat transfer by radiation are often small enough that they can be ignored in most applications that use liquid cooling or forced air cooling. However, radiation can play a significant role in situations in which the system-level thermal resistance is relatively high, such as natural convection or forced air cooling at high altitudes. Since convection and conduction heat transfer are largely proportional to a temperature difference while radiation is a function of absolute temperatures to the fourth power, it can be difficult to compare the relative impact of each heat transfer mode without resorting to the use of a computer or calculator. This article describes a simple approach for estimating the effects of radiation and comparing them to conduction and convection thermal resistances.

This approach defines a radiation heat transfer coefficient, h_{rad}, as a convection coefficient that would produce the same heat transfer (Q) as radiation if the radiating surface (at temperature T_H) were transferring heat to a fluid at the temperature to which heat is being radiated (T_C), as shown in *Equation {1}*.

$$Q = h_{rad} A(T_H - T_C) \qquad \{1\}$$

This heat transfer is set to be equal to the Stefan-Boltzmann law for radiation heat transfer, which is shown in *Equation {2}*

$$Q = \sigma\varepsilon A(T^4_{H,Ab} - T^4_{C,Ab}) \qquad \{2\}$$

Where A is the heat transfer area, σ is Boltzmann's constant (5.67e-8 W/m² K⁴), ε is the emissivity of the radiating surface, and the subscript "Ab" indicates absolute temperature.

The radiation temperature term can be expanded so that the temperature difference term can then be dropped from both sides

$$h_{rad}A(T_H - T_C) = \sigma\varepsilon A(T^4_{H,Ab} - T^4_{C,Ab}) = \sigma A(T^2_{H,Ab} + T^2_{C,Ab}) * (T_{H,Ab} + T_{C,Ab}) * (T_{H,Ab} - T_{C,Ab})$$

$$h_{rad} = \sigma\varepsilon(T^2_{H,Ab} + T^2_{C,Ab}) * (T_{H,Ab} + T_{C,Ab}) \qquad \{3\}$$

The temperature terms can be made dimensionless by dividing by the difference between Celsius and Kelvin temperature scales:

$$T_{H,A} = T_H + 273.15 \text{ and } T_{C,A} = T_C + 273.15,$$

$$\text{let } T_* = 273.15, \quad H = T_H / T_*, \quad C = T_C / T_*$$

This leads to the effective radiation heat transfer coefficient being expressed in terms of the dimensionless temperatures as:

$$h_{rad} = \sigma\varepsilon T_*^3 \, [(H+1)^2 + (C+1)^2] * [H+C+2] \qquad \{4\}$$

Terms can be rearranged as shown below

$$\frac{h_{rad}}{\sigma\varepsilon T_*^3} = [H^2 + 2H + 1 + C^2 + 2C + 1] * [H + C + 2]$$

$$\frac{h_{rad}}{\sigma\varepsilon T_*^3} = H^3 + 2H^2 + 2H + HC^2 + 2HC + CH^2 + 2HC + 2C + C^3 + 2C^2 + 2H^2 + 4H + 4 + 2C^2 + 4C$$

$$\frac{h_{rad}}{\sigma\varepsilon T_*^3} = H^3 + C^3 + 4H^2 + 6H + HC^2 + 4HC + CH^2 + 6C + 4C^2 + 4$$

$$since\ (H + C)^2 = H^2 + 2HC + C^3 \ and\ (H + C)^3 = H^3 + 3H^2C + 3HC^2 + C^3$$

$$\frac{h_{rad}}{\sigma\varepsilon T_*^3} = (H + C)^3 + 4(H + C)^2 - 2HC(H + C) + 6(H + C) + 4 - 4HC$$

$$\frac{h_{rad}}{\sigma\varepsilon T_*^3} = [(H + C)^2 + 4(H + C) - 2HC + 6](H + C) + [4 - 4HC]$$

The terms can be grouped into the form shown in *Equation {4}*

$$h_{rad} = \sigma\varepsilon T_*^3 \left\{[(H + C)^2 + 4(H + C) - 2HC + 6]\frac{(T_H + T_C)}{T_*} + [4 - 4HC]\right\} \qquad \{5\}$$

which can be written as:

$$h_{rad} = \varepsilon\left[C_1 + \frac{(T_H+T_C)}{C2}\right] \qquad \{6a\}$$

in which C_1 and C_2 are functions of H and C. In most electronics cooling applications, surface temperatures are in the range of ~ 0 – 130°C. Thus, the typical values of H and C are likely to be in the range of 0 – 0.47 and the second order terms, $(H+C)^2$ and HC, will be relatively small compared to the constants 4 and 6. Since the term σT_*^3 = 1.156 W/m²K, at temperatures close to 0°C, C_1 will be ~1.156*4 = 4.6 and C_2 will be ~273.15/(1.156*6) = 40.

Minimizing the error over the entire temperature range of 0-130°C leads to values of C_1 = 4.131 and C_2 = 26.75, which has a maximum error of ~8%. A slightly less accurate, but easier to remember, equation is:

$$h_{rad} = \varepsilon\,[4 + (T_H + T_C)/25]\ \mathrm{W/m^2K} \qquad \{6b\}$$

Table 1 shows the error associated with *Equation {6b}* compared to the exact solution for black body radiation between surfaces at two temperatures (with a view factor of 1 between the surfaces).

% error		T1 (°C)													
		0	10	20	30	40	50	60	70	80	90	100	110	120	130
T2 (°C)	0		-9.9	-6.9	-4.4	-2.4	-0.9	0.3	1.2	1.7	2.0	2.1	1.9	1.6	1.2
	10	-9.9		-4.2	-2.1	-0.4	0.9	1.8	2.4	2.8	3.0	2.9	2.6	2.2	1.6
	20	-6.9	-4.2		-0.2	1.2	2.2	3.0	3.4	3.6	3.6	3.4	3.1	2.6	1.9
	30	-4.4	-2.1	-0.2		2.4	3.3	3.8	4.1	4.2	4.1	3.8	3.4	2.8	2.1
	40	-2.4	-0.4	1.2	2.4		4.0	4.4	4.6	4.6	4.3	4.0	3.4	2.8	2.0
	50	-0.9	0.9	2.2	3.3	4.0		4.8	4.8	4.7	4.4	3.9	3.4	2.7	1.9
	60	0.3	1.8	3.0	3.8	4.4	4.8		4.9	4.7	4.3	3.8	3.2	2.4	1.6
	70	1.2	2.4	3.4	4.1	4.6	4.8	4.9		4.5	4.0	3.5	2.8	2.0	1.2
	80	1.7	2.8	3.6	4.2	4.6	4.7	4.7	4.5		3.6	3.0	2.3	1.5	0.7
	90	2.0	3.0	3.6	4.1	4.3	4.4	4.3	4.0	3.6		2.5	1.8	0.9	0.1
	100	2.1	2.9	3.4	3.8	4.0	3.9	3.8	3.5	3.0	2.5		1.1	0.3	-0.6
	110	1.9	2.6	3.1	3.4	3.4	3.4	3.2	2.8	2.3	1.8	1.1		-0.5	-1.4
	120	1.6	2.2	2.6	2.8	2.8	2.7	2.4	2.0	1.5	0.9	0.3	-0.5		-2.2
	130	1.2	1.6	1.9	2.1	2.0	1.9	1.6	1.2	0.7	0.1	-0.6	-1.4	-2.2	

Table 1: Percent error in Equation {6} compared to exact solution, Equation {2}

DISCUSSION

One useful application of *Equation {6b}* is in making a quick determination of whether radiation needs to be considered in a thermal assessment.

For example, if the convection for forced air cooling from a surface is on the order or 100 W/m²K and *Equation {6b}* finds an effective radiation heat transfer coefficient of 8W/m²K, then it is probably safe to neglect radiation. But in free convection air cooling, the heat transfer coefficient will often have a magnitude similar to that of the effective radiation heat transfer coefficient, so radiation does need to be addressed.

A few other issues need to be kept in mind when using *Equation {6b}*:

- *Equation {6b}* is only appropriate for temperatures above 0°C
- You need to account for view factor and relevant areas of the surface that is dissipating power. For example, if the surface is a finned heat sink, then the heat transfer area for convection is the entire fin area (accounting for fin efficiency) while the heat transfer area for radiation is likely to be the planform (base) area.
- The 'cold' temperature for convection is not necessarily the same as the 'cold' temperature for radiation. For example, convection from an outdoor system will be to the ambient air temperature while radiation will be to the sky temperature or cloud temperature.

ACKNOWLEDGEMENT

Thanks to my colleague John Kramer for recently asking me the simple question "Is it physics based or totally empirical?" about *Equation {6b}*.

I had reverse engineered the equation through curve fitting many years ago; John's question, after I had suggested that he could use it in an analysis, prompted me to spend a little time to do the algebra necessary to better understand it.

Summary of the IEEE ITherm 2018 Conference

John F. Maddox
IEEE ITherm 2018 Conference

The IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm) was held at the Sheraton Hotel and Marina in San Diego, CA from May 29th – June 1st. This was the 30th Anniversary of ITherm, first held in 1988. The conference was historically held every other year until 2016 when it switched to an annual schedule, making this the 17th ITherm.

ITherm 2018 was sponsored by the IEEE Electronics Packaging Society (EPS) and co-located with the 68th Electronic Components and Technology Conference (ECTC 2018). ITherm has partnered with the IEEE EPS peer conferences, including the International Workshop on Thermal Investigations of ICs and Systems (THERMINIC) in Europe, and the Electronics Packaging Technology Conference (EPTC 2018) in Asia.

The ITherm 2018 program consisted of 18 professional development workshops on Tuesday, followed by three full days of technical presentations in four tracks with 50 sessions in which 179 papers were presented. Additional technical events included three keynote addresses, five panels, five technology talks, a student poster competition, and an Art-in-Science competition. Of note were a panel and a tech-talk held in honor of Jayathi Murthy on her 60th birthday, recalling her contributions to the development of the Fluent software package and her role in academia, in which she has helped to shape the minds and careers of current leaders in the field of Computational Fluid Dynamics.

There were also two panels held jointly with ECTC–the ECTC/ITherm Young Professionals Panel and the ECTC/ITherm Joint Women's Panel, "Enhancing Women's Participation in Engineering – A View Around the Globe." Both panels were sponsored by EPS and provided an opportunity for closer interaction between the attendees of the two conferences.

