AN OVERVIEW OF ADVANCED ELECTRONICS COOLING
Emphasis on Liquid Metals Solutions

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Abstract: *The paper presents the problems faced by the electronics industry due to increased heat fluxes generated by the electronic components. The modern cooling techniques must employ not only different methods for natural and forced convection, but also novel materials and technologies. The present trends and technologies are mentioned and future trends are suggested.*

Key words: *electronics cooling, heat transfer, convection, liquid metals.*

1. Introduction

Electronic devices' cooling has become a major challenge in last decades due to the advancements in the design of electronic components that are faster and smaller. In the same time the amount of heat that has to be dissipated has increased as well. The thermal analysis of modern PCs shows that CPUs and graphics processors can scale into temperatures that, to the touch, might as well be similar to a nuclear reactor. A number of different cooling technologies have been developed to efficiently remove the heat from these components.

Research has been conducted first in the area of new dissipative materials, then was oriented towards design and optimization of forced air cooled heat sinks, and finally liquid cooling (including here heat pipes as well) came into focus, along with some methods related to solid state and micro-scale devices.

The high heat rates attained in liquid cooling as compared to air-cooled devices, made the first ones very attractive due to higher heat transfer coefficients achieved. Moreover, for phase-change applications, the heat transfer coefficient (Fig. 1, [3]) is larger by at least one order of magnitude.

The present paper brings into discussion aspects related to the use of several cooling methods, with the pros and cons of liquid cooling. The emphasis is placed on the solutions involving liquid metal coolants

2. Trends in Electronics Cooling

This chapter reviews the present cooling techniques, as well as the trends for future advanced cooling solutions for electronic components.

Conduction and Heat Spreading

Heat must travel, via thermal conduction, from electronic components to the surfaces and then is rejected to coolant by forced or natural convection. In classic packaging solution, heat is conducted through chip and heat sink, and then rejected to coolant.

The present market of thermal interface materials offers a large variety and proper selection requires consideration of induced stress, reparability, contact pressure and flatness, as well as thermal considerations.

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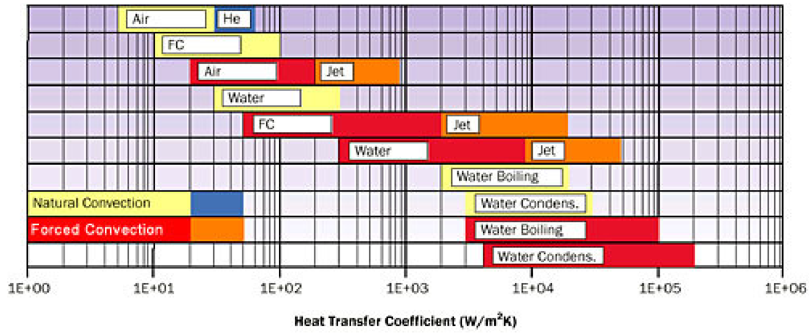

Fig. 2. *Heat transfer coefficients for various cooling technologies, [1]*

Solid-State Cooling

A thermoelectric cooler, based on Peltier effect, is a small electronic heat pump that has the advantage of no moving parts and silent operation. Thermoelectric cooling enables cooling at temperatures below ambient. The coolers operate on direct current and may be used for heating or cooling by reversing the direction of current flow.

Heat Sinks

The heat sink with an integrated fan hit the market in the mid-1990s. Materials used in heat sinks to increase the thermal conductance of components are copper and graphite for bases and fins, and aluminum without or with copper insets for bases. To increase the fin area exposed to the airflow more fins are added, or if space is limited, different fin shapes or bonding methods are used.

Although the recent years witnessed an unparalleled ingenuity in producing cost-effective heat sinks with increased thermal performance, for high power applications air-cooling is no longer an alternative and other fluids are employed. With standard fans a maximum heat transfer coefficient of about 150 W/m^2K can be reached with acceptable noise levels. Using "macro-jet" impingement, theoretically we may reach 900 W/m^2K, but the noise levels are unacceptable. To overcome these issues, piezo-fans and "synthetic" jet cooling were developed. Piezo-electric fans are low power, relatively low noise and solid-state devices with piezo-ceramic patches bonded on thin, low frequency, flexible blades to drive the fan at its resonance frequency. The synthetic jets entrain cool air from ambient, impinge on the top hot surface and circulate the heated air back to the ambient through the edges of the plate.

Fans

Fans were developed at the same rate and subject to the same cost restrictions and form factor demands as heat sinks. For laptop computers miniature fans are now being used. To increase thermal performance of a heat sink, the amount of fluid pushed through by the fan has to go up. On the other hand, dimensions, noise and power consumption have to go down.

