THERMAL MANAGEMENT OF ELECTRONICS: A REVIEW OF LITERATURE

by

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Due to rapid growth in semiconductor technology, there is a continuous increase of the system power and the shrinkage of size. This resulted in inevitable challenges in the field of thermal management of electronics to maintain the desirable operating temperature. The present paper reviews the literature dealing with various aspects of cooling methods. Included are papers on experimental work on analyzing cooling technique and its stability, numerical modeling, natural convection, and advanced cooling methods. The issues of thermal management of electronics, development of new effective cooling schemes by using advanced materials and manufacturing methods are also enumerated in this paper.

Key words: *heat sink, pin fins, liquid impingement, thermoelectric cooling, Peltier effect, phase change materials, heat pipes, cold plate, lasers*

Introduction

Advances in the field of electronics have resulted in a significant increase in density integration, clock rates, and emerging trend of miniaturization of modern electronics. This resulted in dissipation of high heat flux at the chip level. In order to satisfy the junction temperature requirements in terms of performance and reliability, improvements in cooling technologies is required. As a result thermal management is becoming important and increasingly critical to the electronics industry. The task of maintaining acceptable junction temperature by dissipating the heat from the integrated circuit chips is a significant challenge to the thermal engineers. The electronics cooling is viewed in three levels, which are non separable. First, the maintenance of chip temperature at a relatively low level despite of high local heat density. Second, this heat flux must be handled at system or module level. Finally, the thermal management of the computer machine room, office space, or telecommunication enclosure. The thermal design of the system is influenced by the key drivers like chip size, power dissipation, junction temperature and ambient air temperature. The semiconductor industries are taking great amount of effort over the years to reduce the size of the devices. With the increase in power dissipation and reduction in the size, the growth in power density is expected to increase further over the next decade as shown in figs. 1 and 2 [1]. The increasing power density indicates the thermal management solutions play an important role in determining the future semiconductor device technology.

The documentation of heat load in process equipment by a thermal management consortium also projects the increasing trend of power dissipation and its documentation is shown

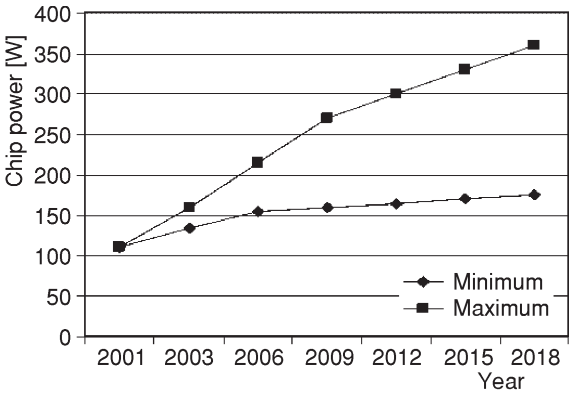

Figure 1. High performance chip power trend

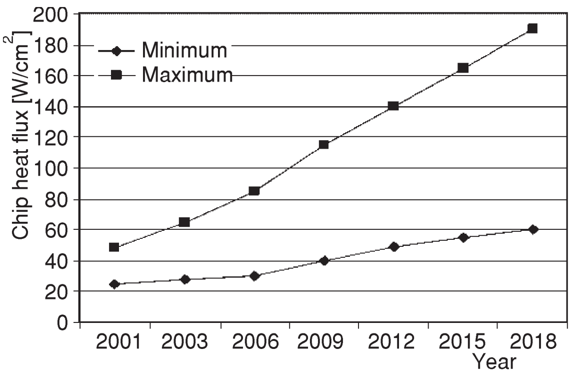

Figure 2. High performance chip heat flux trends

in fig. 3 [2]. Advanced thermal architecture is required to meet this stringent thermal requirement. The high chip temperature results in thermal failures such as mechanical stresses, thermal de-bonding and thermal fracture. The failure in electronics during operation occurs mainly due to temperature and is shown in fig. 4 [3].

Lasance [4] mentioned three typical reasons for the ever increasing importance of thermal management. The reasons are:

– at the component level, designers try to minimize package dimensions while increasing power density, which makes the problem of minimizing the thermal resistance from junction to case, a crucial part of the package density,
– secondly, the electronic industries thermal design tends to be an afterthought of the design process only if the prototype raises any thermal issues, and
– thirdly, the limit of pushing the use of air cooling with heat sink and fan is expected to be reached in the coming years.

Therefore thermal management is a key enabling technology in the development of advance electronics. It is a necessary part of any competitive power density environment. Though the new tool and technologies are employed for cooling, there is no remarkable change in the constraints and design requirements. Thermal management can not be the driving force behind new designs. It must be disposed with other requirements and constraints. The main constraint for any thermal management is the cost. Therefore the cooling technology must be cost effective and keep pace with the reduction in overall package and system cost per function. The cost of cooling is also recognized as a factor playing important role in maintaining competitiveness.