This year saw several improvements resulting from the evolution of the conference. An ITherm LinkedIn page was introduced, which we invite you to join to keep up with announcements and deadlines for ITherm 2019. A mobile app, available for both iOS and Android, was developed, which provided the ability to make a custom agenda, participate in voting for the Art-In-Science competition, and have social interaction with other conference attendees. Finally, new branding for the conference has been introduced through the development of a conference logo.

KEYNOTES

On the first day of the conference, Ravi Kuppuswamy, vice president and general manager of engineering in the Programmable Solutions Group at Intel, gave a keynote address entitled "FPGAs: The Accelerator of Choice from the Edge to the Cloud" describing the potential for Field Programmable Gate Arrays (FPGAs) to be an enabling technology for artificial intelligence and the thermal challenges that need to be overcome to successfully deploy this technology on a large scale.

The customizable nature of these devices is both their greatest strength from an innovation standpoint and their greatest challenge from a reliability and deployment standpoint, with the flexibility provided by end-user reconfiguration of the device operation potentially leading to uneven loading of the device creating hot spot that would need dynamic cooling strategies. Cooperation between the software and thermal design strategies will be critical to the future success of FPGAs.

On the second day of the conference, Dr. Sean Ross, from the Directed Energy Directorate at Air Force Research Laboratory, gave a keynote address entitled "Transitioning Directed Energy Weapons from the Laboratory to the Tactical Edge: The Thermal Interface" describing the unique thermal challenges associated with using high energy lasers and high power microwaves.

As only one of the many challenges associated with these systems, the thermal management solution must be designed with the system size and weight as driving factors, particularly when the intended platform is a small ground vehicle or large aircraft. One of the major constraints on these systems is the need to have enough cooling capacity to enable the sudden shut-off of the energy beam, in response to non-target objects approaching the path of the beam, leading to a large surplus of excess energy being created during the shutdown process that must be removed by the cooling solution at a rate far beyond the loads produced during the normal operation of the device.

On the final day of the conference, Paolo Petagna, leader of the Detector Cooling Project of the CERN Physics Department, gave a keynote address entitled "Detector Thermal Management with Boiling Systems at CERN" describing the usage of as a refrigerant fluid in the thermal management of silicon detectors. The high heat loads generated by the radiation exposure of the detectors, along with the requirement to minimize the interaction of the cooling solution with the particles generated during the proton collisions, have led the team at CERN to utilize boiling flows of in small diameter silicon evaporators with plans for flow boiling in silicon micro-channels to be implemented in 2019.

BEST AND OUTSTANDING PAPERS

An awards luncheon was held on the final day of the conference, at which awards for the best and outstanding papers in each track, based on judging from reviews and inputs from session and track chairs, were unveiled to the attendees.

Best Papers

Component Level Thermal Management

- Joel D. Chapman, Peter A. Kottke, Andrei G. Fedorov, "Nanoelectrosprayed Liquid Jets for Evaporative Heat Transfer Enhancement," Georgia Institute of Technology, p114.

System Level Thermal Management

- Ying-Ju Yu and Carole-Jean Wu, "Designing a Temperature Model to Understand the Thermal Challenges of Portable Computing Platforms," Arizona State University, p118.

Mechanics and Reliability

- Bernhard Wunderle, Daniel May, Jens Heilmann, Joerg Arnold, Josef Hirscheider, Y. Li, Joerg Bauer, Mohamad Abo Ras, "A Novel Concept for Accelerated Stress Testing of Thermal Greases and In-situ Observation of Thermal Contact Degradation," Chemnitz University of Technology, Fraunhofer IZM, Berliner Nanotest and Design GmbH, p170.

Emerging Technologies & Fundamentals

- Quang N. Pham, Shiwei Zhang, Lin Cheng-Hui, Shuai Hao, and Yoonjin Won, "Boiling Heat Transfer Performance of Three-dimensionally Ordered Microporous Copper with Modulated Pore Diameters," University of California – Irvine, p122.

Outstanding Papers

Component Level Thermal Management

- Thomas Germain, Tanvir A. Chowdhury, Jake Carter, and Shawn A. Putnam, "Measuring Heat Transfer Coefficients for Microchannel Jet Impingement Using Time-Domain Thermoreflectance," University of Central Florida, p269.

System Level Thermal Management

- James W. VanGilder, Christopher M. Healey, Michael Condor, Wei Tian, Quentin Menusier, "A Compact Cooling-System Model for Transient Data Center Simulations," Schneider Electric, p157.

Mechanics and Reliability

- Pradeep Lall, Yihua Luo, Luu Nguyen, "A Novel Numerical Multiphysics Framework for the Modeling of Cu-Al Wire Bond Corrosion under HAST Conditions," Auburn University and Texas Instruments, p330.

Emerging Technologies & Fundamentals

- David B. Brown, Xufan Li, Kai Xiao, David B. Geohegan, Satish Kumar, "Thermal Boundary Conductance Mapping at Metal-MoSe 2 Interface," Georgia Institute of Technology and Oak Ridge National Laboratory, p373.

STUDENT POSTER AND NETWORKING SESSION

The student poster and networking session provided an opportunity for students to interact with industry and academic leaders in their fields. This venue enabled students to connect with possible future employers and to receive feedback on their work. Thanks to the generous support of the conference sponsors, the students who presented at the poster session received travel grants to offset the costs of attending the conference. The 65 student posters were subjected to two rounds of judging based on technical merit, clarity, self-sufficiency of the content, originality of the work, visual presentation, and oral presentation with best and outstanding posters selected for each technical track and one poster was selected as the best overall.

Best Overall Poster

- Kshitij Gupta, University of Toronto "Liquid Cooling Solutions for a High-frequency, Bi-directional, On-Board Electric Vehicle Power-hub"

Best Posters

Component Level Thermal Management

- Matthew Clark, Purdue University "Identification of the Dominant Heat Transfer Mechanisms During Confined Two-Phase Jet Impingement"

System Level Thermal Management

- Luke Yates, Georgia Institute of Technology "Electrical and Thermal Analysis of Vertical GaN-on-GaN P-N Diodes"

Mechanics and Reliability

- Abdullah Fahim, Auburn University "Mechanical Characterization of Intermetallic Compounds in SAC Solder Joints at Elevated Temperatures"

Emerging Technologies & Fundamentals

- Ivel Collins, Purdue University "Experimental Characterization of Microchannel Heat Sinks Made by Additive Manufacturing"

Outstanding Posters

Component Level Thermal Management

- Qingyang Wang, University of California, San Diego "High Heat Flux Boiling Heat Transfer Through Nanoporous Membranes"

System Level Thermal Management

- Jayati Athavale, Georgia Institute of Technology "Artificial Neural Network Based Prediction of Temperature and Flow Profile in Data Centers"

Mechanics and Reliability

- Amrit Abrol, Auburn University "Flexible Power-Source Survivability Assurance under Bending Loads and Operating Temperatures Representative of Stresses of Daily Motion"

Emerging Technologies & Fundamentals

- Georges Pavlidis, Georgia Institute of Technology & Improving the Transient Thermal Characterization of GaN HEMTs"

ART-IN-SCIENCE

The science competition provided an outlet for visual creativity in the form of images that arise in the pursuit of research related to heat and mass transfer as well as thermo-mechanical phenomena. Judging was based on originality, aesthetics, visual impact, and relevance. All conference attendees were able to participate in the judging process by voting for their favorite images using the new ITherm mobile app available for both iOS and Android. The winning entry, submitted by Quang Pham, is shown in *Figure 1*, the second-place entry, submitted by Matthew Clark, is shown in *Figure 2*, and a collage of all the entries is shown in *Figure 3*.

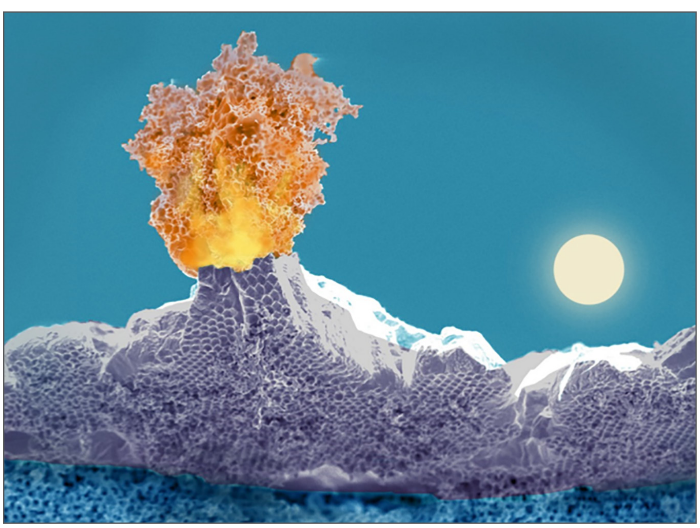

Figure 1: Eruption from Multi-layered Copper Inverse Opal by Quang Pham, University of California – Irvine.

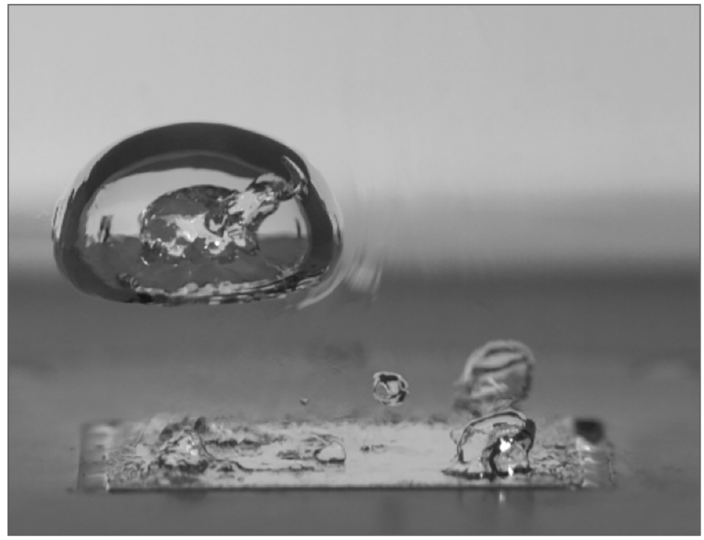

Figure 2: Elephant in a Bubble by Matthew Clark, Purdue University.

