

# High Power Electronic Component: Review

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**Abstract:** A large number of recent patents for cooling of high power electronic components are reviewed. Along with the progresses in the developments of material, fabrication, and packaging techniques, various single and two phase cooling devices are developed for thermal managements of electronic devices. In this respect, practical patents for heat-sink developments and implementations of nanotechnology and two-phase devices are reviewed through which the innovative concepts matching their future developing trends are disclosed.

**Keywords:** Heat-sink devices, liquid cooling systems, heat pipes, wick materials, two phase cooling devices, electronic devices, critical heat flux.

## 1. COOLING SYSTEM FOR HIGH POWER ELECTRONIC COMPONENTS

Driven by the improved performances and miniaturization of electronic components, the dramatic increase of heat fluxes from electronic chips urges the more efficient and effective cooling treatments in order to ensure the reliability of these components with high power densities. For most electronic components, a cooling measure to maintain a relatively constant component temperature below 85°C is essential. Thermal managements of electronic components thus play a crucial role in the development of electronic devices. Owing to the elevated heat fluxes issued by electronic chips from 50 to 200 Wcm<sup>-2</sup> [1], the conventional air convection unit such as the fan-fin assembly has reached its thermal limit in view of the cooling capacity and the heat transfer rate. As a result, developments of electronic cooling system are rapidly evolved from the conduction and air convection models toward the liquid convection models with or without phase change. A review of available cooling solutions for electronic components reveals three fundamental functions; namely (a) heat removal from electronic components, (b) heat transport through the unit and (c) heat convection out of the unit. Fig. 1 (a) illustrates the schematics of heat and coolant flows for an electronic cooling unit that fulfills the three fundamental functions. Fig. 1 (b) depicts the typical layouts of air convection model and the liquid cooling assemblies involving heat pipe in which two phase evaporations significantly raise the cooling capacities and heat transfer rates.

Taking advantages of phase change heat transfer in an electronic cooling unit, heat pipes (or vapor chambers) are often embedded into the base of the heat sink or connected

with the vapor chamber, as seen as the interfacial device in Fig. 1 (a), to transport heat through the unit so that the heat flux issued from the electronic chip across the heat sink can be evenly distributed. As shown in Fig. (1a), the heat flux issued by the electronic chip is convected by the coolant flow and vents to the surrounding ambience through the radiator which is functioned as the condenser if the phase change device is employed. For liquid cooling system with or without phase change, the cool coolant recirculates back to the heat sink by the externally applied pumping power for single phase system or by the self-induced thermally driven pumping forces. However, the electronic chip as seen in Fig. (1a) generally covers a small area of the heat sink and the contact thermal resistance between the electronic component and the heat sink also prevents the spreading of heat flux making a large area of the heat sink ineffective. In particular, the heat pipes that transport heat through the cooling unit are often in circular shapes which reduce the contact areas between heat pipes and the heat sink. Therefore the heat dissipation over a plate-type heat sink generally decreases toward its corners due to the lack of two-phase components provided by heat pipes in these corner regions.

A further performance improvement in this respect can be achieved by replacing the embedded heat pipes with a vapor chamber in which the evaporation process prevails over the entire contact surfaces with the electronic chip(s). Although the vapor chamber operates in the same way as a heat pipe, it allows heat spreading at a lower thermal resistance than that of embedded heat pipes over the entire base area due to the full coverage of two-phase components over the base area of the heat spreader. Nevertheless, numerous designs based on the working principles featured by Fig. (1a) can be developed with a wide range of selections for each subassembly. As the performances of each subassembly depicted in Fig. (1a) are interdependent, the overall performance of an electronic cooling unit are affected by the coupling effects between these subassemblies. The maximum cooling duty of an electronic cooling unit is

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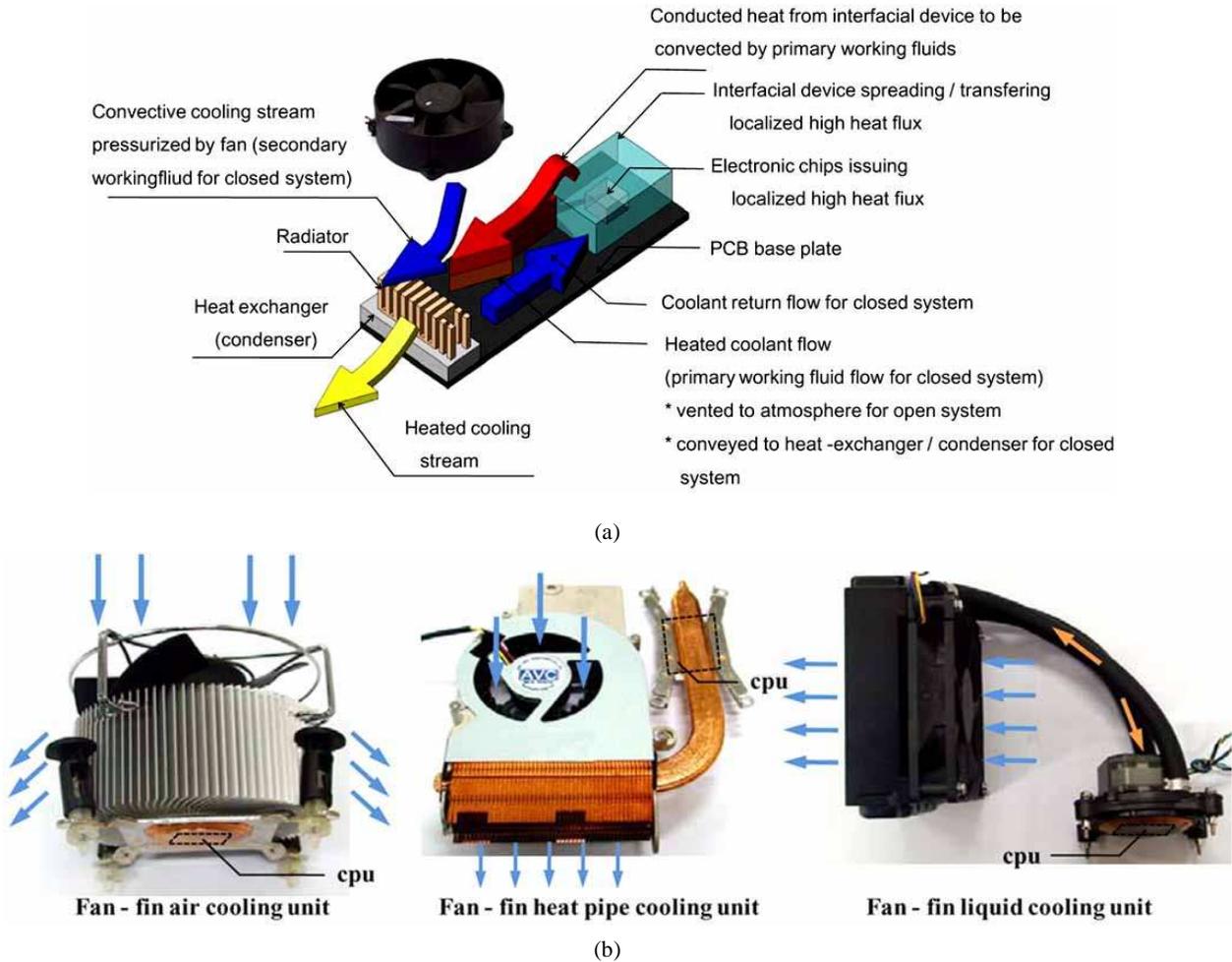