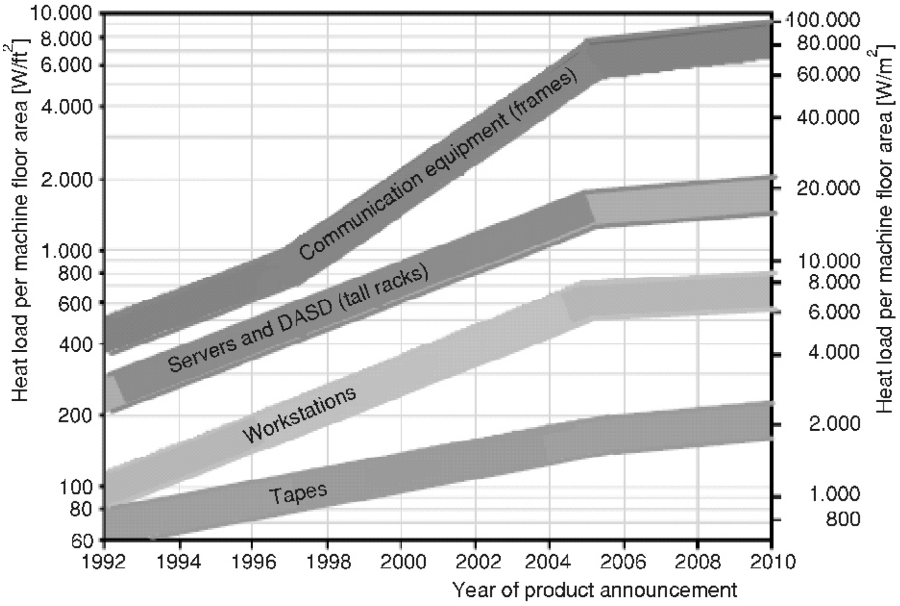

Figure 3. Documentation of heat load in process equipments (The Uptime Institute, 2000)

Classification of cooling techniques

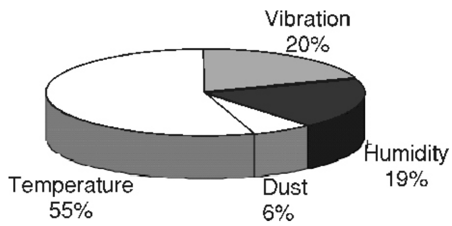

Figure 4. Failure in electronic components

In general thermal management is categorized into active cooling techniques and passive cooling techniques. Mechanically assisted cooling subsystems provide active cooling. Active cooling technique offer high cooling capacity. They allow temperature control that can cool below ambient temperatures. In most cases active cooling techniques eliminate the use of cooling fans or they require less cooling. Air/liquid jet impingement, forced liquid convection, spray cooling thermoelectric coolers and refrigeration systems are the examples of active cooling techniques. The passive cooling subsystems are not assisted by mechanical equipments. The conventional passive cooling techniques include applying effective heat spreaders and heat sinks to the electronic package. For a module with spatial limitation, passive cooling technique is often more practical than active cooling. But it is limited to what it can achieve. Therefore recent technologies include the use of thermal energy storage with phase change materials and integration of the heat pipes to the electronic packages that are commonly used to achieve high cooling capacity.

Scott [5] classified all the methods into four broad categories in order of increasing heat transfer effectiveness, for the temperature difference between the surfaces and the ambient is 80 °C and also compared the methods as shown in fig. 5:

- radiation and natural convection (155-1550 W/m^2),
- forced air-cooling (800-16000 W/m^2),
- forced liquid cooling(11000-930000 W/m^2), and
- liquid evaporation (15500-1400000 W/m^2).

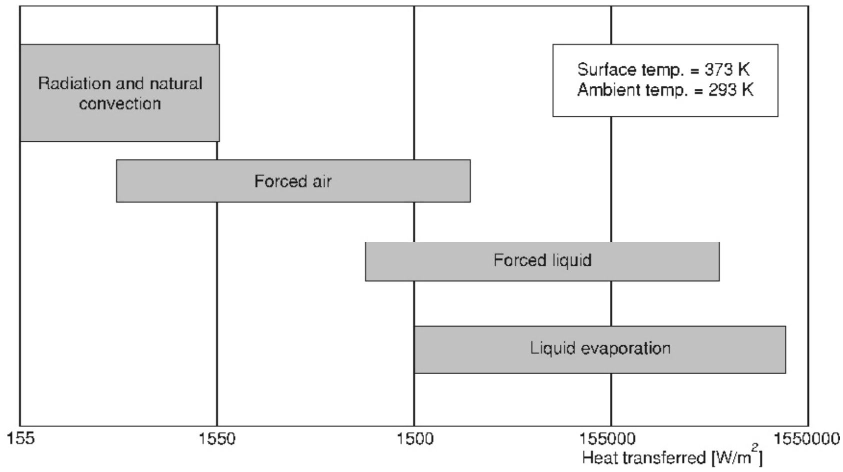

Figure 5. Range of conventional heat transfer modes

Cooling methods

In the present paper all the works reported by various researches are categorized as:
- air cooling,
- liquid cooling,
- heat pipes,
- refrigeration cooling,
- thermoelectric cooling, and
- phase change material based cooling.

Air cooling

Air cooling is the simplest and principal method of thermal control most widely used for variety of electronic systems ranging form portable electronics to large business systems. The advantages of air cooling are its ready availability and ease of application. Before 1964, all IBM computers were cooled solely by forced air. In many cases air moving devices are installed at the bottom or top of a column of boards to provide sufficient cooling. For high heat flux, a push-pull airflow arrangement with air moving devices at both the bottom and top of the column of boards was used to provide high pressure drop capability. Low-power electronic systems are conveniently cooled by natural convection and radiation. When natural convection is not adequate, the forced convection is adopted by a fan or blower to blow the air through the enclosure that houses the electronic components.

Natural convection and radiation

Natural convection and radiation cooling is desirable because of its simplicity. Circuit boards that dissipate up to about 5 W of power can be cooled effectively by natural convection [6]. It is familiar in consumer electronics like TV, VCD, *etc*. by providing a sufficient number of vents on the case to enable the cooled air to enter and the heated air to leave the case freely.

