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Thermal Management Challenges in Telecommunication Systems and Data Centers

Suresh V. Garimella, Lian-Tuu Yeh, and Tim Persoons

Abstract — The framework for this paper is the growing concern about the worldwide increasing energy consumption of telecommunications systems and data centers, and particularly the contribution of the thermal management system. The present energy usage of these systems is discussed, as well as the relationship between cooling system design and the total cost of ownership. The paper identifies immediate and future thermal bottlenecks facing the industry, ranging from technological issues at the component and system level to more general needs involving reliability, modularity and multidisciplinary design. Based on this enumeration, the main challenges to implementing cooling solutions are reviewed. Particular attention is paid to implementing liquid cooling, since this technology seems the most promising to addressing the key thermal bottlenecks, and improving the future sustainability of thermal management in the telecom and data center industry. Finally, an outlook is presented towards future potential challenges.

Index Terms — Communication networks, Central office, Energy management, Thermal management of electronics.

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I. INTRODUCTION

This paper enumerates and discusses present and future thermal management challenges facing the telecommunications and data center industries. These challenges were identified based on the presentations and ensuing discussions at the Workshop on Thermal Management in Telecommunication Systems and Data Centers, held in Richardson, Texas on October 25-26, 2010. Participants at the workshop included representatives from leading telecommunications systems and data center operators, equipment manufacturers and system integrators¹ as well as academic research groups².

II. ENERGY CONSUMPTION AND SUSTAINABILITY OF THE TELECOM AND DATA CENTER INDUSTRY

A. *Evolution of Telecom and Data Center Energy Usage*

The worldwide electricity usage of data centers excluding the contribution of external networking (i.e., the transport of information between a broader network of data centers) has increased between 2000 and 2005 from 71 billion kWh per year (0.53% of the worldwide total electricity usage in all sectors) to 152 billion kWh per year (0.97% of the worldwide usage) [1], representing a growth of about 10% per year. In terms of the annual electricity consumption for 2005, data centers rank between the national consumption of Mexico and Iran [2]. In the USA, the electricity consumption of the datacom industry (this term is used henceforth to represent data centers and telecommunication systems) amounted to 45 billion kWh in 2005 (1.2% of the total national usage), resulting in total utility bills of \$2.7 billion. The equivalent global energy cost was about \$7.2 billion [3]. In Japan, the annual consumption in 2010 of datacom systems amounted to 5 billion kWh, or about 5% of the total national electricity usage. According to predictions by the Japanese Ministry of Economy, Trade and Industry (METI), this fraction is expected to increase to 25% by 2025 in a business-as-usual scenario, which is of particular concern since the average cost for electricity in Japan is approximately twice that in the USA [4].

Within a data center, roughly 50% of the electricity is used by the IT equipment, 33% by the thermal management infrastructure, and 17% for electrical power distribution. Furthermore, the energy cost is the fastest growing expenditure in data centers, currently averaging about 12% of the total operating cost [5].

¹ AT&T, Aavid, Celsia, Cisco Networks, Degree-Controls, Fujitsu Networks, Fujitsu Advanced Technologies, Hitachi, IBM, Laird Technologies, Malico, Momentive, Oracle, Parker-Hannifin, Raytheon, Vette Corporation.

The strong growth in datacom energy usage and its related cost is fast becoming a major concern and has placed energy efficiency at the top of the agenda for both datacom businesses as well as policy makers. The most commonly used descriptor of data center energy efficiency is the power utilization effectiveness (PUE) as proposed by the Green Grid initiative [6]. PUE represents the ratio of total power required to operate the data center (including cooling, power distribution and other overheads) to the power used only by the IT equipment.

Typical PUE values for data centers depend on the cooling system architecture. These range from $PUE \cong 2.7$ for a traditional raised floor data center, 1.7-2.1 by applying additional in-row cooling and a better containment of hot and cold air, to $PUE \cong 1.3$ using advanced containment methods like rear door heat exchangers. Along with this reduction in PUE values, the typical power per cabinet can increase from 5 kW for the former up to 40 kW for the latter systems [7]. One data center in The Netherlands claims a PUE below 1.1 by applying Hitachi tri-generation chillers and geothermal energy from a nearby lake (see Sect. II.C) [8]. A 2006 study by Lawrence Berkeley National Labs benchmarking 22 US data centers showed a similar range of PUE values [9].

The wide spread in reported PUE values may be due to a difference in cooling system design, but also the local climate (e.g., ambient temperature, humidity, and wind speed), the availability of geothermal sources, as well as the duration and frequency of the measurements. Therefore, care should be taken when comparing PUE values reported for different data centers. An objective metric is only obtained by adhering to a strict standardized definition, accounting for instance for local annual climatic variations [10].