Fig. (1). (a) schematics of heat and coolant flows for an electronic cooling unit (b) air convection model and cooling units using heat pipe or forced convective liquid cooling system.

limited by the “worst performance” of the subassembly which can be the interfacial device, the heat pipe, the radiator or the cooling fan as seen in Fig. (1a). Therefore the thermal limit defined by the worst subassembly can arise from a variety of different physical phenomena due to the various working principles adopted by the subassemblies. With design applications, it is customary to follow the schematic arrangement of the subassemblies in an electronic cooling system in order to formulate the network of thermal resistances which include the “contact” resistance between two components. The maximum cooling duty within the allowable temperature difference between the hottest spot and the surrounding ambience is accordingly evaluated. As a result, varieties of relevant researches as well as the innovations documented as patents look into the augmentation of cooling performances for either an individual subassembly or the entire unit. With predefined energy consumption for a conventional fan-fin CPU cooling unit as seen in Fig. (1b), the maximum cooling duty within the limited space and CPU-to-ambience temperature differences is attempted by considering the coupling effects between the spatial heat transfer variations over fin-surfaces, which signify the flow structures developed in the fin array, and the heat conduction in the fin array. Optimizations of fin-array

geometry and reductions of contact thermal resistance between a fin array and the electronic chipset become a focus of recent patent developments.

Depending on the range of heat dissipated by the cooling system, three typical types of cooling system, listed in Table 1, are employed to dissipate the heat fluxes issued from electronic components. Based on the thermal networks formulated for these cooling systems, the relationships between the heat flux ( $\phi$ ) and driving temperature potential ( $T_j - T_a$ ) for the air-cooling type, the thermally driven interfacial-radiator type, and the forced convective liquid-cooling type are respectively expressed as

$$\phi = \frac{T_j - T_a}{R_{c1} + R_{cond} + R_{conv}} \quad (1)$$

$$\phi = \frac{T_j - T_a}{R_{c2} + R_i + R_{c3} + R_{cond} + R_{conv}} \quad (2)$$

$$\phi = \frac{T_j - T_a}{R_{c2} + R_i + R_{c4} + R_{lq} + R_{c5} + R_{cond} + R_{conv}} \quad (3)$$

where  $T_j$  and  $T_a$  respectively denote the maximum junction temperature at the thermal contact with the electronic

component and the ambient temperature. For all three types of cooling system,  $R_{cond}$  and  $R_{conv}$  represent the combined conductive resistance of both heat exchanger and radiator and the convective resistance of radiator, vapor chamber or heat pipe respectively. For the radiator (air-cooling) type,  $R_{c1}$  is the contact resistance between the electronic chip and the heat exchanger. For the thermally driven interfacial-radiator type,  $R_i$ ,  $R_{c2}$ , and  $R_{c3}$  denote the thermal resistances for the interfacial device, the contact resistance between the electronic chip and the interfacial device, and the contact resistance between the interfacial device and the heat exchanger, respectively. For the forced convective liquid-cooling type,  $R_{lq}$ ,  $R_{c2}$ ,  $R_{c4}$ , and  $R_{c5}$ , denote the thermal resistance for the closed system of coolant flow, the contact resistance between the electronic chip and the interfacial device, the contact resistance between the interfacial device and the closed system, and the contact resistance between the closed system and heat exchanger, respectively. For an increase in the heat generated from the electronic device or a decrease in the size of the electronic device, the increase of cooling duties for an electronic cooling system can only be achieved by reducing the thermal resistance of each component in the cooling system because the driving temperature potential is fixed for most applications. The patents reviewed in this work are all proposed to reduce the thermal resistances appeared in equations (1)-(3).