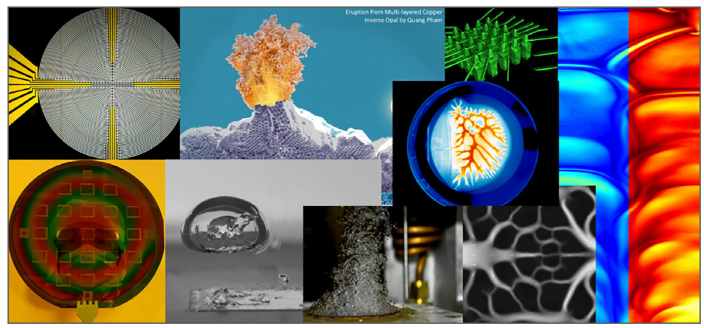

Figure 3: Art in Science Entries.

RICHARD CHU ITHERM AWARD FOR EXCELLENCE

Prof. Kenneth E. Goodson was awarded the Richard Chu ITherm Award for Excellence for his pioneering work in basic heat conduction research. Prof. Goodson chairs the Department of Mechanical Engineering and holds the Davies Family Provostial Professorship and a courtesy appointment in Materials Science at Stanford University. Through decades of research, his work has produced new insights into phonon transport and scattering in nanotransistors, modulated conductivity through phase transitions, and the transport properties of low-dimensional (1D and 2D) nanomaterials.

PROCEEDINGS

We are also pleased to announce that the ITherm 2018 Proceedings have been forwarded to the IEEE Xplore Digital Library, and will be posted soon. Papers appearing in the Table of Contents are available for access and download, along with listings of our Keynote Speakers, Tech Talks, Panels, Sponsors, and Exhibitors.

ITHERM 2019

ITherm 2018 was a great success, and we hope you will join us at the Cosmopolitan in Las Vegas, NV, May 28th - 31st, 2019, for ITherm 2019. Abstracts for the ITherm 2019 conference will be due on Sept 3rd, 2018; the submission website will open later this summer.

SPONSORS AND EXHIBITORS

ITherm 2018 was made possible by those of you who attended and by the generous support of our sponsors and exhibitors: S2TS and CALCE at University of Maryland, Intel, Huawei Technologies, IBM, Dupont, Novark Technologies, Laird, S3IP at Binghamton University, CAVE 3 at Auburn University, Colder Products Company, COFAN USA, Stäubli North America, CoolIT Systems, and Innovative Research LLC.

ITherm
LAS VEGAS, NV 2019

Evening shot of The Cosmopolitan of Las Vegas: Photo by Allen McGregor, distributed under a CC BY 2.0 license.

Towards Green Technology: Modeling of a Compact Plate Heat Exchanger Condenser for Thermosyphon Cooling of Entire High Power Datacenter Racks

August 08, 2018 – Electronics Cooling (online journal)

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Dr. Raffaele Luca Amalfi is a Scientific Collaborator at the Swiss Federal Institute of Technology of Lausanne (EPFL), at the Laboratory of Heat and Mass Transfer (LTCM), in Switzerland. He holds a Ph.D. in Mechanical Engineering from the EPFL. In 2016, he joined Nokia Bell Laboratories in New Jersey, where he performed disruptive research on hybrid air/liquid cooling technologies for shelf-level equipment. In 2012, he joined IBM Research Laboratory in Switzerland, where he worked on a novel cooling system for high-power electronics. His research activities and interests include: energy recovery systems, single- and two-phase flow heat transfer within complex structures, heat exchangers design and rating, electronics cooling and passive cooling technologies. He has authored over 20 articles, including book chapters, journal and conference papers.

Jackson Braz Marcinichen
Dr. Jackson Braz Marcinichen is the founder and CEO of JJ Cooling Innovation SÀRL (Lausanne-Switzerland) and has over 25 years experience in HVAC & R systems. He has authored over 60 scientific and technical papers in indexed journals and international peer-reviewed conferences, book chapters and US patents. All along his career, he has computationally simulated, designed and evaluated several experimental facilities and prototypes, characterizing the thermo-hydrodynamic and control of cooling systems (calorimeters, wind tunnels, hybrid systems, etc.).

John Richard Thome
Prof. John Richard Thome is Professor-Emeritus of Heat and Mass Transfer at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland since 1998 (obtaining his PhD at Oxford University in 1978). Having retired in July 2018, he has now founded a new consulting/thermal engineering software company, JJ Cooling Innovation Sàrl in Lausanne. He is the author of five books and over 245 journal papers on microscale and macroscale two-phase flow, boiling/condensation heat transfer and micro-two-phase cooling systems for electronics cooling, including numerous sponsored projects with IBM, ABB, Nokia Bell Labs, etc.

He received the prestigious 2017 Nusselt-Reynolds Prize, the ASME Heat Transfer Division's Journal of Heat Transfer Best Paper Award in 1998, the United Kingdom's Institute of Refrigeration J.E. Hall Gold Medal in 2008 for his work on microscale refrigeration heat transfer, the 2010 ASME Heat Transfer Memorial Award, the ICEPT-HDP 2012 Best Paper Award on a 3D-IC prototype with interlayer cooling (13,000 TVS's and 260 microchannels inside), the ASME Journal of Electronics Packaging Best Paper Award in 2014, and the Outstanding Paper Award at InterPACK2017.

He founded the Virtual International Research Institute of Two-Phase Flow and Heat Transfer in 2014, now with 25 participating universities to promote research collaboration and education (see http://2phaseflow.org). According to Google Scholar, he has over 21,000 citations.

CONTEXT AND NEW COOLING TECHNOLOGY

Heat dissipations of servers and their racks in datacenters are reaching ever increasing levels, breaching the economical heat removal limits of traditional air-based cooling technologies. Currently, about 40% to 45% of the total datacenter energy consumption is used to cool servers with an annual growth rate of about 15%, presenting significant challenges to keep reasonable values for energy efficiency and noise level within bound [1, 2]. Thus, there is an immediate need to improve the rational use of energy in these systems by implementing a novel passive two-phase thermosyphon cooling technology, as reported in *Figure 1*.

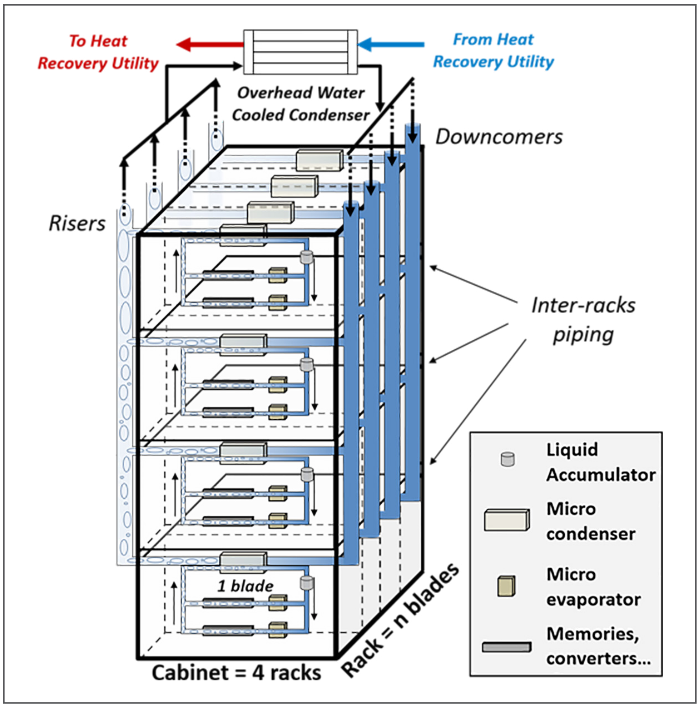

Figure 1 . Concept of the new proposed cooling technology for high heat dissipation servers [3].

The envisioned cooling technology operates with numerous mini-thermosyphons (one per server) in order to dissipate the heat produced by memories, converters, microprocessor, etc. into the evaporator cold plates and out through the two-phase micro-condensers [4]. Then, the heat is transferred to a macro-thermosyphon with a compact plate heat exchanger (PHE) located on top of the rack (see *Figure 1*) acting as the condenser, which dissipates the total heat from the rack (60 kW or much more) into the datacenter's water cooling loop. This approach provides a passive and low energy consumption cooling solution coupled with the possibility to re-use the waste heat from the datacenter (i.e. district heating network), but that is beyond the scope of the present study.

THERMOSYPHON OPERATING WITH A PHE

In general, a thermosyphon is a closed and self-regulated system composed of four main components: an evaporator, a riser, a condenser and a downcomer (see *Figure 2*). The condenser is always installed above the evaporator, while the riser and downcomer connect them together, allowing the working fluid to circulate within the loop.

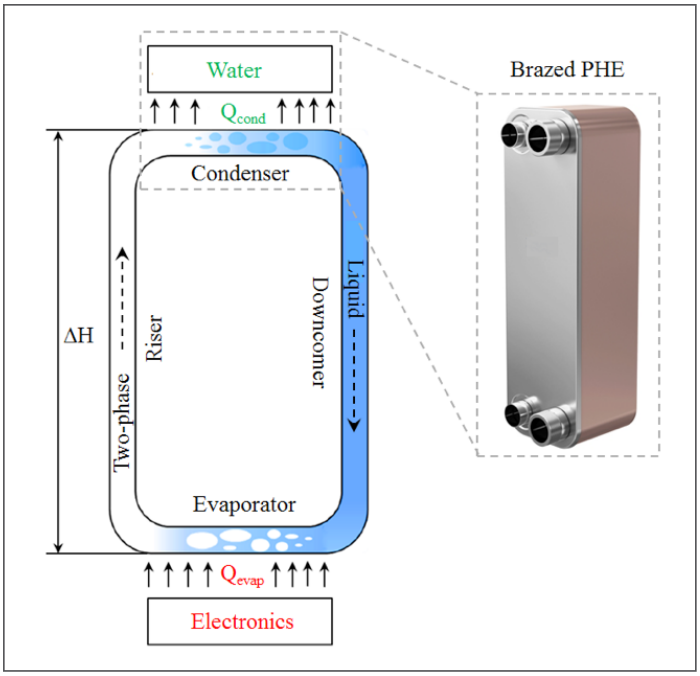

Figure 2. Schematic of a thermosyphon loop and a brazed PHE is proposed as a water-cooled condenser to transfer the heat from the entire datacenter to the recovery utility.

More specifically, the heat generated by the electronics is removed in the evaporator, where two-phase flow is generated. Next, the liquid/vapor mixture, with a lower density, is guided up to the condenser by the riser due to buoyancy effects, where it condenses back to 100% liquid. The subcooled liquid, with a higher density, is then guided to the evaporator by the downcomer thanks to its gravity force, in order to start the loop again. The fluid flow within a thermosyphon loop is self-sustained and does not require any mechanical drivers or controllers. In operation, the thermosyphon seeks an equilibrium state defined by the momentum balance between the static, momentum and frictional pressure drops along the entire loop.