Florio and Harnoy [7] proposed an alternative cooling technique that enhances the natural convection heat transfer from discrete heat sources. The combination of an appropriately placed cross flow opening and a strategically positioned transversely vibrating plate is studied by varying the parameters and geometric configurations. They found this combined effects cause significant improvement in the thermal conditions over pure natural convection. Very few investigations were found in transient natural convection involving discrete heat sources. The related experimental studies are found in the articles [8, 9].

In few applications, such as rotary machines, guided missiles and space based manufacturing process involves natural convection in rotating condition. The detailed literature is available in articles [10-13].

Forced convection

When natural convection cooling is not adequate, forced convection is provided by external means such as a fan, a pump, a jet of air, *etc*. In electronic systems cooling, fan is a popular means of circulating air over hot surfaces. For forced convection the hot surfaces are characterized by their extended surfaces such as fins in heat sinks. The use of micro jet of air to cool hot spots is more attractive [14]. The fan selection is the important aspect in forced convection. The following are the two primary considerations in the selection of the fan:

- the static pressure head of the system, which is total resistance, an electronic system offer to air as it passes through, and
- the volume flow rate of air required for cooling.

Piezoelectric fans are preferred as alternative for conventional fans to cool low-power electronics owing to their low power consumption, minimal noise emission and small dimensions. For elaborate literature on piezoelectric fans readers may refer the articles [15-19].

Enhancement with heat sinks

In many instances, thermal enhancement techniques such as heat sinks is required to cool high density microelectronic packages found in modern circuit boards. It increases the effective surface area for heat transfer and lower thermal resistance between source and sink. Heat sinks can be operated under free or forced convective modes depending on the cooling load requirement. Due to their inherent simplicity, reliability and low long term costs, natural convection heat sinks have proven to be instrumental in cooling single or multiple chip circuit boards [20].

The diverse mix of geometric configuration, thermo physical properties and flow conditions present in microelectronic applications must be factored into thermal modeling tools used for design or reliability assessment. The geometries encountered in heat sink assemblies are difficult to model using analytical techniques because of the complex fluid flow around and between the various components of the heat sink.

Heat sink studies with natural convection

Culham [21] presented the method for calculating the thermal performance of rectangular heat sinks cooled by natural convection using a flat plate boundary layer model and examined several heat sink geometries over a range of Rayleigh number between 10^3 and 10^{10}. The current methodology is different in that the enhanced thermal character will not be assigned to the base plate, but rather to the fluidic block representing the actual heat sink instead of increasing the base plate area or convective heat transfer coefficient to account for the increased surface area due to fins, the idea here is to increase the thermal conductivity of the volumetric block above the base plate in a manner to reproduce the same temperature map as that of the actual sink. As a result, the overall heat transfer coefficient between the base plate and surrounding air will be increased. The overall heat transfer coefficient in this study will include the effects of both convection and radiation to the surrounding.

Van de Pol and Tierney [22] have developed a curve fit for natural convection cooling of vertical fins attached to a base plate, based on the experimental data of Welling and Wooldridge [23]. Jones and Smith [24] performed a similar study for rectangular fin assemblies facing upward and downward in relation to the gravity vector. In both studies, the correlation equations were restricted to a fixed range of geometric and flow conditions limiting their use as general-purpose design tools.

Nottage [25] suggested that the heat sink fin and channel might be thought of as a type of heat exchanger. The solid fin is considered as a hot stream. The flow stream direction relative to heat flow direction plays a significant role in determining the heat transfer effectiveness of a fin-fluid arrangement. The counter flow arrangement has the greatest potential to achieve high effectiveness.

Shvets and Didenko [26] developed a conjugate fin model keeping heat transfer coefficient constant along the length of the fin. Garg and Velusamy [27] presented a model based on the Blasius equation using a boundary layer solution to calculate a nonuniform boundary condition as the coupling condition in their iterative model. Sparrow and Vemuri [28, 29] investigated natural convection and radiation heat transfer from arrays of pin fins with density in the range 0.131-1.33 pins/cm^2. By conducting experiments they found that the ratio of fin diameter to lateral fin spacing play a significant role and its optimum value was close to 0.5. They also studied the orientation effects of pin fins and its influence to overall heat transfer. Zografos and Sunderland [30, 31] experimentally found the optimum ratio of a 203×203 square array of pin fins is 0.333 for natural convection heat transfer. Aihara [32] experimentally investigated about the natural convection and radiation heat transfer from pin-fin arrays with a vertical plate. Totally, 59 types of circular pin-fin dissipaters were used. An empirical expression for the average heat transfer coefficient was derived by conducting flow visualization. Fisher and Torrance [33] developed an analytical solution for free convection, limits for pin-fin cooling. The chimney effect was shown to enhance heat transfer.

Heindel [34] investigated natural convection from an array of discrete heat sources in liquid filled enclosures. They used straight plate-fins to enhance heat transfer and modeled them by treating the plate-fins as porous media. Enchao and Joshi [35] reported a study of enhancement of combined natural convection, conduction, and radiation heat transfer from a discrete heat source in an enclosure using pin-fin heat sinks.

Knight *et al*. [36] characterized the flow and heat transfer behavior of heat sinks analytically, as a function of geometry and fluid characteristics, for developing and fully developed flow. Teertstra [37] developed an analytical model to predict the average heat transfer rate for air cooled plate fin heat sinks. The model is asymptotic between two limiting cases, fully developed and developing flow in parallel plate channels. They validated the model with experiments and found 2.1% root mean square (RMS) error and 6% max error.