As previously described, the increased heat flux from an electronic component together with the trend of miniaturization have led to the requirements for increased cooling duties and heat transfer rates which can sometimes exceed the thermal limits of a forced air convection unit. Alternative solutions for cooling of electronic chips thus divert toward the developments of forced liquid convection units as well as the thermally driven two-phase cooling units involving boiling and condensation processes. The primary issues relevant to the cooling methods involving phase-change heat transfer are mitigation of wall temperature overshoot at boiling incipience, enhancement of nucleate boiling with increased critical heat flux (CHF) and the efficient condensation process to recover the liquid phase after boiling. As CHF forms another performance limit for boiling heat transfer, the upper limit of heat flux from an electronic component cooled by a two-phase device is given by CHF when  $T_{w,CHF} < 85^\circ\text{C}$  and by the value of heat flux at  $T_w = 85^\circ\text{C}$  when  $T_{w,CHF} > 85^\circ\text{C}$  where  $T_{w,CHF}$  represents the wall temperature corresponding to CHF. These alternative techniques using the forced liquid convection and two-phase

capillary cooling often adopt the two-phase microchannel [2], the micro and miniature heat pipe [3] and the loop heat pipe [4,5] as parts of the electronic cooling unit. For two-phase capillary thermal controlled devices, they are self-circulating devices where heat is removed by phase change and the working fluid is circulated by thermodynamic forces. With these two-phase cooling applications [2-5], augmentations of boiling (evaporation) heat transfer from electronic chips by enhanced surface microstructures are reviewed in [6]. These various types of enhanced microstructures can be directly fabricated on a silicon chip and have shown their effectiveness in decreasing wall-superheats at boiling incipience and enhancing the nucleate boiling heat transfer and CHF [6]. Factors leading to improved performances for boiling heat transfer by surface microstructures include the sufficient active nucleation sites at low wall superheats, the evaporation of liquid film within a very small confined space and the considerable increase of effective heat transfer area. In particular, the surface microstructures can also act to hold growing bubbles on the heated surface for a longer period than the smooth surface, thereby increasing the heat transfer rate due to the increased latent-heat absorption. Conclusions drawn from the research results examining the augmentation of boiling heat transfer with electronic chipsets immersed in dielectric liquids using surface microstructures [6] include: (1) the complex microroughness, microreentrant cavity and microporous structure are effective in decreasing boiling incipience superheat; (2) the surface roughness is effective in enhancing nucleate boiling and surface cavities can also increase CHF; (3) the microporous structures are the most effective topology in enchanting nucleate boiling while the micro pin-fins are most effective in increasing CHF. Among these microstructures [6], the brush-like structure has been proposed as the dendritic heat sink with cooling applications to electronic chipsets [7].

To avoid the additional pumping equipments which are essential for single-phase forced liquid convection systems, the thermally driven and self circulating two-phase electronic cooling unit widely adopts heat pipes in which the capillary forces play dominant role for coolant circulations. In a cooling unit involving heat pipes, basic heat transfer phenomena are closely related with liquid-vapor interfacial mechanisms as well as the flows of vapor and liquid in the heat pipe. Returning flow circulation in a heat pipe can sometimes trigger flow instabilities, such as waves, flooding and performance jumps [3]. Interfacial instability in a heat pipe causes liquid accumulation in the condensation section

**Table 1. Typical Types of Electronic Cooling System**

Type of cooling unit	Heat dissipated	Subassemblies in the cooling system
Radiator (air-cooling) type	20W-80W	Heat exchanger, radiator, and fan (Placing the heat exchange directly on top of electronic chip in Fig. (1a))
Thermally driven interfacial-radiator type	80W-150W	Vapor chamber or heat pipe (interfacial device shown in. 1(a)), heat exchanger, radiator, and fan (Placing the heat exchanger directly on top of interfacial device in Fig. (1a))
Forced convective liquid-cooling type	150W-200W	Vapor chamber or metal plate (Interfacial device shown in Fig. (1a)), closed system for coolant flow, heat exchanger, radiator, and fan

which can lead to the development of dry-out spots in the evaporator. Performance drops in a heat pipe may also arise from the presence of non-condensable gases, the surplus liquid and the constrained vapor space. To comply with the trend of miniaturization for electronic devices, micro heat pipes are recently developed. Additional drawbacks for micro heat pipe mainly arise from the miniaturized volumes, which include sensitivities to the presence of non-condensable gases in the vapor channel, the strong liquid-vapor interfacial shear stress, the dry-out effects when liquid accumulates in the vapor channel and the low heat transfer output due to reduced evaporating surfaces. For enhancing capillary forces that drive coolant circulation and promote heat transfer performances, the inner walls of mini heat pipes are covered by sophisticated trapezoidal grooves or capillary-porous coating [3]. In contrast to the conventional surface roughness such as the polygon, triangular or trapezoidal grooved capillary wall, the capillary-porous coating such as sintered powder wicks can offer more sites of micro-evaporators that lead to the considerable increase of total evaporation area. A large number of recent patents therefore focus on wick structures in (mini) heat pipes. The primary properties for developing the wick inside a (mini) heat pipe are the pore size and the permeability. The former (pore size) determines the fluid pumping pressure or the so-called capillary head and the later (permeability) affects the frictional losses when the coolant flows through the wick. Among the various wick structures reviewed in [3] that include metal sintered powder, fin fiber bundle, axially grooves and screen mesh, the metal sintered powder wick appears as the most efficient wick in its function at any position of a (mini) heat pipe and provides improved heat transfer performances. Moreover, as silicon often provides good thermal conductivity with the lower thermal expansion coefficient and permits to obtain much smaller devices than other metals due to the etching process accuracy, augmentations of cooling performance using mini heat pipes are mostly promising when they are fabricated directly in the silicon chips.

In order to operate the thermally driven two-phase cooling unit against gravity to some extents with enhanced cooling capabilities, the loop heat pipe (LHP) is developed as another type of self-circulating devices for electronic cooling system using capillary forces to promote coolant circulation within which the heat transferred from electronic components and to the condenser are removed by phase changes. The thermally driven LHP is a complex system, into which the thermal and hydrodynamic mechanisms between various components in a LHP, such as the evaporator, the compensation chamber, the condenser and the wick are strongly interdependent. Its thermal resistance and maximum heat transfer capability are affected by the thermal-fluid properties of working fluid, the fill charge ratio, the structure and thermal properties of porous wick, the temperature levels of heat-sink and ambience, the geometries of evaporator and compensation chamber, the elevation and tilt, the presence of non-condensable gases and the pressure drops across the loop [5]. With electronic cooling applications, the unsteady responses from the different but *interdependent* components in a LHP, such as the evaporator and the compensation chamber, induce various types of

failure including the evaporator dry-out, the performance degradation and temperature oscillations owing to the liquid-vapor interfacial oscillations and the unsteady behaviors at cold starts. An extensive review as well as the working principles aimed at revealing the coupling effects between the interdependent controlling parameters on thermal performances of a LHP is reported in [5]. In general, five primary heat transfer limitations for (mini) heat pipes or LHP, namely the viscous, sonic, capillary pumping, entrainment or flooding and boiling limitations confine the cooling duty for such a thermally driven two-phase electronic cooling device. With low operating temperatures, the most important performance parameters are capillary pumping and boiling limits. The manufacturing technologies of micro, mini and looped heat pipes must be simultaneously improved in order to find their wide spread of commercial applications for electronic cooling, which have to compete with other potential cooling methods such as forced liquid convection, impingement and two phase direct cooling systems.