Overall energy-based performance metrics such as the number of computations per input power (megaflops per Watt) [11] will gain importance, and are already used for marketing purposes. For typical high-end servers, this performance has increased exponentially over the past years, from about 20 to 600 MFlops/Watt between 2004 and 2010.

B. Impact of Energy Consumption on Cooling System Design: Total Cost of Ownership

The total cost of ownership (TCO) is a financial estimate of the overall cost of a product including direct and indirect costs over its entire life cycle. Although well-known in economics and marketing, the measure was first proposed for use in the IT industry by Gartner Group Research [12],[13] in 1987. The optimal design of the cooling infrastructure for a datacom system is determined by the minimum TCO value, which depends on the overall

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investment and operating costs. The major factors influencing the TCO include the cost of floor space (driving towards more compact designs with increased heat fluxes), the cost of energy (for electricity, cooling and heating) and other overheads (e.g., power distribution, maintenance, training, etc). The TCO is subject to several constraints related to reliability, environmental compatibility (e.g., acoustic noise emission), technology (e.g., signal integrity) and even building architecture, depending on the particular situation.

A trend towards miniaturization and increased power density can be observed not only in datacom equipment but throughout the electronics industry. This evolution brings with it several thermal challenges as discussed in Sect. III and IV. Some data center operators perceive that the preferred solution for IT equipment manufacturers (i.e., driving towards higher power density) differs from their own. While miniaturization yields savings in floor space, it also implies a higher load per cabinet for the cooling system. For a typical air-cooled datacom rack, this is reflected in higher acoustic noise emission and an increase in fan power consumption. Further miniaturization may require a systematic transition to potentially more expensive liquid-cooling techniques. Since the cost of floor space and other parameters are location-dependent, different optimal solutions can result from the TCO balance [14],[15],[16].

Given the growing energy consumption of data centers, it is important to assess how the growing push toward sustainable solutions is influencing the overall system design. A consideration of sustainability can affect the TCO in several ways, for example through a growing market awareness for ‘green’ products, or via legislative measures to promote sustainable operation. When the carbon footprint of datacom systems is accounted for, energy conservation measures such as waste heat recovery approaches increase in importance. A thermo-economic analysis could be used to translate sustainable data center operation into economic valuation.

In free markets, revenue is the principal driving force for businesses. Therefore, the total cost of ownership is often the ultimate determining factor for cooling system design. Its underlying dependencies on costs and technologies determine the ‘sweet spot’ which is inevitably a compromise between all the considerations involved.

C. Strategies for Energy Expenditure Savings

Since the cost of energy is the fastest growing expenditure in datacom operation [5], sustainable design and operation is gaining in importance. Some alternative energy sources and system design methodologies are reviewed below, which can reduce the expenditure related to energy supplied in the form of grid-based electricity and/or natural gas.

1) Alternative Energy Sources

The traditional design of a data center uses central room air conditioning (CRAC) units and a water cooled central chiller system, which are powered by the electric grid. Several alternative energy sources are commonly used in industrial applications, but not yet for data centers.

Savings in the power used for cooling and/or heating can be achieved, for example, by incorporating waste heat recovery for various purposes (heating of residential, office, industrial or agricultural spaces, or low-temperature industrial processing such as desalination, etc), air or water side economizers, enthalpy wheels, evaporative cooling, and geothermal heating or cooling. As an example of waste heat recovery, IBM Zürich (Switzerland) [17],[18] developed a ‘zero-emission’ data center for the Swiss Federal Institute of Technology (ETH Zürich) in 2008. Cold plates for the processors operate on hot water, which enables the recovery of higher-grade heat (at 50 °C or higher) for domestic heating. The high inlet temperature to the cold plates (about 45 °C) poses the main challenge in this case, and maintaining the junction temperature below 85 °C requires high performance cold plates with microchannels, as well as strict tolerances on the cooling system as a whole. The design temperature is a compromise between recovering heat energy with a high availability and ensuring reliable chip operation while limiting leakage power loss (see Sect. III.A).

Savings in electrical power consumption can be achieved in two ways: firstly by reducing the power consumption of IT equipment (e.g., by reducing leakage power through effective chip cooling and choice of operating voltage [19],[20]), the cooling infrastructure (e.g., by reducing fan loads through more efficient liquid cooling), and the electrical power delivery (e.g., by using efficient high-voltage DC conversion [21]); or secondly by installing alternative local energy sources, such as photovoltaic solar cells, wind turbines, or fuel cells.

Finally, overall energy savings are achieved by means of local co-generation or tri-generation of electricity, heating and cooling. These systems are currently being introduced, e.g. by IBM and Hitachi [8]. At Syracuse University, IBM installed a data center in 2009 featuring tri-generation absorption coolers powered by natural gas, with additional waste heat recovery from the turbine exhaust stream [22]. Compared to a more traditional approach which recovers only low grade waste heat from the chiller (and not from the power plant exhaust), the overall energy conversion efficiency (i.e., the ratio of recovered heat energy to primary energy input) of a tri-generation system can exceed 85%, compared to only 30% for the former approach and 0% for a data center without waste heat recovery

[23].