In the cooling system depicted in *Figures 1* and *2*, a brazed PHE is proposed as an overhead condenser, operating in counter-flow arrangement, with the working fluid condensing on the primary side (at the inlet vapor quality from the riser) and datacenter water on the secondary side. PHEs represent an important category of compact heat exchangers widely used for many applications. These units consist of thin, rectangular, pressed stainless steel plates that are stacked together, such that cold and cold fluid streams alternate through the inter-plate passages. The plates are stamped with various corrugation patterns (washboard, oblique washboard, chevron, etc.), providing about 10-20% increase in effective heat transfer area compared to the footprint, and additionally, modify the flow field to promote more turbulence and mixing with higher heat transfer performance [5]. In particular, *Figure 3* shows a schematic of a plate with a chevron corrugated pattern and its associated geometrical parameters defined.

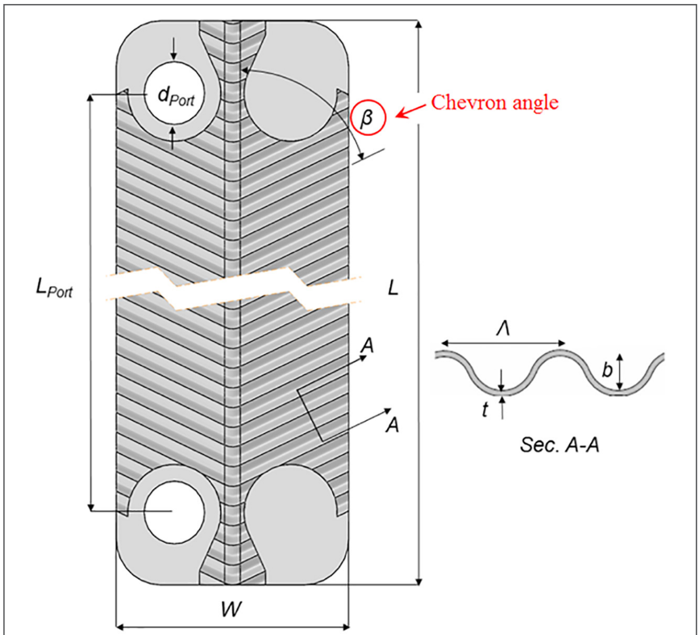

Figure 3. Geometrical parameters of a sinusoidal chevron corrugated pattern with inlet and outlet ports located at the same side [6].

The present study will show a case study simulation of a compact PHE to recover 61 kW from a datacenter rack. These units are easily adaptable to datacenter thermal-hydraulic requirements by changing the number of plates and/or modifying the corrugated pattern and/or plate size. Their compact design has a low weight and a reduced working fluid charge.

They are commercially available from numerous suppliers. However, as their typical application is refrigeration systems, the thermal design simulation codes used for those applications with superheating, desuperheating and lubricating oil effects are not usually accurate for the present partial condenser case in datacenters. Due to its accuracy to locally model two-phase heat transfer mechanisms, our PHE simulation code, which is described below, is used here for predicting thermal-hydraulic performance of a datacenter overhead water-cooled condenser, as reported in *Figure 1*.

PHE SIMULATOR

An in-house simulation code was developed to rate and design refrigerant-to-water chevron PHEs in single- and multi-passage configurations. The present simulator was entirely written in Python and it is able to model evaporation, condensation and single-phase (liquid or vapor) flows on the primary side, while the secondary side is water in single-phase liquid flow.

Furthermore, the simulator includes desuperheating of vapor (both dry-wall and wet-wall local conditions) for flows exiting a compressor in a refrigeration cycle. In addition, it can handle several flow configurations (parallel-flow and counter-flow), different flow orientations (horizontal and vertical) and many plate arrangements, geometries and working fluids. Also, it can handle partial condensers, which are needed in the present study. The code can be classified as a "pragmatic" tool, being able to provide accurate results and guarantee very low computational time (in order of seconds to complete a fully detailed local incremental thermal-hydraulic simulation of a PHE, including its pressure drops with their inlet and outlet port pressure drops).

The local one dimensional Effectiveness-NTU method [7] , which includes the equations of mass, momentum and energy conservation, was implemented and coupled with a set of appropriate correlations to predict the local heat transfer coefficients and local frictional pressure gradients for single- and two-phase flows along the flow in the PHE (more details on the modeling and simulator's flowchart can be found in [8]). It has to be pointed out that the best proven methods for local thermal-hydraulic performance of evaporating flow within PHEs were developed in [9] using an experimental databank of 3416 points, including our data [6, 10, 11] and additional data from 12 other research labs worldwide. The most reliable prediction methods for condensing flow were determined [12] through a state-of-the-art research study that compared the existing prediction methods against another large experimental condensation heat transfer and pressure drop databank from literature. The code has an incremental simulation approach in which the PHE is divided into numerous small control volumes from inlet to outlet, which are then added together to get the total system performance.

Finally, the current simulation tool can be easily managed by the users, thanks to a user-friendly and dynamic GUI, which includes a complete description of the input and output parameters, provides comments from the code and error handling in case of user's mistakes or introducing input values out of range.

CONDENSER CASE STUDY AND SIMULATION RESULTS

This section presents a case study simulation for a compact PHE used as a water-cooled condenser of the macro-thermosyphon depicted in *Figure 1*, chosen here to dissipate 61 kW from a datacenter rack to the utility water. The macro-thermosyphon used refrigerant R134a as the working fluid. The simulation conditions are summarized in *Table 1*, while the geometry of the PHE is reported in *Table 2*.

Table 1. Input flow conditions for the case study simulation

Input	Primary Side	Secondary Side
Fluid	R134a	Water
Mass flow rate	0.97 (kg/s)	0.56 (kg/s)
Inlet condition	Vapor quality = 0.4 (-)	Temperature = 20 (°C)
Inlet pressure	19 (bar)	3 (bar)
Fouling factor	0 (m^2K/W)	0 (m^2K/W)
Oil concentration	0 (%)	-

Table 2. Input PHE geometry for the case study simulation	
Input	Value
Number of channels per side	30 (-)
Port-to-port length	220 (mm)
Plate width	60 (mm)
Pressing depth	2 (mm)
Chevron angle	55 (°)
Wavelength of the surface corrugation	3.5 (mm)
Plate thickness	0.4 (mm)
Plate material	Stainless steel
Total dimensions	286/60/145 (mm)

Figure 4 presents the local temperature profiles for the refrigerant (red curve) and the water (blue curve) as a function of the PHE incremental length. The refrigerant entered the PHE with an inlet vapor quality of 40%, and then was completely condensed and subcooled along the length of the PHE. The refrigerant saturation temperature decreased along the PHE due to its two-phase pressure drop, accounted for within the NTU temperatures. The single-phase water received the heat and its temperature increased from 20°C to 48°C at the outlet of the PHE (this means that the datacenter cooling water at 20°C is sufficient here, since higher temperatures can be used by increasing the size of the PHE).

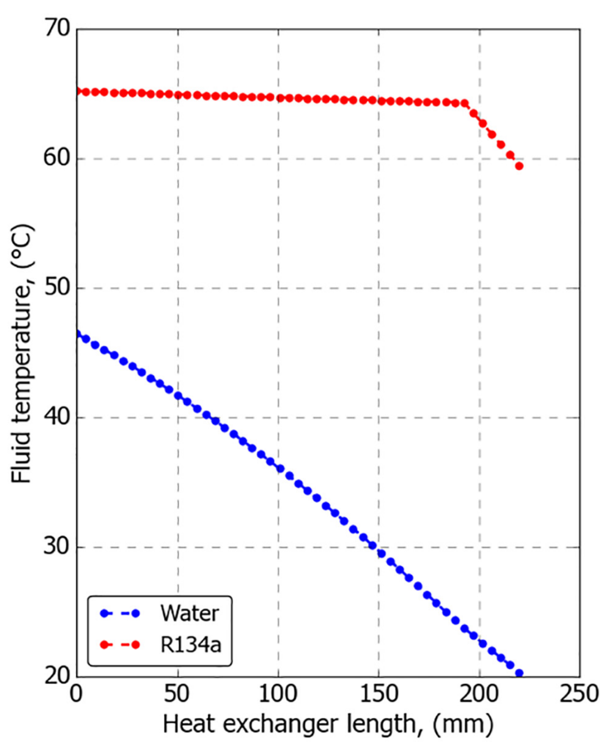

Figure 4. Local temperature profiles for primary (R134a, red curve) and secondary (water, blue curve) sides as a function of the PHE incremental length (1-D discretization using 49 control volumes).

Figure 5 illustrates the local trends of the heat transfer coefficients for both sides. In particular, the water side (blue curve) heat transfer coefficient increased from the inlet to the outlet due to its temperature rise, which provided an increase in thermal conductivity; the refrigerant side (red curve) heat transfer coefficients were higher in the two-phase flow region as expected, compared to the fully single-phase liquid region. It has to be pointed out that the discontinuity at low vapor quality (0%) is due to the transition from two-phase flow to single-phase liquid flow, as well as the use of different prediction methods to estimate the thermal-hydraulic performance in those regions.

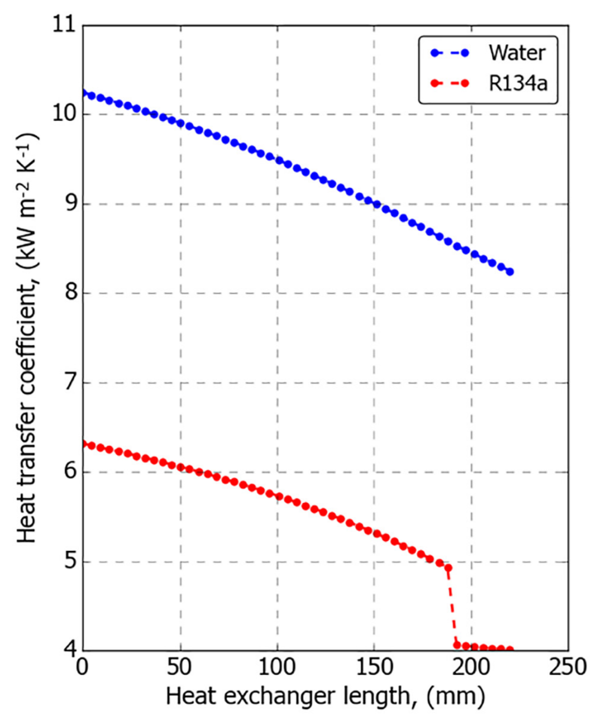

Figure 5. Local heat transfer coefficients for primary (R134a, red curve) and secondary (water, blue curve) sides as a function of the PHE incremental length (1-D discretization using 49 control volumes).