The current state of arts for developing an electronic cooling system as well as the limitations faced by its subassemblies that apply various working principles with complex thermal fluid physics are illustrated. Patent inventions work closely with research developments in the electronic cooling industry. Numerous practical innovations aimed at improving the performances of the complete system or each subassembly of an electronic cooling system as typified in Fig. (1a) are examined. Patents for heat-sink developments and implementations of nanotechnology and two-phase devices for electronic cooling units are subsequently reviewed through which the core technologies and the future developing trend of cooling industry for electronic components are identified.

## 2. HEAT SINK DEVICES

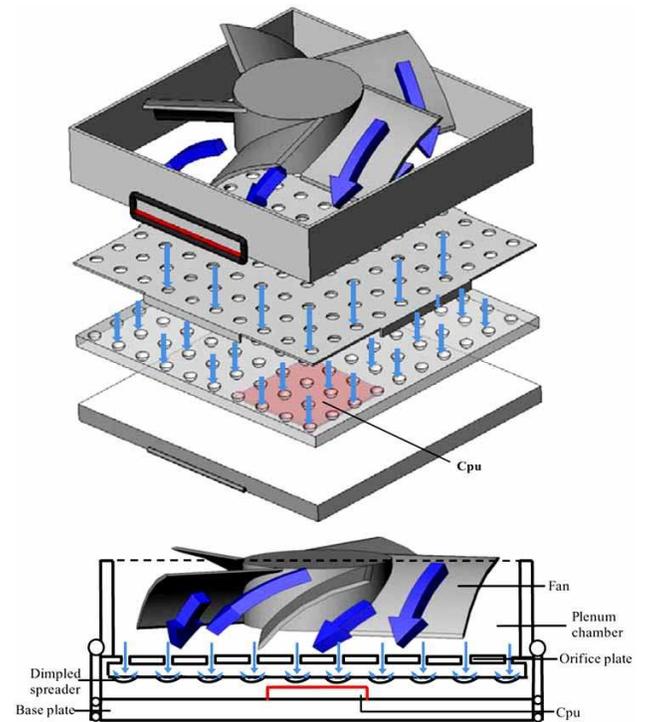
The heat sink referred herein is a cooling device in direct contact with the electronic component to transfer Joule heat from the electronic chip(s) to its surrounding atmosphere or to the radiator (condenser) for the liquid cooling system without (with) phase change process. Following this definition, a heat sink takes the form of fins, pins, vapor chamber or integrated heat spreader. Preliminary attempts for reducing the thermal resistances in association with a heat sink are achieved by increasing the surface area in contact with cooling air. These measures such as the adoption of fin (pin) arrays generally incur the increases of weight and pressure-drop for a heat sink. With the increased needs for miniaturization, alternative approaches to reduce  $R_{c1}$ ,  $R_{c2}$ ,  $R_{conv}$  and  $R_{cond}$  in equations (1) - (3) are developed [8-24]. As an illustrative example, a recent invention [8] devises a heat sink with hollow fin(s) attached on the base heat spreader through which the heat from electronic chip(s) is transferred into the housing of fin(s) such that the liquid coolant in the liquid transfer medium is evaporated and mobilized to the low temperature region of the fin causing the vapor to condense back into liquid and flow back to the liquid transfer medium. Wicks, grooved foam or sintered copper structures which enhance the thermally driven capillary forces can be attached on the inner walls of housing and/or fin(s) and the enclosure of each fin is preferably under vacuum to facilitate vapor flow within. This invention [8]

integrates the heat spreader and fin assembly and takes the advantages of boiling heat transfer to reduce  $R_{conv}$  and  $R_{cond}$  from the scenarios in a conventional air-cooled fan-fin assembly. Recent patent developments for heat sinks gradually employ hybrid techniques to reduce  $R_{c1}$ ,  $R_{c2}$ ,  $R_{conv}$  and  $R_{cond}$ , which are noticeably diverted toward (1) the elevation of convective heat transfer coefficients for heat sink [9-14], (2) the augmentation of cooling performance for heat spreader in direct contact with electronic component(s) [15-20] (3) the development of integrated heat sink unit for air and liquid cooling systems [21-23] and (4) the increase of thermal conductivity of material that constructs the heat sink [24]. Relevant patents in these four aspects for heat sink developments are summarized as follows.

### 2.1. Elevation of Convective Heat Transfer Coefficients for Heat Sink [9-14]

Convective processes transfer heat from the extended surfaces of a radiator, such as plurality of fins or pins that conduct heat directly from electronic components, to the surrounding atmosphere by airflows. With air cooling units, prior arts elevate convective heat transfer coefficients of a heat sink by impinging jets [9] and organizing various types of fin-arrays in a compact assembly in order to improve the fluency of forced convective airflows within [10]. The mechanical layout of the impinging jets air-cooling unit is depicted in Fig. (2). As shown in Fig. (2), the pressurized airflow supplied by an electrical fan generates slot jets impinging onto the dimpled wall through which the heat conducted from the electronic chip is convected by impinging jet-flows. Patents [9-10] feature two examples that considerably reduce the volumes of cooling assembly by way of increasing the convective heat transfer coefficients. With liquid cooling units, patent developments for heat sinks lately look into the elevation of heat convection coefficients inside the heat spreader. Such a liquid cooling unit still employs the radiator to convect heat carried by the primary coolant (water or refrigerant) from the heat spreader to atmosphere; but the additional heat convection process takes place inside the heat spreader where the primary coolant convects the heat from the electronic chip(s) out of the heat spreader by boiling process or single-phase forced convection. As described previously, a large number of porous and micro surface structures [6] are developed to improve the boiling heat transfer inside the heat spreader where the capillary and thermally driven forces are enhanced. The more detailed descriptions for the two phase devices relevant to the patent development with cooling applications to electronic components will be presented in the later section.