2) *Alternative Design Methodologies*

Regardless of the choice of individual cooling techniques, holistic design methods may be applied to achieve energy savings. The objective of a thermo-economic analysis and optimization of a cooling system is to minimize the destruction of exergy based on the second law of thermodynamics, thereby maximizing the exergy efficiency. For individual heat exchangers, this corresponds to maximizing the effectiveness while minimizing pumping power. Exergy-based analyses are underutilized tools to translate cooling need (e.g., minimizing pressure loss and temperature gradients) into economic units, thus enabling an objective comparison of cooling designs based on TCO.

To optimize the energy efficiency of air-cooled data centers, active cooling and computational load balancing strategies are being researched based on reduced order models of these complex nonlinear fluid dynamic systems [24]. The reduced order models are established using proper orthogonal decomposition (POD) based on numerical and experimental temperature and velocity data. Compared to traditional data center cooling, this method can achieve energy savings throughout the lifetime of the data center. Assuming the utilization of the data center (and thus the total heat load on its cooling system) gradually increases during its lifetime, an active load balancing and cooling scheme can achieve initial savings of 45% to about 12% after 10 years of operation, compared to a traditional baseline design without active control [25].

D. *The Role of Legislation*

The strong growth of datacom energy usage has placed energy efficiency at the top of the agenda for both the IT industry as well as legislators, albeit for different reasons. Policy makers can influence the future energy consumption of data centers through the total cost of ownership balance, by enforcing regulatory actions (restrictions, penalties or taxation) or by promoting the development and introduction of new technologies.

Regulatory measures dealing with datacom energy usage are under consideration worldwide. In Japan, the Ministry of Economy, Trade and Industry (METI) is enforcing measures to limit the growth of the fractional energy usage of data centers to below the projected 25% of the total national usage by 2025. In the USA, the Environmental Protection Agency (EPA) and the Department of Energy (DOE) are administering the Energy Star and Save Energy Now schemes. In Europe, the European Commission issued a code of conduct for data center operation [26] via the Joint Research Center (JRC). Although the code is not mandatory yet, it is being adhered to by most major European

IT companies.

In terms of promoting development, the European Commission allocates over €9 billion via the 7th Framework Programme for Research and Technological Development (FP7) towards research and development in ICT technology from 2007 until 2013. This policy is confirmed by a recent report from OECD [27]. For instance, the IBM ‘zero emission’ data center at ETH Zürich received funding from the Swiss government (via KTI) and the European Commission via FP7 [22],[23].

E. The Role of Thermal Management

Cooling and other auxiliary equipment take up about 50% of the total energy consumption of a data center [3], of which thermal management is the main contributor at about 33% of the total consumption. Thermal management should therefore be fully incorporated into energy management. This reinforces the role of thermal design on a higher level, not simply to cool silicon chips but to achieve maximal system efficiency and sustainability. This is exemplified by the introduction of separate microprocessor boards for advanced thermal and power management in high-end server racks [28]. Thermal management is no longer an afterthought for system designers, and liquid cooling could become an enabling technology for waste heat recovery, although some challenges for practical implementation need to be addressed (see Sect. IV.B).

III. IMMEDIATE AND FUTURE THERMAL CHALLENGES

This section reviews the main challenges contributing to the thermal bottleneck in data centers and telecommunication systems. The basic requirement of the cooling system is to ensure efficient and reliable operation of the electronics. However this is no trivial assignment, and requires the system to handle unpredictable boundary conditions on either end: (i) non-uniform, time-varying chip dissipation, and (ii) climate-dependent fluctuating ambient environment.

A. Technological Challenges: Component Level

1) Thermal Effects on Transistor Operation

The power dissipation of a transistor can be decomposed into dynamic power dissipation (depending on the switching frequency) and a static contribution due to leakage. For a typical CMOS transistor operated at normal temperatures (below 100 °C), the total leakage current is the sum of sub-threshold leakage and gate oxide leakage

[29],[30]. The static power scales roughly with V_{DD}^3 while the dynamic power scales fV_{DD}^2 , where V_{DD} and f are the operating voltage and frequency, respectively. The leakage effect has increased with every step in CMOS fabrication technology towards smaller features. For 45 nm down to 28 nm technology, leakage amounts to 40% to 50% of the total power dissipation [31],[32].

The main temperature dependence is due to the sub-threshold leakage current which increases by about 10 %/°C. Nevertheless, the temperature sensitivity of the total power has remained relatively unchanged (between 0.5 and 2 %/°C) [29]. The International Technology Roadmap for Semiconductors (ITRS) identifies the increasing leakage power dissipation as the main issue threatening the survival of CMOS technology beyond 2024 [33].