Based on the simulation inputs reported in *Tables 1* and *2*, the present PHE is able to dissipate 60.6 kW with an overall heat transfer coefficient of 1210.6 $W/m^2/K$. The associated total pressure drops for the refrigerant and water were calculated to be 54.8 kPa and 8.7 kPa respectively. In an actual application, the PHE design would be optimized to reduce its refrigerant side pressure drop, so as to increase the thermosyphon's flow rate.

CONCLUSIONS

In the present article, a passive thermosyphon cooling scheme has been proposed for cooling of high power datacenter racks using a PHE as the overhead water-cooled condenser. The modeling of the PHE was performed by using our in-house simulator that incorporates the local effectiveness-NTU method with the mass, momentum and energy equations, coupled with the best proven methods from literature to calculate the local heat transfer coefficients and the local pressure drops. The simulation results demonstrated the potential to remove 61kW of heat from a rack by installing a small PHE (only 286 mm x 60 mm x 145 mm), with the possibility to go even higher in terms of power by properly modifying the PHE design.

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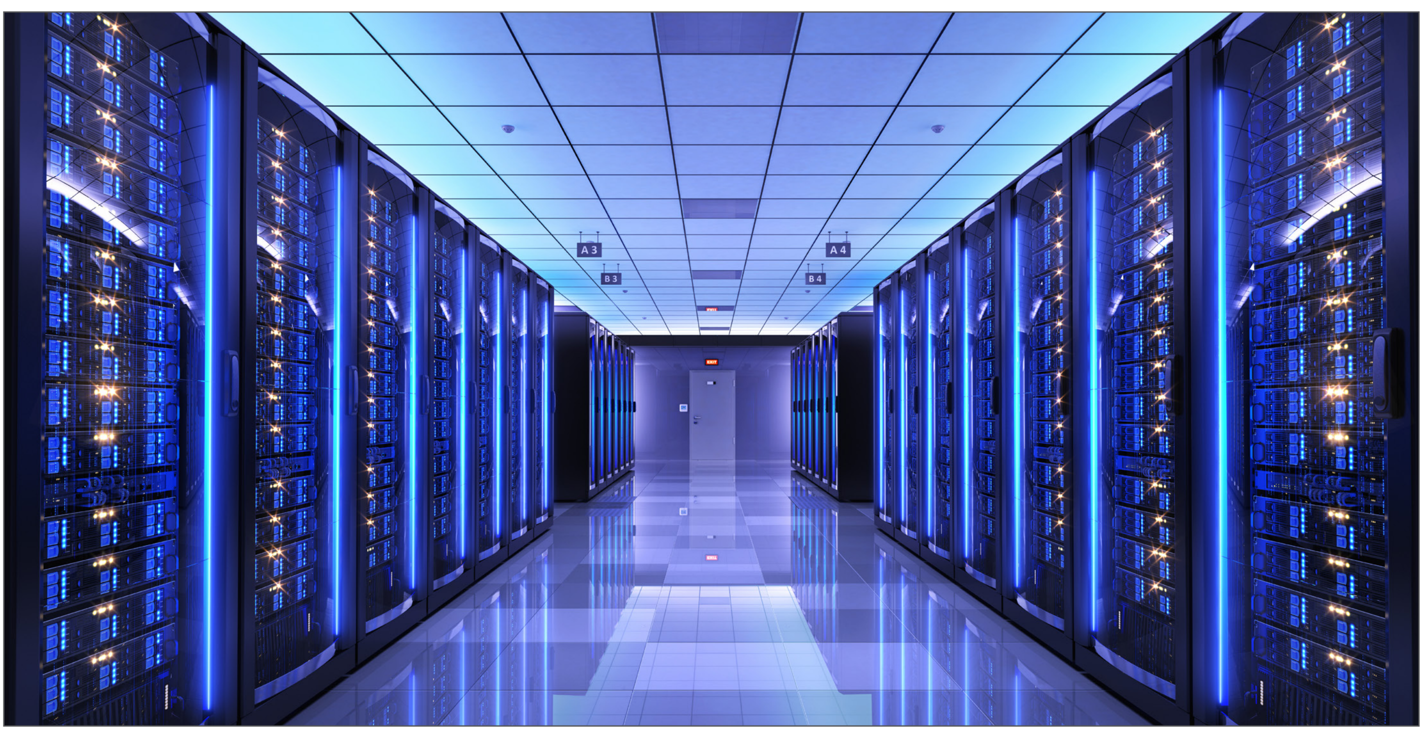

A Thermal perspective on Heterogenous Integration for Harsh Mil/Aero Environment Electronics

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HARSH ENVIRONMENT ELECTRONICS

Harsh Environment Electronics are the unique electronic systems that operate our flights, factories and autonomous vehicles in a safe and reliable manner. As these systems manage the safety of persons and/or vehicles that cost millions of dollars, strict hardware and software system standards have been developed to operate in their harsh environments. For example, class I avionics need to operate in a continuous ambient environment of -54°C to 55°C and a temporary 30-minute free convection ambient environment of 71°C. Given that chip junction limits are typically 95°C to 105°C, it is clear that the thermal budget for the thermal designer for these applications is minimal.

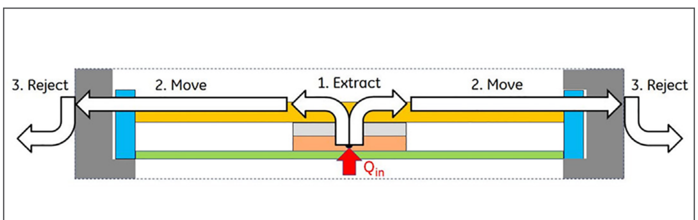

Figure 1. Top-side heat removal path for conduction cooled rugged embedded LRU electronics

Because of the limited thermal budget, rugged embedded electronics typically rely on heat removal from the top of the chip packages, where heat is removed through the thermal interface material (TIM) to the heat spreader as illustrated in *Figure 1* for a typical line replaceable unit(LRU).

HETEROGENOUS INTEGRATION FOR HARSH ENVIRONMENTS

Heterogenous Integration is often described as "packaging technology to integrate dissimilar chips with different functions" [1]. Heterogenous Integration of components is intended to lower power consumption, footprint, development time, and cost while decreasing latency compared to conventional single chip integration approaches [2].

As heterogenous integration uses silicon as the interposer, it also allows for further integration of silicon photonics. Silicon photonic components such as optical, laser diodes, waveguides, modulators, and detectors yield the promise to further advance bandwidth and achieve ultra-low latency. Urino et al. [3] describes this in a concept called "server on a chip" as depicted in *Figure 2*.

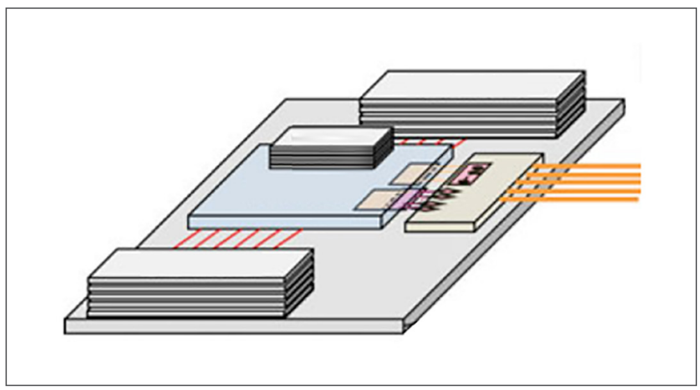

Figure 2. On-Chip Server – adapted from Urino et al. [3]

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In this concept of an on-chip server, dissimilar components are combined onto a single integrated chip, performing all the basic functions of a server, effectively operating as single chip system located on the silicon. This effectively transitions the role of the traditional multi-layer PCB to that of mechanical support and power and I/O management as platform as most of the data communication is managed on the silicon interposer.

When evaluating how heterogenous integrated packages can be applied in for harsh environments, select technology innovation area needs can be identified.

3D THERMAL INTERFACE THERMAL TECHNOLOGY

As stated, rugged harsh environment electronics rely pre-dominantly on chip top-side heat rejection through a thermal interface layer and a heat spreader mounted over the flip-chip package. This thermal interface layer serves to thermally connect components of dissimilar coefficient of thermal expansion (CTE) such as silicon(chip) and aluminum or copper(heat spreader). As ruggedized electronics typically get produced in moderate volumes (100s-1000s), chip height, chip warpage and other non- planarity can be a challenge. The thermal interface material also serves to compliantly compensate for these differences by filling gaps and ensuring good thermal contact between these components.

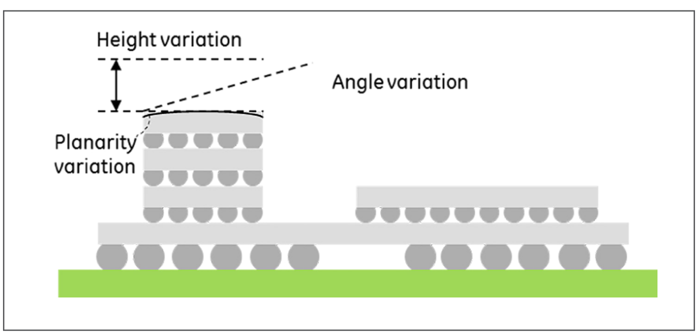

Figure 3. Notional 3D chip architecture and anticipated topology challenges

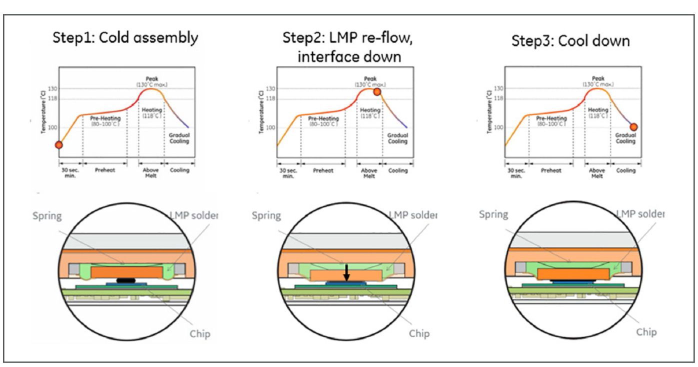

Figure 4. Flexible metallic heat connector as described by Kirk et al. [4]

As heterogenous integration introduces 3D non-planar and large silicon structures, challenges can be envisioned to connect a top-side heat sink using current thermal interface materials. It can also be expected that as multiple micro-ball grid array connections are used to create vertical stacks, height and planarity variations will accumulate resulting in amplified variance in the eventual location of the top-side chip interface as illustrated in *Figure 3*.