In view of performance improvements for heat spreaders in a liquid cooling system, the uses of cooling measures that inherit high convective coefficients such as sprays [11] and the enhanced surfaces with pins, ribs and grooves [12] which trip shear layers to augment turbulent heat convection as well as the adoption of nanofluid as the primary working fluid [13] are developed. In particular, the use of nanofluid can elevate the overall convective capacity and performance for the heat spreader. The nanofluid referred herein is a fluid that has dispersed within it solid particles of high thermal



**Fig. (2).** Air cooling unit based with impinging jet-array onto dimpled heat spreader [9].

conductivities and diameters on the order of nanometers. The increase of Prandtl number for a nanofluid generally increases the Nusselt numbers from the counterpart conventional coolant flows at a constant pumping power; while the increase of thermal conductivity for nanofluid elevates the convective heat transfer coefficient at a fixed Nusselt number. Patent [13] adopts thermally conductive nanofluid to convect heat away from the electronic component. Some embodiments of this invention [13] use a ferrofluid-based pump assembly to drive the nanofluid away from and toward the heat spreader. The ferrofluid-based pump has no mechanical contacts with the driven motor and the driven forces are magnetically transmitted. This particular design minimizes the leakage from the conventional pump assembly that uses seals to prevent leakages between the rotating shaft and the pump casing. With plate-type heat spreader based on the heat pipe principle, patent [14] provides the manufacturing method to produce the rectangular heat pipe using carbon nanotubes as the wick and the nanofluid with metal particles as the working fluid. As the wick includes a carbon nanotubes layer which contains carbon nanotubes of small size and high thermal conductivity, the capillary performances of the wick are improved.

### 2.2. Augmentation of Cooling Performance for Heat Spreader in Direct Contact with Electronic Component (s) [15-20]

Augmentations of heat transfer rate and cooling capacity of the heat spreader in the direct contact with the electronic component(s), which is one type of interfacial devices in Fig. (1a), play the most crucial role for upgrading the performances and capacities of an electronic cooling system. In this respect, improvements of cooling effectiveness/

efficiency of the heat spreader and reductions of the contact thermal resistance between the electronic component(s) and the heat spreader are both under continuous pursuits. For cooling of high performance electronic components, the use of heat pipes and forced convective liquid cooling system have emerged to remove heat out of the heat spreader. Various types of heat spreader are recently developed such as the plate-type heat pipe (vapor chamber), the heat spreader with grooved channels for single-phase liquid cooling system and the multiple heat pipes embedded in a solid heat spreader of high thermal conductivity. In general, the heat removal capacity of a heat pipe is controlled by the length of heat pipe, the wicking media as well as the cross sectional shape and dimensions of a heat pipe. As a heat pipe with diameter of 6 mm can only dissipate about 30-50W of heat, multiple heat pipes embedded in a heat spreader are necessary in order to cool the high performance electronic devices that dissipate more than 100W of heat. Because the spatial distributions of heat flux over an electronic component are non-uniform, the arrangements of heat pipes or coolant channels in a heat spreader need to comply with the local heat flux distributions over the electronic component in order to achieve the optimal cooling performances for the heat spreader. With the multiple heat pipes embedded in a heat spreader, the recent invention [15] optimizes the boiling temperatures of the heat pipes in a heat spreader to ensure that these heat pipes start to boil at approximately the same heat load condition from an electronic component, thereby utilizing the full heat removal capacity of these heat pipes. Heat pipes in a heat spreader can differ in boiling temperatures by various vacuums or differ in cooling capacities by different diameters and/or allocations [15]. For the forced convective liquid (single-phase) cooling system, the compliance with the predefined spatial heat flux distribution over an electronic component is achieved by adjusting the dimensions of circulating coolant channels in the heat spreader [16]. The goal of these inventions [15-16] is to ensure that all of heat pipes or coolant channels in a heat spreader are functioned with their full cooling capacities, resulting in an optimal and efficient cooling performance for the heat spreader in a heat sink.

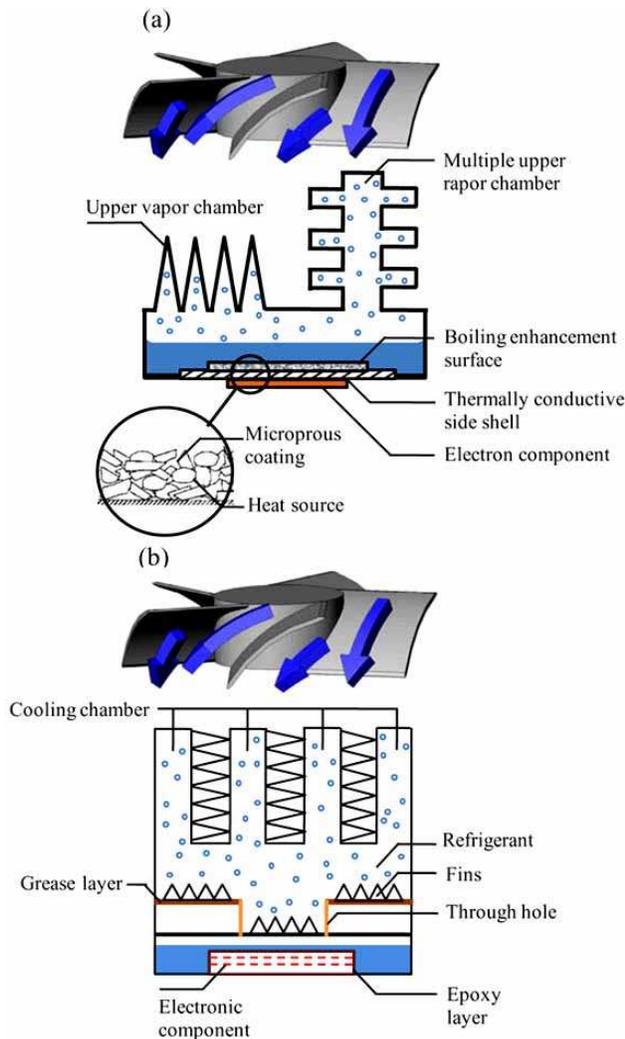
Reductions of contact thermal resistances between the electronic component and the heat spreader or radiator are mainly achieved by increasing the area for heat dissipation using porous material and by elevating the thermal conductivity for the contact layer [17-20]. To increase the area for heat dissipation, a ceramic heat sink utilizes a conductive layer of high thermal conductivity on the electronic component adjoining by a heat dissipation layer having the micro porous structure with hollow crystals [17]. The micro-pores layer serves to increase the contact surface area, thereby reducing the contact thermal resistance. To increase the thermal conductivity for the contact layer, the contact layer can be produced by using a soft matrix material mixed by carbon nanotubes and/or thermal pyrolytic graphite flakes. In particular, the carbon nanotubes or thermal pyrolytic graphite flakes are preferred to be aligned and perpendicular with the contact surface of the electronic component so that the thermal conductivity of this contact layer is effectively elevated but highly directional. It is worth mentioning that, for such applications, these carbon