Until recently, the operating frequency used to be inversely proportional to the square root of the absolute temperature; however, for the current fabrication technology this dependence has reduced and may even start to invert. This is mainly due to the reduction in threshold voltage with increasing temperature. Along with the increase in wire delays and resistance and reduction in electron mobility, this results in a mixed temperature effect [19]. As such, more efficient cooling leads to gains in reduced leakage current, but not to gains in frequency.

According to the latest projections by the ITRS, the chip power dissipation continues to rise, albeit at a decreased rate [33],[34]. At the same time, the trend towards denser packaging and further integration of liquid cooling in datacom racks continues. As such, the power dissipation per rack will continue to grow in the coming years, until the marginal cost of increased power density outweighs the marginal savings in floor space in the TCO balance [14].

2) *Spatial and Temporal Variations in Heat Load*

Regardless of the actual overall power dissipation, the non-uniform and time-varying nature of the heat load is certainly a key challenge in maintaining the junction temperature within its safe and efficient operating limits. Spatially non-uniform heat loads are currently mitigated using effective heat spreading. However more advanced methods are being investigated, such as variable geometry micro-structured liquid flow heat sinks [35]-[37] or chip-integrated arrays of thermoelectric coolers [38]. Compared to single-phase liquid cooled heat sinks with parallel microchannels or other regular microstructures, these methods can mitigate the inherent asymmetry induced by the streamwise increase in coolant temperature and reduce the effect of local hotspots corresponding to regions of high power dissipation on the die. Some studies [35],[36] have shown that thermal gradients can be minimized using geometrical optimization, however the increased cost of such devices also needs to be accounted for.

The transient thermal response of a component to time-varying heat loads is attenuated by the effective heat

capacity of its packaging, including the effect of mounting. While adding mass to increase the heat capacity is typically undesirable, the specific capacity can be increased using a phase-change material (PCM) [39]. Furthermore, active techniques are being investigated which control the computational load distribution [40] or control the local cooling rate [41],[42]. These can be implemented on the chip and/or rack level, and assume that the relationship between computational tasks and their associated heat dissipation is known. Using methods of controlling the local cooling rate (either on the chip itself [41],[42] or in sections of the rack or data center), supervisory thermal control strategies can be used to minimize energy consumption and safeguard thermal operating conditions [40]. More research is needed to develop cost effective methods for on-chip adaptive cooling.

These issues will gain in importance with the introduction of 3D chip architectures. Thermal management of such a closely packed interconnected stack of dies is an extremely difficult problem, involving multi-dimensional heat extraction [19]. An intimate coupling between thermal and electronic design is required, and chip-level liquid cooling could be the enabling technology.

B. Technological Challenges: System Level

1) Multiple Heat Transfer Interfaces

The multi-scale nature of electronics cooling from chip to ambient results in the presence of multiple heat transfer interfaces and cycles. To achieve overall gains in energy efficiency, efforts should be made to eliminate intermediate interfaces wherever possible. A possible approach is to integrate direct refrigeration cooling cycles into individual racks, although the feasibility of this approach should be investigated on a case-specific basis. Different techniques and cooling fluids (air, water, refrigerants and others) exist; yet no single coolant or technique can cover the entire cooling cascade from chip to ambient for current datacom equipment.

An analogous optimization problem is being worked on for electrical power distribution, to most efficiently and reliably supply the chips with a stable low DC voltage from the high-voltage AC grid. To increase energy efficiency, the industry is awaiting standardization regarding high-voltage DC conversion to minimize the number of intermediate power transformations [21].

2) Standardization for IT Cooling Equipment

Standardization for cooling IT equipment used to be prescribed by internal guidelines within each company. This role is now taken over by external bodies. For instance, the American Society of Heating, Refrigerating and Air-

Conditioning Engineers (ASHRAE) sets cooling equipment standards based on the recommendations of a committee composed of representatives of major equipment manufacturers [43]. This approach offers the opportunity for promoting industry-wide energy savings, as exemplified by the widening of the operating inlet temperature envelope for IT equipment from 20–25 °C in 2004 to 18–27 °C in 2008.

3) *Acoustic Noise Emission*

With increasing cooling demands, the operation of traditional air-cooled racks is hitting an acoustic noise constraint mainly due to severe fan loads. Quality and safety standards for noise regulation are enforced throughout the industrialized world, for example in the U.S. by the Department of Labor via the Occupational Health and Safety Administration (OHS) [44]. However, the acceptable thresholds in datacom practice are below the values prescribed in the standards, mainly to avoid the additional cost of various overhead expenses related to monitoring, training, handling complaints, etc. Equipment manufacturers do not always recognize or address these actual constraints, and more attention is needed on *a priori* noise-mitigating designs rather than *a posteriori* problem solving.