Axial fans and radial fans remain the most often used solutions. Axial fans find their applicability where high flow rates and low pressure heads are required, while radial fans are used in high pressure applications, as in air cooling of high-power devices. An intermediate solution is represented by mixed-flow fans, where air is drawn axially in impeller and exhausted diagonally. As a result, mixed-flow fan can generate a higher pressure for the same overall dimensions and speed than an axial fan, with application in large scale servers.

Liquid Cooling

Liquid cooling for electronics application is generally divided into two categories, of indirect (heat pipes and cold plates) and direct liquid cooling (immersion cooling and jet impingement), detailed in the subsections below.

Heat Pipes

Heat pipes represent an indirect, passive liquid cooling application. They are sealed and vacuum pumped vessels, partially filled with working fluid.

When heat is applied to one end of heat pipe the liquid starts evaporating. Thus a pressure gradient occurs causing the vapor to flow to cooler regions. Vapor condenses at the cooler end, and is transported back by wick structure, closing the loop.

Heat pipes provide an enhanced mean of transporting heat from a source to a heat sink (Fig. 2), where it will be rejected to environment. Thermal performance of heat pipes may range from 10 W/cm^2 to over 300 W/cm^2.

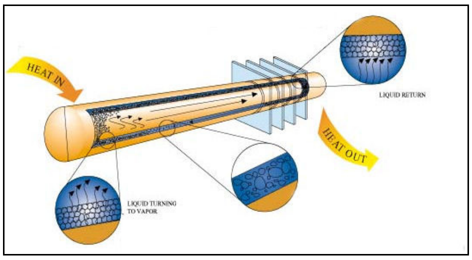

Fig. 2. *Heat pipe loop setup*

Heat pipes are used now in combination with heat sinks or embedded in a loop (a setup where liquid and vapor do not move opposite each other but rather travel in a loop), capable of larger heat fluxes with less sensitivity to gravity.

Thermal design engineer has the choice of configuration, fluid, wicking structure, housing material for a configuration that meets the cooling requirements at a reasonable cost.

Liquid Metal Cooling

A special area in electronics liquid cooling of is liquid metal cooling. Apart from heat pipes based on liquid metals, mainly for the high-temperature range, an increasing amount of research is devoted to Ga-Sn-In eutectics that remain liquid down to -19°C. This solution combines the high heat capacity of liquid metals with reduced pumping requirements; the reduced value of thermal expansion coefficient is also a plus. Because liquid metals exhibit high-heat absorption capability, a low inventory of working fluid is then required. On the down side, there is the inherent fear of dealing with such potentially dangerous materials, as well as technical difficulties related to the cold-side heat exchanger.

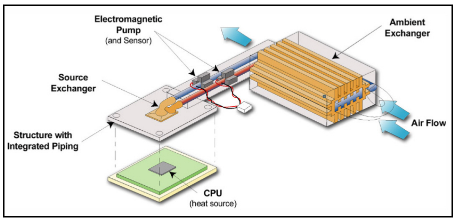

Fig. 3. *Liquid metal loop setup*

High-performance liquid metal cooling loops use magneto-fluid-dynamic pumps and two heat exchangers (Fig. 3), the hot-side (source) and cold-side (ambient). As presented in literature, large heat fluxes are removed from the source, but the same amount has to be removed from the working fluid towards the ambient at the other end. That is, the loop partially solves the cooling problem by moving the heat from one location to another. The ambient exchanger has to have high cooling capabilities as well in order to supply cold working fluid towards the source. Thus, the system requires high-performance heat exchanger at ambient. This adds to the costs for safety equipment, resulting a relatively large overall cost.

Immersion Cooling

A method for accommodating high heat fluxes is immersion cooling. An electronic device is submerged in a pool of dielectric liquid. Heat dissipated produces vapor bubbles that are driven by buoyancy forces into upper regions of the pool, where the vapor condenses and drips back into the liquid pool. The main disadvantage of this method is the need for a compatible liquid – device pair.

Jet Impingement and Spray Cooling

A new method of liquid cooling is using a direct jet impingement technique that deploys an array of tiny nozzles and a distributed return architecture. Research revealed that an array of tiny nozzles will perform better than a single large one. The spray cooling technique breaks the liquid into fine droplets that impinge individually on the heated wall. Surface cooling is achieved through a combination of thermal conduction through the liquid in contact with the surface and evaporation at liquid-vapor interface. Droplet impingement both enhances spatial uniformity of heat removal and delays liquid separation on the wall during vigorous boiling.