Copeland [38] suggested using a laminar flow heat exchanger model for parallel flow in isothermal rectangular channels to model the heat sink. The Nusselt number data was taken from Shah and London [39] and fitted to an equation of the Churchill-Usagi form. Second law of thermodynamics was considered to minimize the entropy generation in heat transfer and viscous dissipation of plate fin heat sinks by Culham and Muzychka [40]. Hilbert [41] developed a novel laminar flow heat with two sets of triangular or trapezoidal shaped fins on the two inclined faces of a base. Biskeborn [42] reported experiment results for a TISE (top inlet side exit) design using unique "serpentine" square pin fins. Sparrow [43] performed heat transfer experiments on an isothermal TISE type single channel passage.

Heat sink studies with by-pass flow

Butterbaugh and Kang [44] developed a nodal network of flow paths to study heat transfer of heat sinks and detailed the calculation of each network element. They accounted flow by-pass and tip leakage.

Shaukatullah [45] reported the thermal performance for in-line square pin fins and plate heat sinks for different fin thickness, spacing, height and angle of approach for velocities under 5 m/s, while allowing flow to partially by-pass the exchanger. Jonsson and Moshfegh [46] characterized plate and circular, rectangular and strip pin fins, in both staggered and in-line configurations for different dimensions, allowing for variations on tip and side bypass.

Numerical studies on heat sinks

Copeland [47] reported theoretical, experimental, and numerical analyses on a manifold micro channel heat sink with multiple top alternated with top outlets. Kang and Holahan [48] formulated one dimensional thermal resistance model of impingement air cooled plate fin heat sinks to understand how the heat sink performance depends on the different geometry variables. Holahan [49] investigated the impingement flow field in the channel between the fins as a Hele-Shaw flow. Kondo [50] performed an experimental study and formulated a zonal model of a thermal resistance prediction for impingement cooling heat sinks with plate fins.

Sathe [51] developed a computational model for three dimensional flow and heat transfer in the IBM 4381 heat sink. Biber [52] reported a numerical study to determine the thermal performance of a single isothermal channel with variable width impinging flow. Sasao [53] developed a numerical method for simulating impingement air flow and heat transfer in plate fin heat sinks.

Due to flow separation and complex three dimensional flow at the pin-base junction, computational fluid dynamics is extensively applied to study flow in heat sinks, for example by Jonsson and Moshfegh [54], Biber and Belady [55] and Dvinsky [56]. The theoretical and experimental studies on thermal performance of pin-fins are available in the articles [57-60] and for selection and optimization of pin cross-section for electronics cooling readers may refer to the works of Sahiti *et. al*. [61].

Shuja [62] described an exergoeconomic analysis for pin-fin array to optimize fin operation parameters based on minimum cost.

Heat sink studies with forced convection

For cooling high density chip packages thermally-induced buoyancy currents is not adequate, where operating heat sinks under forced convective modes become inevitable. For a more elaborate literature readers may refer to the works of Bar-Cohen, Elperin and Eliasi [63], Krueger [64], Culham, Yovanovich and Lee [65, 66], Linton and Agonafer [67], Butterbaugh and Kang [68], Visser and Gauche [69], Patel and Belady [70, 71], Kim and Lee [72] and Narasimhan and Kusha [73]. Brucker [74] adopted porous block model that is based on replacing an actual heat sink by the volume of fluid that once enveloped the fins to study heat transfer in free and forced convection. In their study, they extended the analysis to cover most fundamental body shapes and flow configuration under both free and forced convection.

Micro channel heat sinks

Micro channel heat sinks are one of the effective cooling methods for high power density and compact electronic devices. A number of studies are available in the articles [75-79].

Liquid cooling

Because of high heat transfer coefficients with liquids than gases, liquid cooling is far more effective than gas cooling for high power electronic collections. The potential problems such as leakage corrosion, extra weight and condensation makes liquid cooling reserved for applications involving power densities that are too high for safe dissipation by air cooling. The electronic components are in direct contact with the liquid, therefore the heat generated in the components is transferred directly to the liquid. The electronic components are usually completely immersed in the dielectric fluid. Such cooling schemes may be in the form of single-phase liquid impingement jet cooling, pool boiling, or two phase liquid spray cooling. The heat transfer from the components to the fluid may be natural convection or forced convection or pool boiling depending on the temperature levels involved and properties of the fluid. Liquid cooling is classified as direct and indirect cooling.

Direct liquid immersion cooling

The electronic components are completely immersed in the dielectric fluid as shown in fig. 6. Such cooling involves the pool boiling of a working fluid on a heated surface, which is an example of a two-phase cooling technology used in microelectronic applications [80]. It is a highly effective cooling strategy for the following reasons:

– the phase change, liquid to vapor greatly increases the heat flux from heated surface, and
– the high thermal conductivity of the liquid medium enhances the accompanying convection.

A prominent cooling scheme for micro electric devices is immersion cooling with dielectric fluids. The dielectric fluids used for immersion cooling are a refrigerant-type fluid that has a moderated boiling point, such as R-113. R-113 is used for power electronic devices; however it is not compatible for computer because of probable long term corrosion. A special fluid, such as the Fluorient^{TM} or Novec^{TM} developed by 3M Company is used. These dielectric fluids have low thermal conductivity and low latent heat of vaporization which results in poor heat transfer characters when compared to water.

A comprehensive literature survey on thermal management of electronic components with dielectric liquids is given by Bar-Cohen [81]. The problem of boiling-curve hysteresis also exists due to the extreme wettability of these fluids [82]. There is a particular need to elevate the peak nucleate or burnout heat flux for these fluids. Some enhancement techniques are required to accomplish this and to reduce the wall superheat.