The concern over acoustic noise emission has grown since the operating envelope for datacom equipment has been widened by recent ASHRAE standards [43], since higher room temperatures usually require higher fan speeds. As a rule of thumb, the energy consumption of an axial or centrifugal fan increases with the third power of rotational speed, however its acoustic noise emission increases with the fifth power [45].

Besides noise emission, air blowers and fans are causing concerns in terms of reliability and energy consumption. On the reliability front, rack-mounted fan impellers require synchronization to avoid damaging disk drives due to coupled vibration induced by fan beat noise. To reduce fan-related energy consumption, liquid cooling or enhanced local air cooling techniques can be considered. In case of parallel board arrangements, piezo-electrically actuated synthetic jets are reliable, energy-efficient and offer high local cooling rates [46],[47]. Using fluidic interaction between these jets, a cross-flow may be induced without the need for fans [48].

The issue of acoustic noise emission is a general problem not only for datacom systems, but for electronics cooling at large. The push to avoid fan-induced noise could trigger a further penetration of liquid cooling in various consumer electronics such as laptops. A logical transition is via hybrid cooling techniques using liquid cooling on a few high-power components in combination with residual air cooling.

C. Reliability of Modeling

Designing a datacom cooling system usually involves some degree of numerical modeling and simulation of complex flow dynamics. The wide range of length scales in data center cooling combined with stringent time constraints of an industrial design process makes it difficult to use the most accurate simulation techniques (e.g., direct numerical simulation, or large-eddy simulation). Less accurate (Reynolds-averaged Navier-Stokes) approaches ensure a faster design cycle, however these simulations should be supplemented with careful validation experiments [49].

All simulation techniques require expert knowledge in modeling, validating and interpreting the results. This is certainly true for computational fluid dynamics (CFD), but equally important in obtaining and interpreting experimental results. In fact, it is important to establish the validity of both models and experiments. In typical industrial practice, model validation receives only limited attention. Most issues arise due to poor meshing, and well-known validation techniques such as a grid sensitivity analysis are often completely or partially omitted due to time and resource constraints [49]. A common approach is to compare the simulation results of a detailed model and a simplified model which takes about an hour to run, with an acceptable accuracy level of about 85%. Whereas a complete grid sensitivity analysis would require several simulations at incremental grid refinements, the former approach is usually the best possible compromise within the given time constraints. While attempts are made to standardize the operating conditions for equipment, there is no standardized approach for modeling and validation, as well as representation and communication of these results to customers.

Convective air cooling design using CFD is particularly challenging, because of the strong nonlinear nature of the fluid dynamics equations. Airflow patterns are very sensitive to minor changes; for example, a clogged filter can cause flow redistribution within a system, significantly altering local flow velocities around a critical component which may lead to an unexpected failure. Commercial CFD software packages currently have several shortcomings, such as the lack of reliable models for two-phase flow. Actual boundary conditions are also difficult to model accurately since they are inevitably more complex than constant flux or constant temperature conditions.

Full-field flow diagnostics tools for experimental validation such as particle image velocimetry (PIV) are expensive and require expert operators. As such these are usually restricted to large academic or industrial research and development groups. However there is a trend towards using locally mounted airflow sensors near critical

components which can provide more direct feedback than temperature sensors.

D. Modularity

Datacom cooling system design is subject to various degrees of location-dependent constraints (building architecture, existing infrastructure, etc). Especially when an existing system is being upgraded, problems may arise related to the use of raised floors for cool air distribution, or restricted over-cabinet space due to the presence of cable racks installed for earthquake safety, for example. These constraints often prove difficult to overcome using traditional computer room air conditioning (CRAC) systems.

Hybrid liquid cooling techniques such as rear door heat exchangers (RDHx) promote modularity, by partially decoupling the rack cooling performance from the room air conditioning and flow patterns [50]. A well-designed RDHx can absorb 80% of the total power dissipated in a rack (at 60 kW per rack) [50]. It can even eliminate the need for further air conditioning by absorbing the entire power dissipation in a 35 kW rack unit [51]. Local liquid cooling enables a modular ‘pay as you go’ cooling system design strategy, whereby the initial investment cost is reduced since the cooling system can be designed to fit only the initial heat load without accounting for future load increases.

The introduction of reliable and standardized thermal and/or fluidic connectors would further benefit modularity, facilitating equipment upgrades and retrofitting of existing datacom centers (see Sect. IV.B.2).

E. Multidisciplinary Design

Various disciplines are involved in the overall design of datacom systems, and combine electronic, thermo-mechanical, thermal, electrical, electromagnetic, mechanical, material, chemical and other aspects. Computer-aided design in these fields often takes a very different approach, for instance the use of finite volume codes for solving conservation equations (e.g., fluid dynamics) versus finite element codes for solving non-conserving equations (e.g., structural mechanics). Further integrated design requires methods for interfacing these approaches [49].

