BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi,
Tomul LIX (LXIII), Fasc. 1, 2013
Secţia
CONSTRUCŢII DE MAŞINI

LIQUID METAL COOLING FOR MICROELECTRONICS

BY

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Received: June 5, 2012
Accepted for publication: September 3, 2012

Abstract. The paper presents some aspects related to usage of liquid metals and alloys as coolants for microelectronics. Micro-heat-sinks and liquid cooling become, again, potential options in electronics industry, due to their capacity of removing increased heat fluxes generated in electronic components. The authors' previous work in this area generated the basis for analysis of modern cooling techniques, and finalized in this overview of a less known technology, liquid metal cooling. The present trends and technologies are mentioned and future trends are suggested.

Key words: electronics cooling, heat transfer, liquid metal, micro-scale.

1. Introduction

The extreme miniaturization of components and ever-increasing chip integration density in the last few decades made possible an exponential growth of products based on microelectronic industry: PCs, laptops and notebooks, tablets and mobile phones. The trend established by Moore's Law in 1965 has continued for the last half a century, that is, the number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years. But currently, design engineers are facing a barrier, the "thermal barrier",

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as the electronic system capabilities are limited by over-heating, with unwanted results such as shortened life, malfunction, low reliability and failure of work.

The daunting task of thermal management engineers is to deal with two factors, high temperature and heat dissipation. Therefore, removal of the large amount of heat generated in microelectronic components represents a challenging issue in electronics thermal packaging.

Following the work presented in previous papers by the authors, here are presented significant facts and new ideas in microelectronics cooling using liquid coolants, among which liquid metals and liquid metals alloys are more desirable due to their characteristics and technical packaging solutions.

2. Thermal Packaging Management

The air-cooled heat sink solution is increasingly failing in meeting the demands of removing high heat fluxes emerging from electronic systems. To even come close to the challenges, the air cooled heat sink solution involves expensive novel materials and unacceptably large package volumes.

Heat sinks are available in just about any shape and size to suit nearly every application. With the trend of shrinking package size and increasing heat dissipation, technologies involved different materials (from refined copper and aluminum to graphite and silver-diamond composites) or technologies (power-fans or macro-jet impingement cooling) (Mohapatra, 2005).

Given the limited options exhibited by air cooling, various liquid cooling technologies emerged. As presented in a previous paper (Popescu, 2008), there are several solutions involving liquid coolants, divided into categories, passive or active, direct or indirect contact etc. Some of them are briefly described here.

Forced convective liquid cooling in microchannel heat sinks represents one of the most promising technologies that have been proposed for achieving very high heat removal rates. But regular applications require a sizeable external pump to drive the flow, due to large pressure drops involved. To overcome this, novel pumping strategies have been developed, such as ‘micropumps’ that offer significant advantages for electronics cooling applications, as they can be potentially integrated into the microstructures.

The heat pipe technology represent an indirect and passive liquid cooling application and is used in applications where space limitations are important, as laptops, high-powered electronics and spacecraft thermal controls. Heat pipes provide an enhanced method of transporting heat from the electronic component to a heat sink, where it will be removed from the package to the environment.

Liquid metal cooling solutions combines the coolant high heat absorption capacity with reduced pumping requirements; low inventory of working fluid and reduced value of thermal expansion coefficient are also a plus. On the down side, some of these coolants are potentially dangerous materials, as well as some technical difficulties related to the cold-side (ambient) heat exchanger.

Also, combinations of such methods are developed. A breakthrough high-dissipation substrate, Integrated Plated Circuit Heat Sink (IPCHS), incorporates an aluminum base with a filled anodized dielectric layer and plated patterned circuits. Some use nanotechnology to improve heat sink performance, which makes use of liquid and vapor layers that act as thermal interface materials between the heat sink and the fins. In the literature, are mentioned several types of heat spreaders, involving liquid coolants and liquid metals, as well.

Here, we only mention some other possibilities, namely jet impingement cooling, spray cooling, immersion cooling, phase-change materials and heat accumulators, use of nano-particles seeded coolants, ionic coolants etc.

3. Liquid Metal Cooling Characterization

The selection, from several coolants (both dielectric and non-dielectric), of the best coolant for a particular application requires a proper understanding of all characteristics and properties of these fluids.