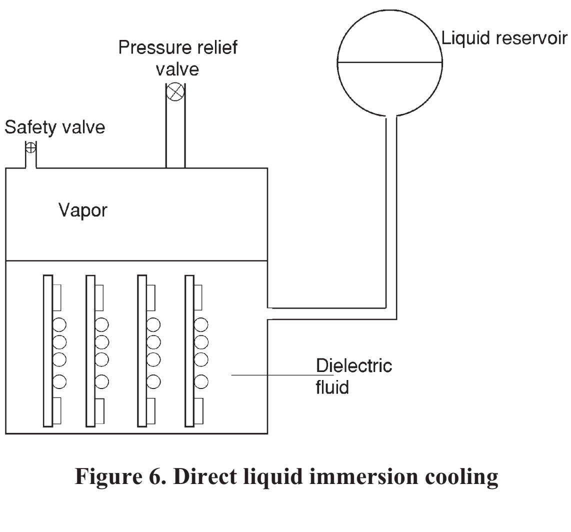

Figure 6. Direct liquid immersion cooling

Enhancement techniques for boiling heat transfer

Realizing the importance of enhancement of boiling heat transfer from electronic components many have investigated the use of surface micro structures that were fabricated directly on a silicon chip or a simulated chip. These include sintered or flame sprayed porous coatings [83, 84], laser drilled cavities [85, 86], a sand blasted and KOH treated surface [87, 88], a dendritic heat surfaces [87], hexagonal dimples fabricated by photo-etching [89], reentrant cavities [90-92], porous surfaces fabricated by alumina particle spraying [93, 94] and painting of silver flashes [95], diamond particles [96, 97] and aluminum and copper particles [98] and micro pin fins produced by dry etching [99-101]. Heat sink studs with drilled holes, micro fins, multi layered micro channels and pores, and pin fins with and without micro porous coating have been developed and tested. These includes a vapour blasted surface, drilled cavities, micro fins, micro studs and microgrooves [102], multilayered micro-channels and pores [103-105], pin fins, pyramid and square studs with microgrooves, cylindrical pin fins and single cylindrical stud with low profile microstructures [106, 107] and square pin fins with and without painted aluminum particles [108, 109].

You [110] introduced a novel particle layering, an effective and convenient technique for enhancing boiling nucleation on a surface. The demonstration showed, this technique results in a decrease of heated surface temperature and more uniform temperature of the heated surface. Both this effects are important in immersion cooling of electronic equipment.

Jet impingement

One of the successful methods to remove high heat flux dissipated by the electronic components is jet impingement. A jet of liquid with high heat transfer coefficients is directed at the heat source to cool the surface, and large heat transfer rates will occur at or near the stagnation point and drop off further away. Depending on the surface temperature of the component and working fluid, the jet impingement can be single phase or two phase heat transfer. The jet is also classified into free surface and submerged. The jet flows within the same fluid in the same state (*i. e.*, gas into gas or liquid to liquid) means submerged and free surface, which means that the liquid jet is injected into a gaseous environment. Extensive studies have been performed in the past particularly on single phase jet impingement configurations such as single and multiple free surface jets, single and multiple submerged jets and confined jets as shown in fig. 7 [111].

The impact of vast array of parameters such as jet velocity, jet diameter, impact angle, nozzle to chip spacing, nozzle to nozzle spacing, turbulence levels, nozzle shapes, nozzle length, jet confinement, chip surface enhancement, and fluid properties on the chip surface heat transfer coefficient are covered in detail in comprehensive reviews [112-114]. These studies include

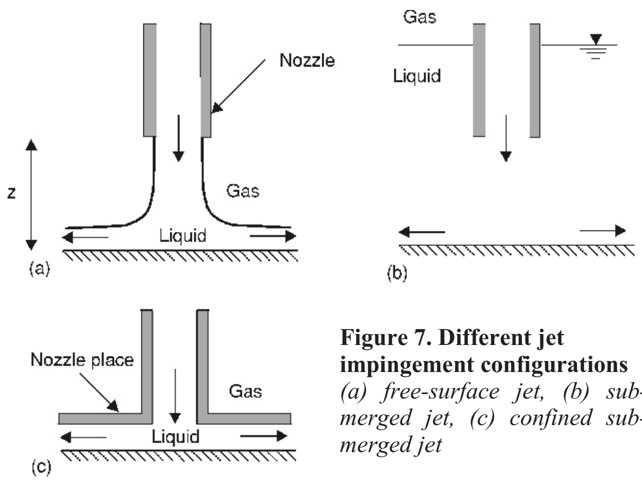

Figure 7. Different jet impingement configurations
(a) free-surface jet, (b) submerged jet, (c) confined submerged jet

experiments, theoretical analysis, and numerical solutions. Extensive literature is available on single- phase jets. A summary of this is presented in tab. 1 along with main parameters.

Table 1. Literature on single phase jets

Reference	Reynolds number	Jet pitch/nozzle diameter	Nozzle diameter [mm]	No of jets	Fluid
[115]	2800-12600	5.8, 10.16	0.5, 1.0	1, 4, 9	FC77, H_2O
[116]	5000-20000	2, 4, 6, 8	1, 2, 3	7, 9	H_2O
[117]	500-20000	4.98-19.8	0.513, 1.02	4, 9	FC77, H_2O
[118]	3150-11300	–	1, 1.59	4, 7	H_2O

The above literature summary revealed that in single phase impingement cooling with multiple jets, only the liquid mass flow rate, or the number of jets influences the heat transfer. The nozzle to heater distance has no significant effect on the heat transfer unless it is decreased to the point where the jets become submerged. Fabbri [119] tested ten different arrays of microjets using deionized water and FC40 as working fluids. The jet diameters employed ranged between 69 and 250 μm and the jet Reynolds number varied from 73 to 3813. The data were correlated by using commercial software to perform the least square fitting process.