A partial transition to liquid cooling enables denser packaging for minimal floor space usage. However, this evolution also increases the rack mass density beyond 2000 kg/rack [28],[52], which requires additional mechanical and vibration analysis. In particular, thermal designers should strive for a close coupling with packaging and electronics designers, especially regarding the challenges of 3D chip integration. There is a need for better communication and understanding between thermal and electrical engineers, as well as between component and

equipment manufacturers and end users.

IV. OVERCOMING THE CHALLENGES TO IMPLEMENTATION OF COOLING SOLUTIONS

This section reviews the main challenges that should be addressed for advanced cooling solutions to be implemented. A particular focus is on a widespread introduction of liquid cooling (Sect. IV.B), due to its potential for improving the sustainability of data centers.

A. *General Cooling System Design Challenges*

Electronics cooling is by nature a multi-scale problem, covering a wide range of length scales and heat flux levels from chip to ambient. As such, a wide palette of heat transfer approaches is available and it is important to evaluate a variety of solutions [53]:

- Interfaces: improved contact conductance and heat spreading [54], novel high-conductivity materials and embedded thermoelectric elements.
- Liquid cooling: both passive (e.g., optimized transport in metal foams wicks [55] and miniature heat pipes [56]) and active approaches (e.g., electro-hydrodynamic liquid flow actuation [57] and two-phase boiling in microchannels [58],[59]).
- Enhanced heat rejection to ambient air (e.g., ion-driven flows [60], piezoelectric fans [61] and synthetic jets [46]-[48]).
- Micro- and nano-scale sensing and control (e.g., electro-actuated droplet cooling [41],[62], micro-scale temperature measurements using laser-induced fluorescence [63], infrared micro-particle image velocimetry in a silicon microchannel heat sink [64], high dynamic range particle image velocimetry [65]).

Liquid cooling will likely not take over the entire market, but can give huge benefits by improving silicon performance and enabling energy-efficient operation when appropriately matched to application. Different coolants exist (e.g. air, water, refrigerants and dielectric fluids), but no single coolant is ideal for all applications. A hybrid approach is often the most appropriate.

B. *Implementing Liquid Cooling*

1) *Perception Problems and an Ingrained Preference for Air Cooling*

As recently as a decade ago, the widespread use of direct liquid cooling of electronic components seemed an

exotic idea, even as liquid-containing heat pipes and vapor chambers were finding widespread use in the industry. The successful market penetration of these passive devices with a small amount of encapsulated liquid is paving the way for the introduction of more complex circulation loops, capable of transporting heat over larger distances. Increasingly, a liquid cooling system where the fluid is entirely contained in a reliable manner does not suffer from the same perception as a few years ago. Liquid cold plates are now widely used at the board and rack levels.

Although the basic technology for forced liquid cooling (direct or even indirect) is available, its development has still been largely restricted to research laboratories and select high-end products. It is clear that the electronics industry will continue to prefer air cooling methods until acoustic noise considerations no longer allow for their use. Strategies for reducing the operating power so as to reduce the heat dissipation are also widely practiced, so that the life of air cooling approaches may be extended.

2) *Technology*

a) *Effect on System Performance*

Academic research is typically focused on the development and optimization of specific cooling techniques such as liquid cooled microchannels, two-phase flow and spray cooling. However, the performance of such cooling solutions when embedded in overall systems is often overlooked, linked to proprietary system architectures, and specific to individual systems, making it difficult to investigate in generic terms. Examples include the effect of system performance of secondary heat exchangers, condensers and even the connecting tubing [66].

b) *Thermal Interconnects: Fluidic*

A key challenge in the implementation of liquid cooling at the board level is the need for standard fluidic interfaces, both for permanent connections and quick disconnects. Standardization of thermal interconnects should be comparable to that available for rack geometries and electrical connectors. While reliable small-scale fluidic connectors are not widely available, it is important for the industry to establish a standard rack-to-room thermal-fluidic connector as well as a chassis-to-rack port interface. This would significantly decrease the threshold for the introduction of liquid cooling, while at the same time promoting modularity of the data center design.

c) *Thermal Interconnects: Solid State*

The risk of leakage from connectors is a major obstacle to the introduction of liquid cooling. As such, a conduction-based solid-state thermal connection could provide a desirable solution. The analogy in the electrical

domain would be the use of electro-magnetic coupling instead of electrical current. Such solid-state devices are currently under development, using internal heat pipes to conduct the heat toward an interface consisting of detachable mating surfaces. Internal channels in the thermal socket can circulate chilled water or refrigerant [67].

d) Choice of Liquid Coolant

Existing liquid cooling systems use a wide range of coolants, from water and aqueous solutions to various dielectric liquids and refrigerants. The main design choice is between the dielectric properties of refrigerants and custom-developed fluids (e.g., 3M Fluorinert™ and Novec™ series, or mixtures thereof [68]) on the one hand, and the superior thermal properties of water on the other. This choice is strongly linked to reliability demands (see Sect. IV.B.3). Due to the electrical risk in the event of liquid leakage, system integrators and equipment manufacturers may prefer to use chilled water cooling only for their own internal data centers, while dielectric fluids may be preferred for data centers marketed for external customers.