nanotubes are nanometer wide but are many microns long, which are essentially rolled-up sheets of carbon hexagons with a thermal conductivity on the orders of  $2000 \text{ Wm}^{-1}\text{K}^{-1}$  [18]. However, the thermal interfacial layer formed by injection molding may cause the carbon nanotubes to be disposed in the matrix material randomly and multi-directionally which can not sufficiently utilize the heat conduction capability of the carbon nanotubes. To overcome this manufacturing difficulty, the carbon nanotubes are capsulated in a nanometer-scale metal having high thermal conductivity and the array of carbon nanotubes is directly formed on the contacting surface of the heat spreader before packaging [19]. As a result, the high temperatures needed for forming the carbon nanotubes are obviated. Such manufacturing method can lead to the more efficient use of high thermal conductivity of carbon nanotubes to reduce the contact thermal resistance. Alternative approach by coating a layer of Fullerenes, which are a class of carbon molecules having an even number of carbon atoms arranged in the form of a closed hollow cage, between the heat spreader and the electronic component in order to prevent the tiny air gaps within the interfacial layer is documented in [20] to reduce the contact thermal resistance.

### 2.3. Development of Integrated Heat Sink Unit for Air and Liquid Cooling Systems [21-23]

Miniaturizations of electronic devices along with improved performances have led to the development of integrated heat sinks involving phase change and/or forced liquid convection. An integrated forced convective liquid cooling unit [21] comprises a heat spreader in contact with the electronic component, a pump and a heat exchanging section that is thermally connected to the cooling section to radiate heat convected from the heat spreader to the atmosphere. A low cost boiling heat sink that utilizes the enhanced microporous coating to significantly augment the nucleate boiling heat transfer and the critical heat flux integrates the vapor chambers and radiators as shown in Fig. (3a) [22]. As seen in Fig. (3a), the boiling cooler comprises a vessel that is partially filled with a liquid coolant, consolidated with the vapor chambers (condensers) for the vapor to spread heat around the extended surfaces around which the secondary coolant flows (airflows) convect latent heat away to convert vapors into liquids. A layer of microporous coating for boiling heat transfer enhancement is applied on the thermally conductive wall, which is at least partially submerged in the liquid within the vessel. As the pumping force to circulate vapor and condensate within the heat sink as shown in Fig. (3a) is driven by free convection, cooling performances for such a heat sink are orientation dependent. Another integrated heat sink involving phase change processes is depicted in Fig. (3b) [23] in which a thermoelectric module or a thermosyphon is adopted to transfer heat in the lateral direction from the central portion of the heat plate to its periphery and then to the fin-assembly for heat exchanges. The thermoelectric module indicated in Fig. (3b) establishes a differential potential of thermal energy between the cold and hot sides to electrically pump heat from the cold to hot sides by using the electrical energy. The thermoelectric module is assigned to transfer heat from the central portion of an electronic chip toward its peripheral portion that smoothes out the non-uniform heat fluxes over

the electronic chip. Also such integrated heat sink (see Fig. 3-b) can be comprise by a thermosyphon cooling system within which a refrigerant is disposed in the lower portion of the thermosyphon for liquid-to-vapor transformations. Extended cooling fins are disposed in the lower portion of the thermosyphon for transforming heat from the electronic component to the refrigerant that vaporizes the refrigerant. Upper portions of the thermosyphon are equipped with fins in contact with the externally supplied cooling airflows as the condenser to recover vapors into liquids.



**Fig. (3).** Integrated two-phase heat sinks (a) microstructure enhanced [22] (b) thermosyphon enhanced [23].

#### 2.4. Increase of Thermal Conductivity of Material that Constructs the Heat Sink [24]

As described before, a conventional heat sink employing fins to extend heat transfer surface cause volume and weight problems. Using graphite is one feasible solution to overcome these problems by increasing the thermal conductivity of these extended fins, which can reduce the volume of fin-array needed. However, previous graphite developments

were directed toward the graphite sheets that comprise plurality of graphite layers at the micrometer level. Thermal conductivities for prior art graphite layers are usually directional with the thermal conductivity in the direction parallel to the heated plane to be greater than that in the perpendicular direction. Such characteristics limit the applications of graphite from constructing the heat sink assembly. Further developments using ultra-thin material to construct the heat sink has led patent [24] to devise the heat sink material comprising at least a graphite layer exhibiting a thermal conductivity which is anisotropic in nature and is greater than  $500\text{Wm}^{-1}\text{K}^{-1}$ . The graphite layer is structurally supported by the thin metal and mixed with polymeric resin and or ceramic. Such thermal pyrolytic graphite composite can be coated on or folded to a plurality of fin assemblies, which increase the thermal conductivity of material and reduce the weight of these extended convective surfaces.