Liquid metals represent a special class of coolants. Their basic advantage stems from a high molecular thermal conductivity which, for identical flow parameters, enhances heat transfer coefficients. Other distinguishing features of liquid metals are high melting point (except mercury and sodium-potassium), low electrical resistivity, and low pressure of their vapors, which allows their use in power engineering equipment.

The most widespread liquid metals used in engineering are alkali metals. Sodium is used as fast reactors coolant and a working fluid of high-temperature heat pipes. Potassium is a promising working medium for space power plants. In some cases eutectic Na−K and Pb−Bi alloys and Hg, Li, and Ga are also used. Recently, an increasing amount of research is devoted to the use of Ga-Sn-In eutectics that remain liquid down to -19°C. Basic information on liquid metals heat transfer was compiled by Kutateladze (1959). Detailed data on Na and Na-K alloy were given by Foust (1976) including chemistry, physical properties, heat transfer correlations and industrial applications. Other liquid metals handbooks were previously edited by Lyon (1952) and Jackson (1955).

The high thermal conductivity and, hence, low Prandtl numbers of liquid metals signify a fast thermal dissipation within the fluid by molecular thermal conduction even in a fully developed turbulent flow. This implies that the thickness of thermal boundary layer is substantially larger than the thickness of the hydrodynamic boundary layer. The hydrodynamic characteristics of liquid metal flows (friction factor and the coefficient of local resistance) are calculated by conventional formulas.

For single phase, forced convection is governed by two dimensionless parameters: the Reynolds number (Re) and Peclet number (Pe). The specificity of liquid metals is in the low value of Prandtl number, so Pe << Re. The forced convection heat transfer correlations for liquid metals depend on Peclet number, while for classical fluids (water, air) they depend on Reynolds number.

The heat transfer correlations for liquid metals in a heated tube have been reported by Foust (1976). For the case of uniform temperature at the wall

$$\mathrm{Nu} = 5 + 0.025\mathrm{Pe}^{0.8} \qquad (\mathrm{Pe} < 4 \cdot 10^3, \mathrm{Pr} = 0.004 - 0.04) \tag{1}$$

where, Nusselt number is Nu = hd/k and Pe = ud/α, in which k is heat transfer coefficient, d is tube diameter, k is thermal conductivity, u is fluid velocity and α is thermal diffusivity.

For the case a uniform heat flux at the wall,

$$\mathrm{Nu} = 7.5 + 0.005\mathrm{Pe} \qquad (300 \le \mathrm{Pe} \le 10^4) \tag{2}$$

An approximate calculation of mean heat transfer in the entrance region in the case of turbulent flow can be performed with Eqs. (1) and (2) by introducing a correction factor for this region

$$\varepsilon_e = 1.72(d / l)^{0.16} \tag{3}$$

where l is tube length. Typical length of thermal entrance region is 10 to 15d.

For tube bundles in longitudinal flow

$$\mathrm{Nu} = 6 + 0.006\mathrm{Pe} \qquad (30 \le \mathrm{Pe} \le 4 \cdot 10^3, \mathrm{Re} > 10^4) \tag{4}$$

and

$$\mathrm{Nu} = 2\mathrm{Pe}^{0.5} \qquad (50 \le \mathrm{Pe} \le 7 \cdot 10^3) \tag{5}$$

where Pe is calculated from the free-stream velocity and outside tube diameter. These relationships are valid for pitch-to-diameter ratios s/d = 1.2 − 1.75 and may also be used for staggered and in-line tube bundles in cross flow.

Natural convection is governed by two dimensionless parameters: Grashof number (Gr) and Boussinesq number (Bo), Bo = $(\mathrm{Gr})(\mathrm{Pr})^2$ = (Ra)(Pr).

Liquid metals are characterized by Bo << Ra << Gr. Natural convection heat transfer correlations of liquid metals depend on the Boussinesq number while for classical fluids, they depend on Rayleigh number.