Kirk et al. [4] developed a novel thermal interface method that connects to the chip after assembly by using a controlled spring loaded expansion that occurs during a low temperature re-flow process as illustrated in *Figure 4*. The novel insight used by this method is the use of low melt point (LMP), high thermal conductivity solders such as Indium contained in thin flexible high temperature polymer foil like urethane. As select polymers have a melting point higher than that of LMP solders, they can successfully retain a solder in liquid state and "freeze" when the solder re-solidifies. In this concept, the connector is attached to the heat spreader in a state where the spring is compressed.

The system is then assembled over the chip with some thermal grease on the chip in step 1. In step 2, the LMP solder melt point is exceeded during a brief re-flow, allowing for the spring to expand and lower a copper heat spreader down to the chip interface, compressing the thermal grease. Finally after cool-down, the heat connector is frozen in state that is matched with the height and angle variation of the chip. Further variations of this technology can be envisioned, where not one, but multiple tiles press down to follow the contour of 3D heterogenous chip topology.

In variant of this concept, a thermal interface material system by de Bock et al. describes a thermal interface system that uses a thicker layer of LMP solder, encapsulated by an ultra-thin layer micro layer of a high temperature polymer [5]. When pressure is applied during heating, the LMP solder flows conformal to the chip shape while being contained by the thin polymer "bag" as illustrated in *Figure 5*. When the containment layer polymer is sufficiently thin, its detrimental contribution to the TIM thermal resistance can be sufficiently small, outweighed by the superior thermal conductivity of LMP solders like Indium(k ~ 70 W/m-K), which exceeds common thermal interface materials.

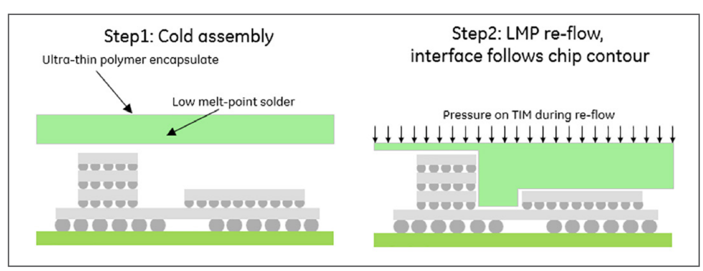

Figure 5. Encapsulated LMP solder thermal interface system with the potential to conform to 3D chip topology [5]

The benefits of this concept are similar to the aforementioned flexible metallic heat connector as in compensating for chip height and angle variation, but in addition, non-planar chip warpage and 3D topologies can potentially also be managed. As LMP solder never comes in full contact with the silicon chip, no inter-metallics are formed, eliminating the need for barrier coatings and allowing for re-workability.

SEMICONDUCTOR CTE MATCHED HEAT SPREADERS

As 3D stack-ups can contain multiple layers of heat generating components, managing hot-spots can be increasingly challenging. Heterogenous integrated architectures hotspots will likely occur in the layers furthest away from heat sinks such as the PCB and the top-side of the chip.

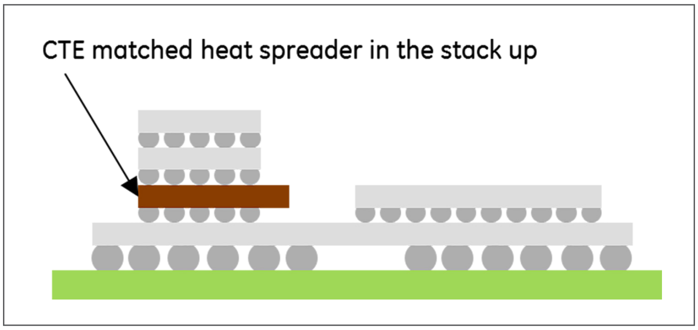

Figure 6. 3D chip architecture with CTE matched spreaders

A semiconductor CTE matched heat spreader embedded in the 3D package as illustrated in *Figure 6* can bring heat out from the center of the 3D stack-up to the periphery where a TIM or via based solution can be used to remove heat. These dedicated heat spreader layers would require electrical pass through to allow for connections from the interposer to the top-side chips. Minimizing thermal stress and warpage is also important as electronics used in harsh environments experience extreme thermal transients. Therefore, a heat spreader-silicon CTE match is preferred.

The Defense Advanced Research Project Agency's (DARPA's) thermal ground plane (TGP) program led to the development of a variety of semiconductor matched heat spreaders [6] (*Figure 7*). These heat spreaders are effectively two-phase vapor chambers designed for operation in high-g environments.

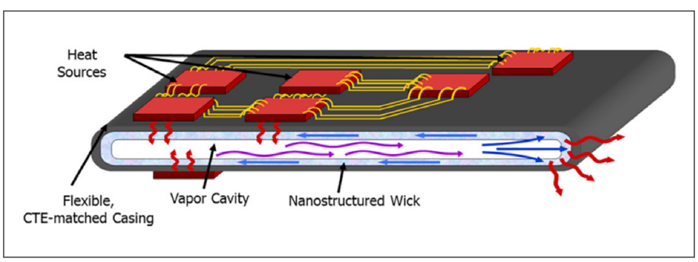

Figure 7. DARPA Thermal Ground Plane CTE matched heat spreader vision – adapted from A. Bar-Cohen et al. [6]

Materials such as Silicon [7], CuMo [8], Kapton [9] and AlN [10] were evaluated as vapor chamber vessels by a variety of teams under this program. By development of two-phase evaporator and condenser zones, it was demonstrated that effective thermal conductivities could be achieved that greatly exceeded the inherent vessel thermal conductivity, even in the presence of adverse g-forces [10]. Likely through re-development of this TGP concept, novel versions can be developed to address hot-spot mitigation needs for heterogenous integrated packages.

ACTIVE TRANSIENT HOT SPOT THERMAL MANAGEMENT

Another way to manage local hot spots is by providing active in-package hotspot mitigation. Especially when 3D heat rejection is considered, moving heat from an embedded chip layer to another that has top-side cooling can be advantageous. Bar-Cohen and Wang pioneered in-package thermoelectrics extensively enabling several degrees hot-spot cooling [11].

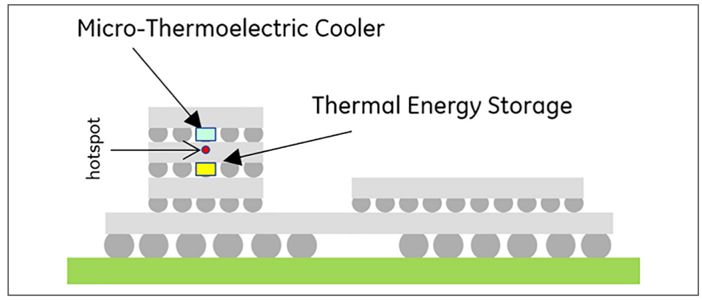

Figure 8. 3D chip architecture with thermoelectric cooler and thermal energy storage for hotspot management

Further work from Green and Fedorov et al. [12] further explored the use of in-package micro-thermoelectrics and thermal energy storage technology, allowing for novel transient thermal management approaches for management of hotspots internal to 3D packages as shown in *Figure 8*. As thermoelectrics are effectively heat pumps, they can also be used to manage mechanical stresses by providing heat or cooling to select areas of a 3D package to counter any thermal gradients produced by the electronic loading of the chipsets.

Such technologies can especially be effective in enabling on-package silicon photonics as optical components require temperature stability and/or temperature control near the temperature sensitive components such that the laser diodes and detectors do not experience any lasing wavelength shifts.

CONCLUSION

Heterogenous Integration is an integration technique offering the combination of dissimilar components onto a 3D package. Several technical challenges in the application of Heterogenous Integration for harsh environment electronics exist. Expanded temperature range operation, extreme hot and cold operation, severe mechanical requirements and minimized thermal budgets are examples of requirements that illustrate the challenges of developing thermal solutions for harsh environments.

As with most electronics lifecycles, operation of new technology often starts in highly competitive applications with limited operational life, of which some can be consumer electronics. As these technologies mature and gain more pedigree, more and more application for critical electronics in harsh environment can be considered. The study identified three areas of technology research that can be focused on to further accelerate this progression. These are, the development of 3D thermal interface technology, application of CTE matched heat spreaders and active transient thermal hot spot management. It is anticipated that with time and development support, these technologies will further advance allowing one day for safe and reliable operation of heterogeneously integrated electronics in the aerospace, industrial and other safety critical harsh environment electronics systems of tomorrow.

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The Effect of Ambient Conditions on Local Climate Inside a Pump Electronics Enclosure

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Nomenclature	
C_p	Specific heat of the fluid at constant pressure (J/kg·K)
D	Moisture diffusion coefficient (m/s)
F	Volume force vector (N)
g	Acceleration due to gravity (m/s²)
I	Unit tensor
p	Pressure (pa)
T	Temperature (K)
t	Time (s)
u	Velocity vector (m/s)
Greek Symbols	
μ	Dynamic viscosity (Pa·s)
ρ	Mass density (kg/m³)
Subscripts	
x, y, z	Direction coordinates

INTRODUCTION

Condensation and moisture related problems are the cause of failures in many cases and consequently serious concerns for reliability in electronics industry. Therefore, it is important to control the moisture content and the relative humidity (RH) inside electronics enclosures. Understanding the transport phenomena and the effects of different parameters on the RH management and local climate inside the enclosures and applying this knowledge during the design phase is crucial for reducing the chance of failure and controlling maintenance costs. For decades thermal management has been extensively studied; however, the RH of the operating environment is commonly disregarded during the design of electronics enclosures [1]–[3].

Numerous parameters affect the local climate inside electronic enclosures, such as material properties, dimensions of the enclosure and the electronics, components and their configurations and finally environmental conditions. Ambient condition changes significantly affect the local climate inside electronic enclosures.