### 3. APPLICATIONS OF NANOTECHNOLOGY

Researchers have achieved many progresses on researches and developments in the area of nanotechnology or nanoscience, particularly in the area of nanomaterials, in recent years. Substantially amounts of patents are granted for improving the thermal performance of devices that are employed in cooling systems for electronic devices. Major efforts are focused on the following areas, namely, contact resistance between two solid surfaces, convective resistance from heat exchanger surface to the atmosphere, capillary limit of interfacial device, thermal performance of working fluid.

#### 3.1. Reduction in Contact Resistance

Contact resistance between two solid surfaces is a major concern for assembling the thermal module that is used in electronic devices. Conventional approach is to employ a clamping device that exerts pressure on two attached components of which the interface is filled with thermal grease with high thermal conductivity for alleviating the large thermal contact resistance caused by the air layer. Most inventors take the advantages of large thermal conductivity of carbon nanotube to improve the contact thermal resistance between two solid surfaces. Experimental results show thermal conductivity of multi-wall carbon nanotubes (CNT) ranges from 300 to 3000 W/mK, depending on length and diameter of nanotubes [25]. The lower bound of thermal conductivity of multi-wall carbon nanotubes is almost same as that of gold in bulk form. If the carbon nanotubes can be applied to the interfacial material between two solid surfaces that undergoes the heat exchange, they can dramatically reduce the thermal contact resistance,  $R_{c1}$  to  $R_{c5}$  in Eqns. (1) - (3).

An interfacial material between two solid surfaces is composed of silver colloid and carbon nanotubes and is developed by Leu *et al.* [26]. Nanotubes are aligned parallel in the interfacial material and are attached normally to these two solid surfaces. In addition, nanometer-scale silver is filled into the empty spaces inside nanotubes. Leu *et al.* further introduced such an interfacial material in an intergrated circuit package between a heat spreader and a wafer die [27]. Li and Meyyappan revised the CNT-filler composite by allowing one end of CNT exposed in the

atmosphere from the filler material [28]. The exposed ends of nanotubes are pressed against a solid surface that transports heat through these nanotubes. Santana *et al.* also proposed a heat dissipated component packed with an integrated circuit device and a radiator, which is filled with carbon nanotubes [29] that can help to transport heat from the circuit device to the radiator. In these prior inventions, the devices contacted with the heat dissipated component or interfacial materials are not directly adhesive together. Dubrow developed adhesive nanofibers to bound two surfaces [30]. Nanofibers are initially implanted on one surface. The second surface is adhesive to the nanofibers through van der Waals forces when the second surface is moved to attach the nanofibers. This phenomenon is similar to the way that a gecko with foot-hairs (setae) can hang from ceiling. The empty space between two contacted solid surfaces can be significantly reduced by the presence of adhesive nanofibers. Unfortunately, none of experimental results of prior inventions except the one by Li and Meyyappan [27] is presented to show how many percentages of thermal contact resistance between two solid surfaces are improved if the interfacial material with nanotubes or nanofibers is employed.

### 3.2. Reduction in Convective Resistance from Heat Exchanger Surface to the Atmosphere

Fig. (4) shows a schematic view of arrayed nanorods that are immobilized on a substrate surface. The heat exchange area of substrate with ambient is increased significantly with the nanorods attached on the substrate. Jiang proposed a radiator of which the surface is covered with aligned carbon nanotubes normal to the radiator surface [31]. If a substrate with an area of  $1 \text{ cm}^2$  is uniformly covered by nanotubes with a length of  $1 \text{ }\mu\text{m}$ , a diameter of  $40 \text{ nm}$ , and spacing between centers of neighboring nanotubes of  $100 \text{ nm}$ , the heat exchanger area is increased by 12 times. If the convective heat transfer coefficient over the tube surface is similar to that over the substrate, the value of  $R_{conv}$  in Eqns. (1) to (3) is dramatically reduced. However, the question remains whether can the air flow be driven into the narrow gaps between nanotubes or not? It requires further experimental studies to confirm it.

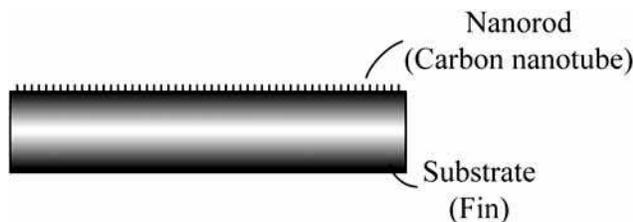


Fig. (4). Increase in heat exchanger area of a substrate with arrayed nanorods.

### 3.3. Increase in Capillary Limit and Boiling Limit of Interfacial Devices

The maximum heat that a convective heat pipe can dissipate is dominated by three major limits, namely, sonic limit, capillary limit, and boiling limit, [32]. If de-ionized water is used as the working fluid in a circular copper heat

pipe with an operating temperature ranging from  $60^\circ\text{C}$  to  $85^\circ\text{C}$ , typical junction temperatures for electronic devices, the heat transport capacity of the heat pipe is decided by either capillary limit or boiling limit among these three aforementioned limits. If the heat transport capacity of heat pipe is constrained by the capillary limit, the heat pipe does not have small enough wick structures on the wall surface to create enough capillary force to drive condensed liquid from the condenser section back to the evaporator section for the case that applied heat is over the capillary limit. The evaporator section is finally dried out. If the heat transport capacity of heat pipe is constrained by the boiling limit, it is directly related with the critical heat flux of de-ionized water on the heat pipe wall. When the applied heat is over the critical heat flux, a vapor film is formed on the wall of evaporator section.