Other case-specific considerations influence the choice of coolant, especially in extreme environments as found in military and aerospace applications. These include environmental operating conditions (e.g., exposure to freezing temperatures), supply chain constraints (e.g., the use of polyalphaolefin in military aviation), and health and safety issues (e.g., evolution from ethylene glycol water solutions to propylene glycol water solutions [69]).

e) Two-phase Liquid Cooling

Two-phase liquid cooling offers the possibility of achieving very high heat transfer rates while intrinsically minimizing temperature gradients in the electronic components being cooled. Two-phase cooling for thermal management of electronics is still in its infancy, and is currently limited to enclosed applications like vapor chamber or heat pipe spreaders, or specialized applications that encounter extremely high heat fluxes. Although significant progress has recently been made to identify boiling regimes in two-phase microchannel flow [58], no reliable and widely accepted correlations are as yet available. Commercial CFD codes also do not contain the physics of boiling and two-phase flow to the requisite level of detail. Some crucial challenges remain to be addressed before the technique can reach sufficient maturity for widespread industrial application:

- Achievement of well-controlled bubble nucleation in terms of predictable bubble departure frequency and size.
- Optimization of surface treatment for better surface wetting to reduce superheat temperature.
- Pressure drop reduction for flow boiling in microchannels.

- Improved prediction and mitigation of two-phase flow instabilities.
- Development of reliable models and correlations for incorporation into commercial CFD software.

3) *Reliability and Serviceability*

The reluctance to adopt liquid cooling is largely due to the inherent risk of leaks. Since reliability and serviceability are determining factors in decision making, the issue of leaks should be adequately and systematically addressed by means of strategies such as the standardized fluidic thermal interconnects discussed above.

In the event of a leak of liquid coolant, minor and major disruptions may be distinguished depending on whether the cooling performance is immediately affected. The more typical occurrence is a minor leak (e.g., a pinhole in tubing or a leaking connector), which does not cause an immediate loss of cooling performance. A risk of electrical damage in such circumstances exists only for conductive fluids like water. Refrigerants have good dielectric properties and also typically a high vapor pressure, resulting in rapid vaporization of the leaking fluid.

As discussed above, the choice of coolant largely depends on the required level of serviceability, which may be less strict for in-house data centers. Nevertheless given the superior thermal properties of water, a solid-state thermal connector [66] could prove to be a key enabler for the use of water as coolant.

Depending on the service level agreement and following a cost-benefit analysis, backup power for the cooling system is provided typically in the form of electrical backup power. While thermal storage is a potential solution in the event of power interruptions, it is currently not widely implemented.

Within the context of serviceability, a transition from a purchase-dominated to a lease-dominated datacom industry could evolve where customers outsource datacom services to well-equipped providers. This evolution could enable a wider application of less serviceable cooling technologies.

C. Implementing Alternative Cooling Techniques

Apart from liquid cooling, research and development in some other techniques is ongoing. In some cases these can provide cost-effective and robust alternatives to liquid cooling. However most approaches are complementary and can be jointly applied in a hybrid cooling solution. This section lists some of their implementation challenges.

1) *Enhanced Heat Spreading*

a) *High-conductivity Materials*

In a typical electronics cooling configuration, contact resistance between a package and its heat sink is one of the

main contributors to the overall thermal resistance. Because of the contradictory demands involved (high thermal conductivity, high geometric compliance, low clamping pressure, long-term stability), development of thermal interface materials (TIMs) remains an active research area. Particular attention has been devoted to developing TIMs based on carbon nanotubes (CNT) because of their superior thermal conductivity. A key challenge is to produce consistent geometries of free-standing and dense nanotube arrays, while achieving good bonding to mating surfaces [70].

Most high-conductivity candidate materials including thermal pyrolytic graphite (TPG) and CNTs have strongly anisotropic conductivity (typical conductivity ratio of 100:1) which can act as an advantage in achieving directional heat extraction. Inferior mechanical properties can be addressed by embedding these materials into composites.

b) Two-phase Heat Spreading

Although heat pipes and vapor chambers are widely used, further research into the fundamentals of boiling and transport in wick structures is needed. Boiling heat transfer characteristics of wicks can be improved by the use of micro- and nano-scale structuring that leads to a decrease in the surface superheat and an increase in the critical heat flux. Nanofluids may also offer a solution: while the thermophysical properties of water are not adversely affected by adding small quantities of nano-particles (up to 1 g/l Al₂O₃) [71], a nano-particle coating may be deposited onto a smooth heater surface [72] during boiling. Due to enhanced wetting and increased surface area, optimized coatings can achieve a 100% increase in critical heat flux when boiling in pure water.