Spray cooling

Spray cooling can be implemented by means of liquid jets or liquid droplets. In spray cooling, the cooling agent is injected through nozzles or orifice onto the electronic module as shown in fig. 8. The pressure drop across the nozzle or orifice forms the spray that impinges on the surface and forms a thin liquid film. The heat dissipated from the equipment initiates boiling, which leads to evaporation of the cooling agent. The constant impingement by the spray forces convection of the cooling agent and contributes there by the cooling of equipment. The hot liquid and vapor cools in the container returns to reservoir through a drain to repeat the cycle. Spray cooling is attractive for the following reasons:

– direct spraying on the heat source eliminates the thermal resistance present in the bonding layer used for attaching heat source to the heat spreader, and
– the ratio between power spent for cooling process and the heat removed decreases faster for spray cooling than channel cooling.

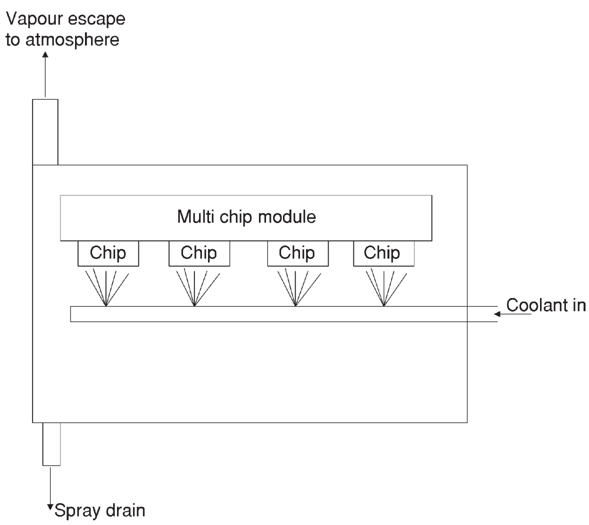

Figure 8. Spray cooling

According to Mudawar [120], the spray cooling is one of the most promising high heat flux method. The key requirements for the liquid used for spray cooling of electronic components is that it must be non-conducting or a dielectric liquid. Water is employed frequently as a cooling agent. A thin protective layer is coated onto the electronic components to protect against short circuits because water has a very low dielectric strength. This limitation results for an alternate candidate to provide more effective cooling. Very few candidate liquids are available.

The Fluorinert^{TM} liquids manufactured by 3M Corporation are claimed to be practically non-toxic and non-flammable. These are available with molecular masses ranging from 340 to 670. Extensive literature is available on heat transfer studies using FC-72 for spray cooling of electronic equipments. The volatile methyl siloxanes manufactured by Dow Croning are also available, labeled as OS series fluids, it is highly volatile. Their suitability for spray cooling of electronic components is yet too being established, so little information is available on their heat transfer characteristics. The common refrigerant R134a is also suggested as a candidate for electronic cooling by Oak Ridge research group. They have conducted a series of experiments to establish its feasibility for use with automotive electronics. Extensive literature on spray cooling is available in the review article [121].

Indirect cooling

Indirect cooling has been used in the past to cool high performance electronic modules. The liquid as cooling agent does not have direct contact with the module. Instead, a thermal pathway, usually a cold plate made with metal of high thermal conductivity is furnished between the module and the cooling agent as shown in fig. 9. Since there is no contact between the module and cooling agent, the cooling agent can be any liquid. Water is the most commonly used cooling agent because of its high thermal conductivity and environmental compatibility. For high heat flux cooling solution for electronics, foam filled cold plates have great potential compared to conventional cold plates. A summary of the literature on clod plates is given in tab. 2.

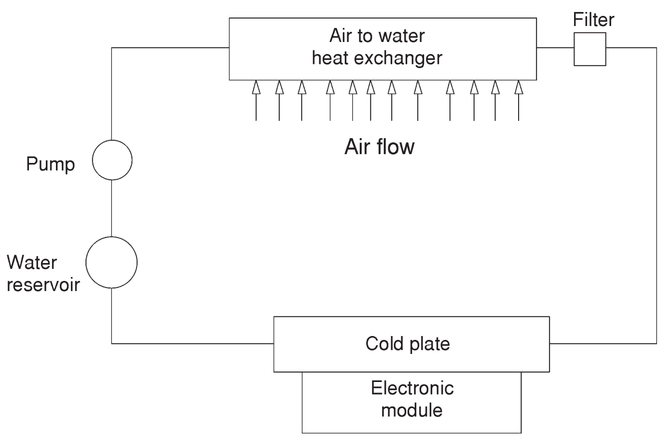

Figure 9. Indirect cooling of electronic module

Refrigeration cooling

The large systems and work stations have employed refrigeration cooling; mainly vapor compression refrigeration system to lower the temperature of CMOS (complementary metal oxide semiconductor) processor in order to achieve high performance. Due to high reliability, low cost when compared to cryogenic cooling, achievement in operating temperature in the

Table 2. Literature on cold plates

Reference	Application	Foam/coolant	Heat flux [kW/cm^2]
[122]	Laser mirrors	Copper/water	2.5
[123]	Laser mirrors	Copper/water	8
[124]	Laser mirrors	Copper/water	4 to 5
[125]	Fusion power systems	Water	5
[126]	Fusion power systems	Copper/water	7.4
[127]	Fusion power systems	Copper/water	4
[128]	High power optical components	Porous metal/water	6
[129]	High power optical components	Porous metal/water	0.92
[130]	High power optical components	Porous metal/water	1

range of –20 to 40 °C and its greater efficiency, it is chosen as suitable technology for large systems. Because refrigeration cooling is a mature technology, the detailed literature survey is not included in this review. Readers may refer to the articles [131-138].