Micro and Mini-scale devices

The term 'micro' is applied to devices having hydraulic diameters in the range of micrometers [2], while 'mini' refers to diameters on the order of one to a few millimeters. Miniaturization provides high heat transfer coefficient [5], pressure drop for the coolant flow increases as well.

A reliable prediction of the heat transfer rates and pressure drops in micro-channels is not possible for design applications such as micro-scale heat sinks. It is not practical to etch the micro channels directly on the chip due to high cost of high-performance processor chips. Instead, a separate micro channel cold plate is bonded to the back of the chip. If the micro-cooler is based on silicon, a rigid bonding means that silver-filled epoxies or solder should be used.

When comparing jet impingement and micro-channel cooling for high heat flux applications, the latter is more effective for smaller surface areas. Micro-channels are easier to fabricate and implement, but the temperature non-uniformity is larger.

Phase Change Materials and Heat Accumulators

Phase change materials are successfully used as heat-storing materials, functional materials and many industrial applications. For electronics thermal management, the use is limited to applications where time-dependent phenomena are important.

Chemical heat accumulators are using composite materials based on granulated open-porous matrix filled with hygroscopic substance. The advantage is a significant increase in the heat that can be stored as compared to sensible heat and latent heat. The main advantage is the ability to store the accumulated energy for a long time, if the reaction is controlled by the presence of either a catalyst or a reagent. Chemical heat accumulators could potentially be used for outdoor electronic applications when a night-day rhythm is present.

3. Liquid Coolant Requirement

When choosing a certain cooling method thermal design engineer must select the proper cooling agent. The requirements for a liquid coolant for electronics applications may vary depending on specific conditions imposed for appropriate functioning:

- Good thermo-physical properties: high thermal conductivity and specific heat; low viscosity; high latent heat of evaporation for two-phase application;
- Low freezing point and burst point;
- High atmospheric boiling point (or low vapor pressure at operating temperature) for single phase system; a

narrow desired boiling point for a two-phase system;
- Good chemical and thermal stability for the life of the electronics system;
- Non-corrosive to structure materials;
- No or minimal regulatory constraints, i.e., environmentally friendly, nontoxic, and possibly biodegradable;
- Economical.

Electrical conductivity (not mentioned above) becomes important if there is direct contact between fluid and electronics, or if it leaks out of a cooling loop or is spilled during maintenance. Therefore, a dielectric coolant is a must for such cases.

As a conclusion, the best electronics coolant is an inexpensive and nontoxic liquid with excellent thermo-physical properties and a long service life. Good thermo-physical properties are required to obtain the high heat transfer coefficients and low pumping power needed for the fluid to flow through a tube or a channel.

The main liquid coolants types used in electronics cooling are [4]:

Synthetic hydrocarbons (i.e., aromatics) are common heating and cooling fluids used in a variety of applications. However, these compounds are toxic or with strong, irritating odors.

Silicate-ester was used as a dielectric coolant radar and missile systems.

Aliphatic hydrocarbons of paraffinic and iso-paraffinic type (including mineral oils) are used in a variety of direct cooling of electronics parts as well as in cooling transformers.

Silicone oil is a synthetic polymeric compound with thermo-physical properties (freezing point and viscosity) that can be adjusted by varying the chain length. Silicone fluids are used at temperatures as low as -100°C and as high as 400°C. However, low surface tension gives these fluids the tendency to leak.

Fluorocarbons have certain properties that can be used in contact with the electronics. Some of these fluids are non-toxic, with zero ozone depleting potential and low freezing points and low viscosities at low temperatures. However, these fluids are expensive, have low thermal properties and extremely low surface tension.

Ethylene and *Propylene Glycol* (EG, PG) are commonly used as antifreeze, but electronics cooling applications include low temperature process cooling.

Methanol/Water is a low cost antifreeze solution that can be used down to -40°C, with relatively high rate of heat transfer. Its main disadvantages as a heat transfer fluid are its toxicological considerations.

Liquid Metals of Ga-In-Sn chemistry have been used with magnetofluiddynamic (MFD) pump. It utilizes the high thermal conductivity and density of the metal alloy to remove very high heat flux from microprocessors.