2) Thermoelectrics

The development of thermoelectric materials remains an active research area, characterized by incremental improvements in the thermoelectric figure of merit $ZT (= S^2 \sigma T / k$, where S , σ , T and k are the Seebeck coefficient, electrical conductivity, absolute temperature and thermal conductivity, respectively) [73]. Unless their performance is improved significantly, thermoelectric devices are typically not suited to handle the entire heat load. However, they can be used to actively mitigate hot spots on non-uniformly heated components [38],[74]. Hot spots only account for a small fraction of the total dissipated heat; yet, they are the main driver for cooling design as they are most responsible for deterioration in reliability. Local active cooling using integrated thermoelectric elements could therefore help to address the reliability challenge of electronics cooling, in light of the evolution towards 3D chip architectures. Thermoelectric modules remain useful for niche applications, such as temperature control for

stabilizing the emitted color of light emitting diodes (LEDs). The key challenges are the advancement in materials research, as well as the development of reliable models for thermoelectric modules as part of the overall cooling system [75].

3) *Advanced Air Cooling*

Forced air convection is currently challenged by constraints on power consumption (Sect. II and III.B), acoustic noise emission (Sect. III.B.3), and reliability. Some alternative air cooling techniques could be used to reduce the fan load thereby lowering energy cost and noise emission. These techniques typically increase the heat transfer coefficient by promoting local turbulence and mixing, close to the heat source. Examples include piezo-electrically actuated vibrating cantilevers [61] or synthetic jets [46]-[47]. Both approaches combine high local cooling rates for targeting hot spots while being energy-efficient and reliable. Arrays of synthetic jets enable active fluidic control which can eliminate the need for cross-flow fans [48]. A key challenge for synthetic jets is noise suppression although a better understanding of the fluid dynamics and heat transfer fundamentals is also necessary to optimize their performance.

V. CONCLUSION AND OUTLOOK ON FUTURE THERMAL CHALLENGES

As the demand for IT and networking expands rapidly and chip fabrication technology evolves towards further miniaturization and integration of functionality, thermal designers for datacom systems face significant challenges. The reduction of energy consumption in datacom systems (of which 33% is currently attributed to cooling) is increasingly becoming a top priority for IT businesses and policy makers. Techniques to reduce energy consumption and promote waste heat recovery will quickly gain in importance, and liquid cooling offers some particular advantages in both areas.

The core business of a datacom system is the operation of a large number of small electronic devices in the most efficient and reliable manner. Minimizing the total cost of ownership (TCO) continues to be the underlying driving force behind cooling system design. Yet through their impact on the TCO balance, the cost of energy as well as the growing demand for sustainable products is already influencing datacom design and marketing. As such, the design and operation should be led by a holistic view, incorporating energy-based metrics such as the computational performance per unit energy consumption.

In terms of cooling techniques, liquid cooling will likely not take over the entire market, but it does offer

significant benefits in terms of improving chip performance, enabling more compact design, as well as waste heat recovery. Different techniques and coolants (including air and various liquids) are available, but the appropriate choice of coolant is specific to each application and packaging level.

For the short term (next 5 to 10 years), research and development attention is focusing on liquid cooling as well as alternatives such as enhanced heat spreading and thermal conductance, active hot spot cooling, and advanced convective air cooling. These efforts are complementary, and hybrid cooling solutions combining several techniques are likely to be the optimal approach. The evolution towards 3D chip architectures will significantly increase the level of complexity, requiring a combination of advanced heat spreading, on-chip liquid cooling and active sensing and control.

Regarding liquid cooling, the superior thermal properties of water are driving the introduction of water cooling at the processor level. Dielectric liquids still have the advantage in terms of reliability and the possibility of direct contact cooling. However, innovative thermal interconnects could tip the balance in favor of water cooling. Serviceability is an important obstacle to the introduction of liquid cooling. This problem could be addressed by the development of solid-state thermal connectors. A possible evolution from a purchase-dominated to a lease-dominated datacom industry could promote the introduction of less readily serviceable technologies such as direct water cooling.

A recurring theme in discussions of thermal challenges in this industry, and a challenge for future thermal design, is the need for multi-level standardization: (i) standardized thermal interconnects for liquid cooling (Sect. IV.B.2), (ii) a standardized approach to modeling, validation and reporting (Sect. III.C), and (iii) standardized performance metrics that account for energy efficiency and sustainability (Sect. II.B).

For the longer term (beyond 2020), it remains to be seen which transistor technology will succeed CMOS, and what the particular thermal constraints for this technology will be. However, from the current perspective of a heavily constrained design process, a closer coupling between the relevant disciplines is crucial to overcoming present and future challenges.

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