Thermoelectric cooling

Thermoelectric cooling are solid state pumps, which draw electrical energy along with several phenomenon, the Peltier, Seeback and Thomson effects to implement cooling. It is used in application where temperature stabilization, temperature cycling or cooling below ambient are required. The thermoelectric architecture for cooling electronic equipment is shown in fig. 10. Thermoelectric micro coolers are considered as a potential candidate for integrated cooling of optic electronic devices, such as semiconductor lasers and detectors which require low temperature for high performance [139, 140].

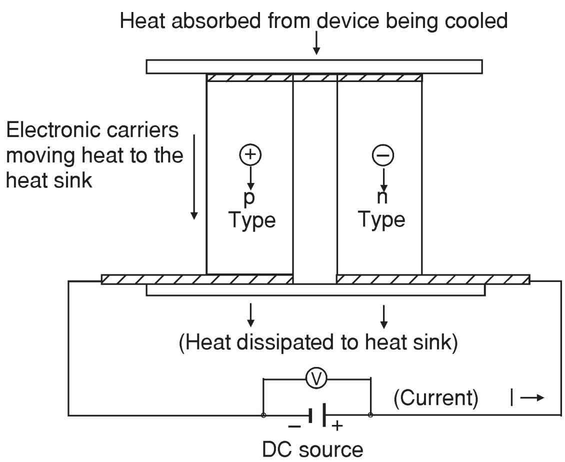

Figure 10. Thermoelectric architecture for cooling electronic equipment

One stage thermoelectric cooling is not sufficient to achieve desired operation temperature for some specific applications in electronics and optoelectronics under steady-state applications. There are two options to achieve desired temperature, one is transient cooling which is suitable for the pulsed operation of certain devices [141] and second method is the most standard approach – the use of multistage module, which is known as cascade coolers [142]. In some applications, it is necessary to isolate the electronic components completely from the environment to avoid large accumulation of particles that could cause harm to electronics. Normal conventional cooling cannot be used under these conditions. Hermetic thermo cooler is the suitable cooling system to cool hermetic devices. The study was done for a personal computer and different cooling alternatives are presented: natural convection using standard radiators and forced convection using radiators and fans. It was reported that by using thermoelectricity the heat transfer is highly increased [143].

Heat pipes

A heat pipe is a passive two phase heat transfer device capable of transferring large quantities of heat with a minimal temperature drop. It consists of three sections: evaporator, adiabatic section, and condenser as shown in fig. 11. When heat is added to the evaporator section, the working fluid vaporizes. The resulting pressure difference drives the vapor to the cooler section of the heat pipe where it condenses and releases latent heat. The capillary forces provided by the wick transports the condensate to the evaporator. This closed loop process continues as long as heat is applied. The wick structure may be extruded grooves, screen mesh and powdered metal depending on the application. The materials used for containers are copper, aluminum, stainless steel, and nickel. Copper is widely used due to the material compatibility with common working fluids, high thermal conductivity, and manufacturability. The working fluid depends on the operating temperature and its selection can be made from heat pipe hand book. The working fluid, wick and container compatibility data are available in the book [144].

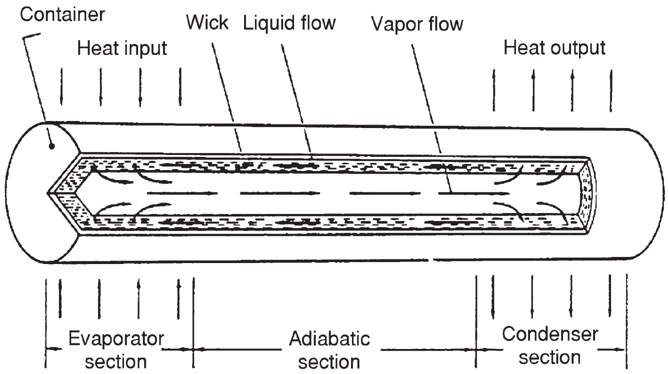

Figure 11. Working principle of heat pipe

Generally the heat pipe applications can be classified into three categories for cooling of electronic equipments [145]:

– indirect cooling technique, like heat sinks, the heat pipe is in direct contact with the components or devices,
– direct cooling technique, the heat pipe is an integral part of the device; it may have the contact with working fluid, and
– it is located at system level to control the temperature in equipment cabinets or systems.

The simplest heat pipe heat sinks are of cylindrical shape. Since most of the electronic components are shaped as thin plates, flat heat pipes are commonly used to reduce the thermal contact resistance. In some cases bellow heat pipe are used to reduce the transmission of stress from condenser to the electronic components.

The heat pipe array mounted vertically on a semiconductor base plate is investigated by Howard and Peterson [146]. The heat pipe array consists of sixteen small copper/water heat pipes, 25.3 mm in length, placed on an aluminum plate. The wick structure consists of two layers of phosphor bronze wire screen. The evaporator section of each heat pipe is pressed into an aluminum sleeve and the condenser section of each heat pipe is pressed into an aluminum sleeve with ten circular aluminum fins. The experiment results are compared to similar heat pipe system without fins. They found the convective cooling capacity is improved by a factor of about ten compared to a system without fins. For the maximum heat input of 50 W, a Reynolds number in excess of 1200 is required to maintain the electronics junction temperature at an acceptable level. These high Reynolds numbers could create a problem due to excessive pressure losses, noise or vibrations.