The correlations for basic configuration of natural convection along a heated plate are presented by Sheriff (1979). For vertical plate with a uniform wall temperature, the local Nusselt number is:

$$\mathrm{Nu} = \left(0.57 \pm 0.03\right)\left(\mathrm{Gr_x} \cdot \mathrm{Pr}^2\right)^{0.25} \tag{6}$$

and for vertical plate with a uniform heat flux,

$$\mathrm{Nu} = 0.73\left(\mathrm{Gr_x} \cdot \mathrm{Pr}^2\right)^{0.2} \tag{7}$$

where $\mathrm{Gr_x} = \beta g x^3 \Delta T/\nu^2$, ν is viscosity, g is gravitational acceleration, ΔT is temperature difference between the surface and the fluid, β is coefficient of volumetric thermal expansion and x is the vertical distance along the plate.

The configurations of downward-facing plate, upward-facing plate and the influence of inclination have also been reported by Sheriff (1979).

Heat transfer by natural convection from a horizontal cylinder is

$$\mathrm{Nu} = \mathrm{C}\left[\mathrm{Gr} \cdot \mathrm{Pr}^2/\left(1 + \mathrm{Pr}\right)\right]^{\mathrm{n}} \tag{8}$$

where $\mathrm{Pr} = c_p\nu/k$, c_p is specific heat capacity, C = 0.67, n = 1/4 for Gr = 10^2–10^8, and C = 0.35, n = 1/3 for Gr > 10^8.

For a vertical cylinder of height H and radius r, the equation:

$$\mathrm{Nu} = 0.16\left[\mathrm{Ra_H}\frac{\mathrm{r}}{\mathrm{H}}\right]^{0.3}, \quad \left(\mathrm{Ra_H}\frac{\mathrm{r}}{\mathrm{H}}\right) = 1.6 \cdot 10^6 - 4 \cdot 10^7, \quad \frac{\mathrm{r}}{\mathrm{H}} = 0.39 - 1.5 \tag{9}$$

where $\mathrm{Nu_H} = hH/k$; $\mathrm{Ra_H} = \mathrm{Gr_H}\mathrm{Pr} = g\beta\Delta T H^3/\nu\alpha$.

It has been established that heat transfer in liquid metals depends, to a high degree, on fouling resistances at the wall-liquid interface. Special attention has to be given to chemical compatibility of the liquid metal coolant and the wall material, but also to the degree of metal purity.

“Metal-metal” heat exchangers used in electronics cooling with a bilateral flow of single-phase coolant are calculated by conventional relations. However, the design of such apparatus has to account for a high heating of the coolant due to relatively low specific heat of liquid metals.

High-performance liquid metal cooling loops take advantage of the “metallic” characteristic of the coolant and use magneto-hydro-dynamic pumps and two heat exchangers, the hot-side (source) and cold-side (ambient). Liquid metals are good electrical conductors, and they interact with electromagnetic fields so that various MHD applications are possible. Various applications of MHD in liquid metals have been developed in industrial processes: metallurgy, liquid metal cooled nuclear reactors, prototypes for fusion reactors, ship propulsion, and power conversion.

As presented in literature (Miner, 2004), large heat fluxes are removed from the source, but the problem is just moved to the cold-side heat exchanger, as the same amount has to be exchanged towards the ambient. That is, the loop partially solves the cooling problem by moving the heat from one location to another. Nevertheless, as coolants, liquid metals prove enhanced capabilities and emerge as the fluid of choice in many high-heat-flux removal applications. A discussion and comparison based on figure of merit and Mouromtseff number between various liquid coolants has been presented previously (Popescu, 2009).

6. Conclusions

The paper continues the work developed by authors in the area of microelectronics cooling technologies, presenting modern cooling techniques employed for high-heat-flux dissipation problems. Following the analysis of liquid coolants, the authors detail the theoretical information regarding usage of liquid metals in electronics cooling applications. The equations presented are useful for heat exchanger design and the thermal management engineer may have a base for developing an appropriate cooling strategy for each specific application, in the case they decide for a liquid metal cooling solution.

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RĂCIREA CU METALE LICHIDE A COMPONENTELOR MICROELECTRONICE

(Rezumat)

Lucrarea prezintă câteva aspecte legate de folosirea metalelor lichide şi a aliajelor acestora drept agent de răcire pentru componentele microelectronice, datorită capacităţii acestora de a înlătura fluxurile termice ridicate ce apar în aceste componente. Autorii continuă astfel munca depusă în perioada anterioară, în acest domeniu, finalizând cu acest studiu despre detaliile teoretice ale unei tehnologii mai puţin cunoscute, răcirea cu metale lichide.