4. Emphasis on Liquid Metal Cooling

To establish the rating of liquid metals amongst the other usual coolants from the electronics industry, some thermo-physical properties have to be analyzed: viscosity, density, specific heat, thermal conductivity and freezing point. In literature [1, 6] some criteria were developed for comparison:

- Mouromtseff number:

$$Mo = \frac{\rho^a \cdot k^b \cdot c_p^d}{\mu^e} \tag{1}$$

- Figure of Merit (for laminar flow):

$$FOM_L = \frac{k \cdot c_p}{\mu} \tag{2}$$

- Figure of Merit (for turbulent flow):

$$FOM_T = \frac{\rho^{0.05} \cdot k^{0.67} \cdot c_p^{1.33}}{\mu^{0.72}\,.} \tag{3}$$

In the above equations ρ, k, c_p, and μ are density, thermal conductivity, specific heat at constant pressure and dynamic viscosity of fluid. The exponents a, b, d, and e take values appropriate to heat transfer mode.

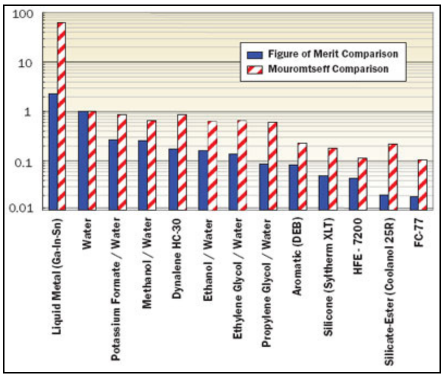

Fig. 4. *Laminar flow comparison*

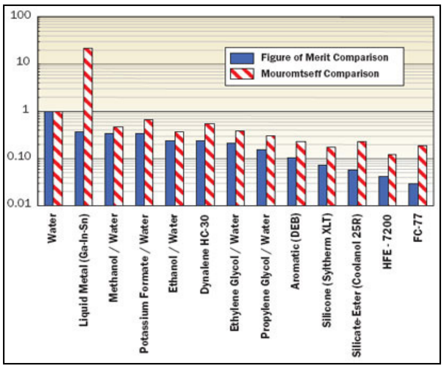

Fig. 5. *Turbulent flow comparison*

Liquid metal - water comparison Table 1

Property	Liquid Metal	Water
Density (kgm^{-3})	6363	998
Heat capacity ($Jkg^{-1}K^{-1}$)	365	4181
Kinematic Viscosity ν (m^2s^{-1})	3.5×10^{-7}	10^{-6}
Electrical Conductivity (Sm^{-1})	3.3×10^{6}	10^{-12}
Thermal Conductivity ($Wm^{-1}K^{-1}$) @20°C	39	0.61
Boiling Point (°C) at STP	>2000	100

5. Conclusions

The paper presents the modern cooling techniques employed for proper cooling of electronic devices with emphasis on liquid metal coolant. Fluids comparison based on single phase convective heat transfer and both caloric and hydraulic behavior show that liquid metals may have better transport properties over the other fluids.

The only fluid that comes close to liquid metals is water, Fig. 4, 5 and Table 1.

The liquid metal is an eutectic alloy, non-toxic and environmentally safe. It is highly conductive (65 times more than water) and boiling point above 2000°C, eliminates power density as limiting factor in cooling applications. It represents the true single phase cooling process.

However, liquid coolant selection cannot be based on FOM alone; factors such as materials compatibility, environmental and economic criteria must be considered, as industrial economics plays by many rules, not only strict engineering ones.

References

1. Ellsworth, M.J.: *Comparing Liquid Coolants from both a Thermal and Hydraulic Perspective.* In: *Electronics Cooling,* Vol. 12, No. 3, 2006, p. 15-18.
2. Garimella, S., Sobhan, C.: *Transport in Microchannels - A Critical Review.* In: *Ann. Rev. Heat Transfer*, Vol. 13, 2003, p. 1-50.
3. Lasance, C., Simons, R.: *Advances in High Performance Cooling for Electronics.* In: *Electronics Cooling*, Vol. 11, No. 4, 2005, p. 22-39.
4. Mohapatra, S.C.: *An Overview of Liquid Coolants for Electronics Cooling*, In: *Electronics Cooling,* Vol. 12, No. 2, 2006, p. 12-13.
5. Popescu, A., Welty, J.R., Pfund, D.M., Rector, D.: *Thermal Measurements in Rectangular Microchannels.* In: ASME Publication: *Theory and Fundamentals of Heat Transfer*, Heat Transfer Division, ASME – HTD, Vol. 372 (1), 2002, p. 277-284.
6. Simons, R.E.: *Comparing Heat Transfer Rates of Liquid Coolants Using the Mouromtseff Number.* In: *Electronics Cooling*, Vol. 12, No. 2, 2006, p. 35-39.