Groll [147] reported the experimental investigation of a cylindrical bellows heat pipe carried out by Babin and Peterson [148]. The heat pipes of different dimensions and wick structures were constructed. The heat input to the evaporator is axial through the end face and heat rejection in the condenser occurs radially. The adiabatic and condenser section are provided with a cylindrical wick structure of two layers of copper wire screen. For the three heat pipes, the boiling limit occurs over most of the operating temperature range were tested.

Mochizuki [149] designed and tested hinged heat pipe cooling system. The heat pipe is provided at the back of the liquid crystal display screen of a notebook computer. The primary heat pipe of outer diameter 4 mm transfers heat to secondary heat pipe of outer diameter 3 mm through a hinge made of copper. Then the heat is transferred to an aluminum heat spreader plate ($250 \times 174 \times 0.41$ mm), which dissipates it into the back of LCD. Experiments showed the capability of the hinged heat pipes in the 10-12 W range of input heat.

The remote heat exchanger system: a combination of heat pipe, heat sink, and fan, is another common mobile thermal solution. The remote heat exchanger system can dissipate 20 W with a junction temperature limit of 90 °C and ambient 20 °C. Micro and miniature heat pipes are small scale devices that received a considerable attention in the past decade for cooling microelectronics [150, 151]. It is desirable for two reasons: (1) higher heat transfer coefficient and (2) higher heat transfer surface are per unit fluid volume. The fluid channels of micro heat pipe have small hydraulic diameter in the order of 10-500 μm while miniature have hydraulic diameter in the order of 2-4 mm. Nguyen *et al*. [152] tested the concept with copper heat block, copper heat pipe and aluminum heat sink. A short review on micro and miniature heat pipe is available in the review article [153].

Pastukhov *et. al*. [154] suggested a alternative low noise cooling system for personal computers using loop heat pipes. They presented the results of developments and tests of four variants of desktop personal computer CPU cooling systems which use copper-water loop heat pipes. The experimental investigation on heat sink heat pipe is available in the articles [155-157].

Phase change material based cooling

Active cooling requires bulky and massive equipment which is not suitable for use in mobile devices and in IC packages which work in a Boolean manner switching on and off. One alternate passive cooling which is light and simple is to use phase change materials (PCMs), which has a high latent heat of melting. Dissipating heat from electronic equipment is stored in heat sink containing phase change materials. PCM energy storage is based on the heat absorbed or released when a material reversibly changes its phase, usually between the solid and liquid states. It is well suitable for transient power dissipation by electronics. PCM can reduce the size of the cooling system and save money, space and other system resources. PCM storage system is one of the alternatives to cool outside plant enclosure. A PCM is used to absorb peak energy loads during one time of the day and reject that heat load at another time. Thereby it can prevent the use of assisted systems or fully active systems to maintain the electronics at the desired conditions.

One major disadvantage of this passive cooling is high thermal resistance found in PCMs. Therefore these materials are combined with heat spreaders such as heat sinks and are also encapsulated or sealed in the heat spreader [158-160]. Pal and Joshi [161] analyzed and conducted experiments on a phase change heat sink for avionics applications. The performance of a phase change material heat sinks was studied by O'Connor and Weber [162]. The performance and optimization of phase change material is found in the literature [163-165]. Fosset *et. al*. [159] studied the cooling of aircraft communication devices using microencapsulated PCMs. Hodes *et. al.* [166] reported the use of PCM in cooling of communication hand set. Gauche [167] presented a set of transient computational analyses of IC packages like 192 lead 27 27 mm flip chip plastic ball grid array (C4 PBGA) and a 176 lead 22 × 22 mm thin plastic quad flat pack (TQFP) in different configurations.

Gurrum [168] carried out a numerical study of the feasibility of using solid-liquid PCM's for periodic power dissipating devices. Metallic PCM's are found to be a suitable candidate for the high flux temperature pulsed electronics. The use of PCM for cooling mobile electronic devices, such as personal digital assistants (PDA's) and wearable computers was experimentally studied by Tan [169]. The high latent heat of n-eicosane in the heat storage unit placed inside the device absorbs the heat dissipated from the chips and maintains the chip temperature below the allowable service temperature of 50 °C for 2 hours of transient operation of the PDA. The PCM based enclosure cooling was observed by Marongiu and Clarksean [170] using finite element numerical model. Warm air from enclosure due to high temperature dissipates heat into the Glauber's salt (PCM) inside tubes by convection and changes its phase from solid to liquid. Subsequently, heat was transferred out to the other end to the ambient air, which was at a lower temperature.

Kandasamy *et. al*. [171] proposed a three dimensional computational fluid dynamics model to simulate the transient cooling of electronics using phase change material based heat sinks. They validated the model experimentally.

Conclusions

High heat flux cooling of electronic equipments and devices with various methods is reviewed. Based on the papers reviewed, it revealed the research needs are to be focused to investigate advanced cooling technology that uses high performance heat pipe, thermoelectric coolers, low acoustical novel micro-fans for air cooling, and phase change material based cooling to satisfy the thermal technology needs. The challenges of cooling electronic equipments may be expected to continue through the remaining of this decade. As the size of semiconductor and power dissipation are at opposite roads, breakthroughs are needed in advanced cooling to reduce cost without sacrificing effectiveness of cooling.

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