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Jesper Henri Hattel
Jesper Henri Hattel received the M.Sc. degree in structural engineering and the Ph.D. degree in mechanical engineering from the Technical University of Denmark (DTU), Lyngby, Denmark, in 1989 and 1993, respectively. He currently holds a Full Professorship in modeling of manufacturing processes with the Department of Mechanical Engineering, DTU. His current research interests include modeling of processes like casting, joining, composites manufacturing, and additive manufacturing. This involves the use of computational methods within the disciplines of heat transfer, fluid dynamics, solid mechanics, as well as materials science. Applications range from microelectronics over automotive industry to large structures like wind turbines.

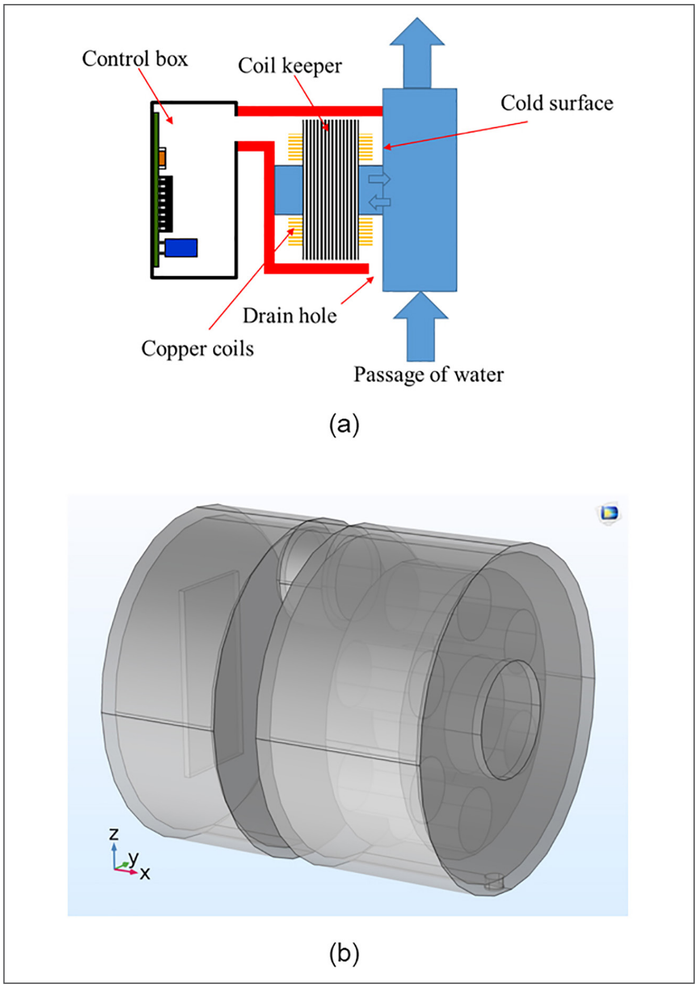

Figure 1. The 2D schematic (a) and the 3D geometry of the cold-water pump (b).

In applications such as military, industrial, commercial or consumer electronics, certain equipment may contain devices highly sensitive to environmental conditions [1].

In order to precisely predict the local climate inside electronics enclosures, one has to perform coupled momentum, heat and mass transfer analysis on the system composed of several components of various sizes (such as PCBs, heat sinks …). The method of choice for making such predictions is mostly CFD (computational fluid dynamics). Application of CFD analysis has the potential to provide accurate solutions and allow the user to assess them in different cases [3]–[5].

The main objective of this work is study the effect of ambient conditions on local temperature and RH inside the enclosure so that to prevent the 100 (%) RH and the consequent condensation. Exposure to high RH leads to condensation of water on the electronics. The concentration of water molecules rises as the RH increases. The thickness of the molecular layers of water eventually permits ionic conduction which can lead to changes in electrical resistance and even short circuits. This phenomenon accelerates the rate of corrosion [2].

In this study, the effect of ambient conditions in three cities on a summer day (July 1st, 2016) is studied on local RH and temperature on a PCB (printed circuit board) in a cold-water pump enclosure. Furthermore, the results from the transient simulations can be used to improve the humidity management inside the enclosure. *Figure 1a* shows a 2D schematic view of the pump. The enclosure consists of two chambers, connected with a small tube.

The chamber on the left side (the control box) contains the electronics and the chamber on the right houses the copper coils, coil keeper and the shaft. The 3D geometry of the pump is shown in *Figure 1b*. The dimensions of the pump are listed in *Table 1*.

Table 1 Dimensions of the pump

	material	Specific heat capacity (J/(kg·K))	Thermal conductivity (W/(m·K))	Length (cm)	Diameter (cm)
Control chamber	Aluminum			Inner: 3.5 Outer: 4.1	Inner: 10 Outer:10.6
Connecting tube	Aluminum	904	237	Inner: 2.1 Outer:2.1	Inner:2.6 Outer:3.2
Shaft chamber	Aluminum			Inner: 5 Outer:5.6	Inner: 10 Outer:10.6
Shaft	Stainless steel	475	44.5	3.75	3.6
Drain hole				0.4	0.6
Coils	Copper	385	400	2.5	2
Coil keeper	Polycarbonate	1259	0.192	2.5	8.8
PCB	FR-4	1369	in plane: 0.3 through: 17.8	W×D×H: 0.2×3×6	

Table 1. Dimensions of the pump

NUMERICAL SIMULATION METHOD

Temperature gradients in the system generate buoyant forces that lead to an air flow. In this work, to estimate the velocity profile caused by these volumetric forces, the energy equation is fully coupled with the momentum and continuity equations. *Figure 2* demonstrates the way that these equations are coupled. The continuity equation or equation for the overall mass balance is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

The equation for the momentum transport is:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[-p\mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right] + \mathbf{F} \tag{2}$$

To consider the buoyant flow, the volume force is considered as given below:

$$\begin{aligned} F_x &= F_y = 0; \\ F_z &= -\rho \times g_z \end{aligned} \tag{3}$$

The energy equation reads:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{4}$$

Several material properties are included in these equations, namely density, viscosity, thermal conductivity and specific heat capacity. Both temperature and RH influence these thermophysical properties of air. Thus, it is crucial to consider the changes during the calculations [6]. The effect might be significant or insignificant depending on the temperature and RH range of the study. Tsilingiris [7] evaluated the thermophysical properties of moist air as a function of mixture temperature (from 0-100°C) and RH, ranging from dry air to saturation conditions. In another study, Melling et al. [8] provided simple analytical correlations for humid air. The correlations were derived from theory and numerical curve fitting in the temperature range of 100-200°C. Zhang et al. [9] also estimated the thermophysical properties of humid air using the same concepts for the binary mixture of air and water vapour as the two other studies. In the current study, the thermodynamic correlations from the Tsilingiris' work [7] are used.

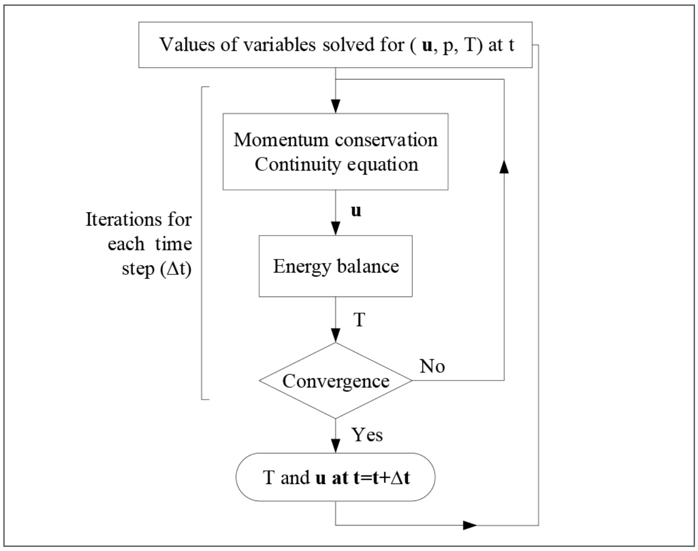

Figure 2. Flowchart of the solving method.

The commercial software package COMSOL Multiphysics TM version 5.1 was used for all the CFD simulations. Due to the complicated structure of the modeled system, an unstructured mesh composed of tetrahedral elements is applied on the computational domain in all the simulations. The adaptive mesh refinement method was used to improve the mesh quality.

The average temperature on the PCB was monitored to examine the mesh independency. The final mesh consists of 1,055,444 elements with an average quality of 0.79. The element sizes in x, y and z direction are on order of micrometers. With such a fine mesh, each simulation took about five hours on 20 nodes of scientific Linux 6.4 cluster; where each node was configured with an Intel Xeon Processor X5550.

The solver split each problem into one or more linear systems of equations by approximating the given problem with a linearized problem. In this work, the parallel direct solver (PARDISO) was utilized as the linear system solver. This memory efficient solver works on general sparse linear systems of the form Ax = b and use LU factorization on the matrix A to compute the solution x.

RESULT AND DISCUSSION

The temperature and RH on the PCB are calculated while the pump enclosure is exposed to the ambient conditions in Copenhagen, Atlanta and Singapore for a day (July 1st, 2016). *Figure 3* shows the ambient conditions for these three cities, using data from [10]. The working cycle of the pump is shown in *Figure 4*. For all the three cases, the initial temperature, gauge pressure and velocity are 25°C, 0 Pa and 0 m/s) respectively. The cold wall temperature is always the same as the cold water (the water entering the pump), which is 5°C. The initial RH follows the conditions of each city. The RH of the trapped air inside the enclosure follows the ambient changes transiently, due to the relatively large drain hole and the internal air flow.

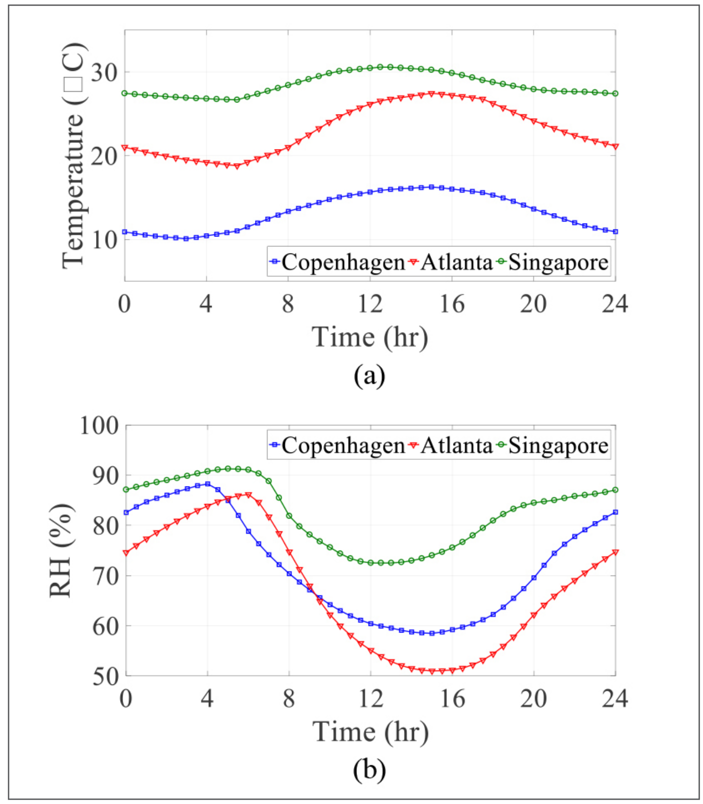

Figure 3. Ambient temperature (a) and RH (b) for Copenhagen, Atlanta and Singapore.

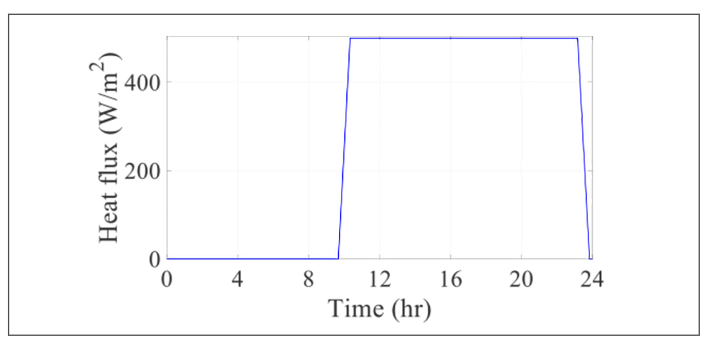

Figure 4. Working cycle of the pump.

The temperature and consequently the RH of the PCB are affected by the heat capacity of each of the components inside the enclosure. This effect is extensively studied in another work [1]. Thus, to make a comparison between the cities, all the parameters are the same in the depicted cases.

In the first 10 hours that the pump is not working, the temperature of the PCB follows the same trend as the ambient. For Copenhagen and Atlanta, the initial temperature is colder than the 25°C PCB. Thus, the RH on the PCB is lower compared to the ambient value (see *Figure 5*). For Singapore, the temperature of the PCB is initially lower than the ambient. That leads to a 100% RH on the PCB. After about 10 hours, the pump starts working. During this time, the heat generated by the electronics on the PCB increased the temperature, which significant decreases the RH on the PCB.

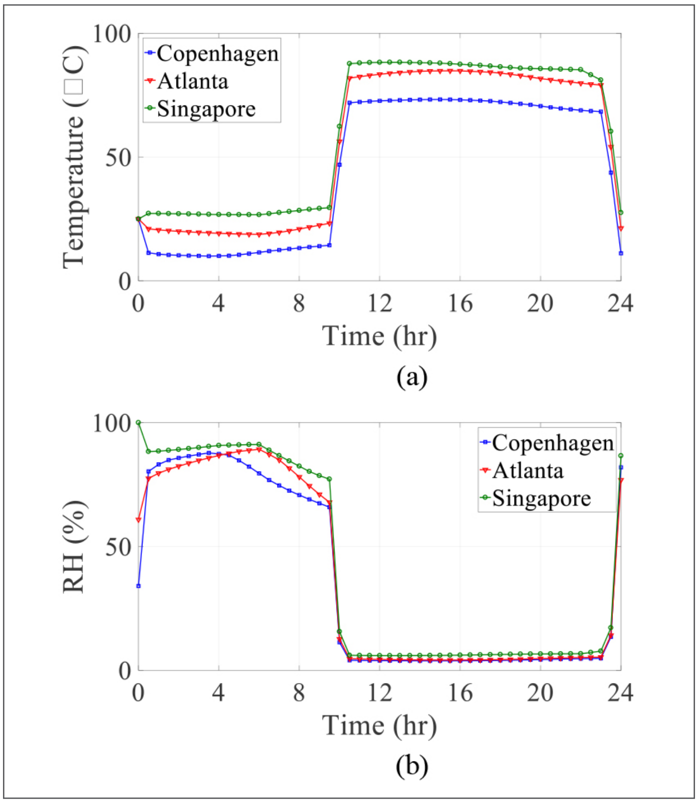

Figure 5. The average temperature (a) and RH (b) on the PCB for Copenhagen, Atlanta and Singapore.

It is worth mentioning that, despite the fact the PCB temperature is mainly affected by the heat flux, it still follows the peaks and valleys of the ambient changes. Regardless of the working cycle of the pump, the condensation risk is generally higher in the first 6 hours of the day due to lower ambient temperatures and higher RHs. From 8:00 to 18:00 hours, the temperature increases and consequently the RH decreases. On the other hand, in most of the applications, pumps work some time from 8:00 to 18:00. This causes even lower RH on the PCB.

Therefore, while the electronics are safe during the working hours, they are exposed to high RH while not they are not operating. In general, the RH on the PCB can be reduced by increasing the temperature (maximizing the saturation limit) or by reducing the moisture content of the air in contact with PCB. Considering the fact that there are drain holes in many electronics enclosures, it is quite challenging to control the moisture content. Furthermore, the natural convection of the trapped air makes the moisture transfer even faster. In the case of this pump enclosure, the presence of the drain hole is necessary to eliminate the condensed water on the cold wall. Thus, temperature control of RH, such as with internal heaters, is a more feasible approach.

CONCLUSION

A 3D finite element based CFD model is developed for investigating the RH evolution on a PCB inside a pump enclosure. The pump is exposed to the ambient conditions of Copenhagen, Atlanta and Singapore in a summer day. The following concluding remarks can be made:

- The condensation risk is higher in the initial hours of the days. This is due to the low ambient temperatures and the fact that, in many cases, the electronics are not operating during that time of the day.
- From 8:00 to 18:00, both ambient conditions and the generated heat by the electronics reduce RH on the PCB. This demonstrates that a heat source in the PCB box can be very effective for reducing the condensation risk on the PCB in the early morning and during the time that the pump is not operating.

It is worth mentioning that the power consumption of the heat source should be optimized according to the ambient conditions, working cycle of the electronics and other components inside the enclosure.

ACKNOWLEDGEMENT

The current research has been conducted as part of the ICCI project from the Danish Council for Independent Research, Technology and Production (FTP) and the IN SPE project from the Danish Innovations Fonden which are highly acknowledged. Moreover, the authors would like to acknowledge the commitment and help of the industrial partners in this project.

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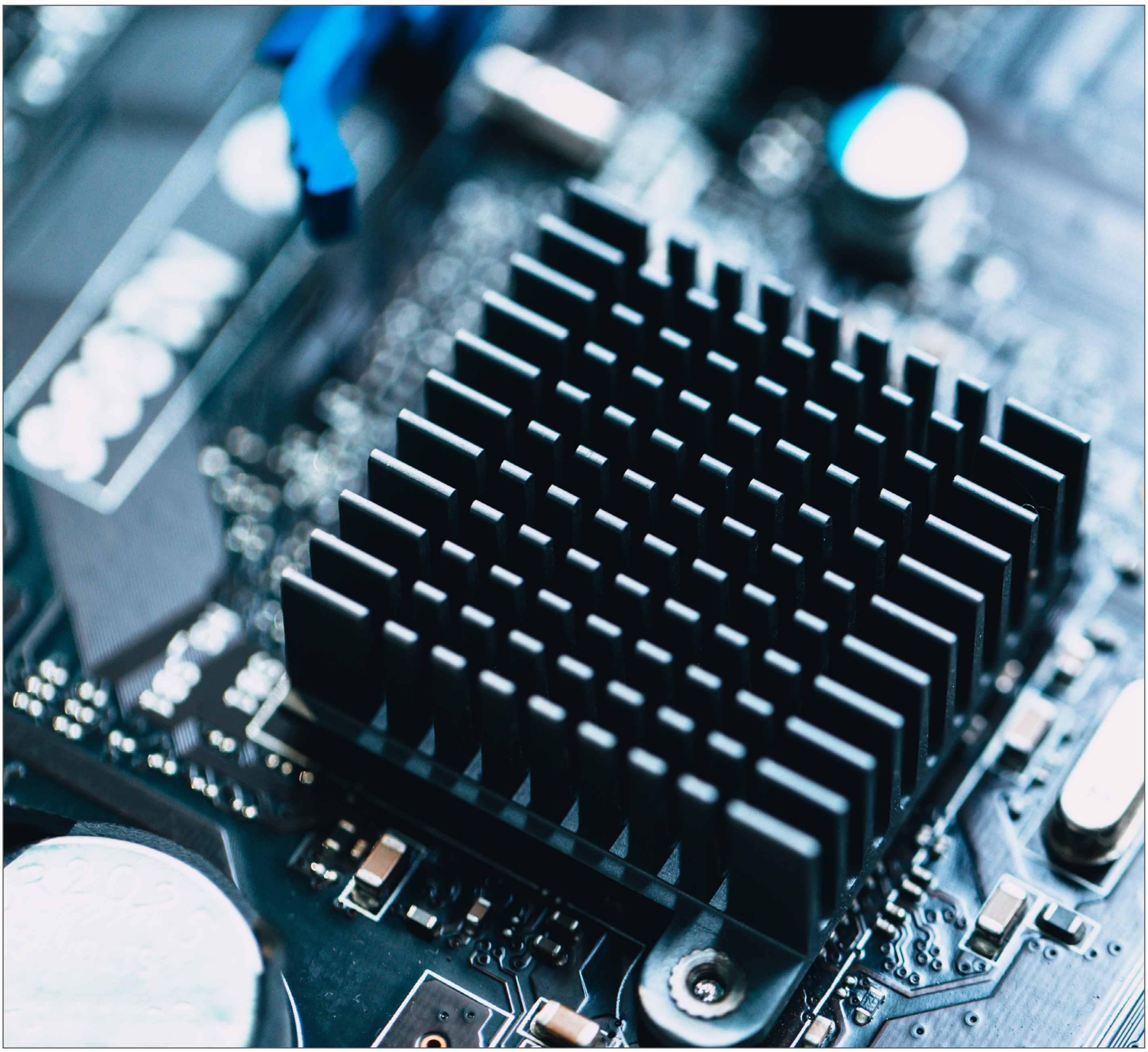

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