Note that the capillary limit is linearly proportional to the reciprocal of effective capillary radius ( $1/r_c$ ) of wick pore at the liquid-vapor interface. The reduction in wick pore can also result in an increase in CHF [6]. In commercially available heat pipes used in electronic devices, the capillary radius is at an order of around hundred micrometers. Therefore, nanotechnology is a perfect choice to replace micro wick structures with nanostructures on the wall surface of heat pipe for raising both the capillary and boiling limits. It is worthy of noting that the contact angle of water with a solid surface could be significantly varied if the surface is covered with nanostructures. Through the help of available fabrication technologies, the material of nanostructures could be different from that to surface. Therefore, the material of nanostructures must be properly chosen to assure a hydrophilic surface. With the same nanostructure on the surface, a hydrophilic surface has less chance to trap vapor than a hydrophobic surface, too.

Applications of nanotechnology in heat pipe are intended to reduce both the effective capillary radius and surface roughness from micrometer to nanometer on the wick layer on heat pipe wall. Consequently, both capillary and boiling limits of heat pipe can be significantly increased. As a result, the value of  $R_i$  in both Eqns. (2) and (3) can be reduced. Fig. (5) shows a cross-sectional view of a circular heat pipe. The pore size of wick structure on the inner wall of heat pipe is reduced from micrometer to nanometer in two prior inventions [33-34]. A fluid with suspended nanoparticles was also applied in the heat pipe with nano wick structures [34]. Chen proposed a hierarchical layer on the inner wall of heat pipe [35]. The hierarchical layer is established by immobilizing nanoparticles on a mesopore layer of which the pore size ranges from  $2 \text{ nm}$  to  $50 \text{ nm}$ . The diameter of immobilized nanoparticles ranges from  $1 \text{ nm}$  to  $20 \text{ nm}$ . Note that none of aforementioned applications are applied to the wick structures in vapor chambers.

### 3.4. Increase in Thermal Performance of Working Fluid

Choi and Eastman are the first ones to propose by adding suspended nanoparticles into a base fluid to enhance the thermal conductivity of base fluid [36]. Addition of suspended nanoparticles into a base fluid becomes what is called nanofluid. Wang, and Mujumdar provided a complete review on thermal performance of nanofluid [37]. They

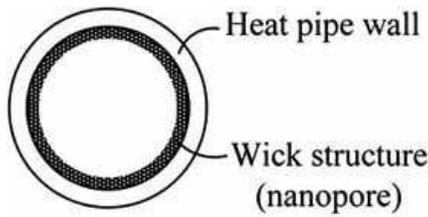


Fig. (5). Cross-sectional view of a circular heat pipe.

show the dramatic effects of suspended nanoparticles on thermal conductivity, convective heat transfer coefficient, and CHF of base fluid. With such a significant enhancement in thermal performance of base fluid by adding suspended nanoparticles, nanofluid becomes the best candidate that is suggested to be implemented in a liquid cooling system of electronic devices. However, the sediment time of suspended nanoparticle is a key factor to affect the reliability of nanofluid used in a liquid cooling system. The concentration of suspended nanoparticles in the base fluid drops significantly 800 hours after the nanofluid is prepared [38].

Bonsignore and Gurin proposed a heat transfer composite that is composed of a transfer medium and an additive with stabilized surfactant [39]. The size of additive material ranges from 1 nm to 100  $\mu\text{m}$ . The materials for both heat transfer medium and additive claimed in their patent almost cover most available materials in the world. Withers and Loutfy specified the additive is carbon nanoparticle without stabilized surfactant [40]. Davidson and Bradshaw further specified that the heat transfer medium is soy-based oil and the additive is diamond nanoparticle. Zhang and Lockwood specified not only the material of additive as carbon but also the capability of stabilized chemical agent covering the additive. The stabilized chemical agent must have a low hydrophile-lipophile balance value of 8 or less [41]. Although nanofluid is proposed or developed in those aforementioned patents, none of those patents specify how to drive nanofluid in a closed system. Ouyang proposed a specific ferrofluid-base pump to drive working fluid with ferro-nanoparticles for transporting heat from a heat generator to a heat sink [13].

#### 4. HEAT PIPE TECHNOLOGY

The increasing integration of logic and memory onto a single processor poses two challenges, namely: (1) the total power dissipation from a single processor is about 100W or above, with an averaged heat flux of about  $100\text{W}/\text{cm}^2$ ; and (2) the peak power densities can increase up to  $500\text{--}1000\text{W}/\text{cm}^2$  in the future. To dissipate this power and power density with a resistance at less than  $0.1\text{K}/\text{W}$  requires innovative solutions. The use of conventional air-cooled heat sinks alone is precluded in these applications [42]; while the closed loop system will transfer the heat from the electronic chipsets to the surrounding atmosphere by way of air cooling unit. In this respect, a conventional air cooled heat sink has the drawbacks of: (1) a large capacity fan undesirably produces very loud noise; (2) it cannot be used alone if the heat density exceeds a certain limit (e.g.,  $30\text{W}/\text{cm}^3$ ); (3) the use of this type heat sink leads to a relatively large size [43]. For an electronic cooling system, to lower the thermal

resistance, heat pipes or vapor chambers are used as heat sinks.

The modern concept for a capillary driven heat pipe was first suggested by R.S. Gaugler of General Motors in 1942 [43]. A heat pipe is a heat transfer device that can transport large quantities of heat with a very small temperature difference between the hotter and cooler interfaces. Inside a heat pipe at the hot interface, the working fluid turns to vapor and the vapor naturally flows and condenses on the cold interface. The liquid falls or is moved by capillary action back to the hot interface to evaporate again and repeat the cycle. Such conventional heat pipe consists of a sealed pipe or tube made of a material with high thermal conductivity such as copper or aluminum, as shown in Fig. (6). A sintered metal powder or a series of grooves parallel to the pipe axis inside the pipe wall is commonly used to exert this capillary action on the liquid. The heat pipe may not need a wick structure if gravity or some other source of acceleration is sufficient to overcome flow resistance and surface tension, and cause the condensed liquid to flow back to the heated end, like a thermosyphon. The performance of a heat pipe is often expressed in terms of "equivalent thermal conductivity". A tubular heat pipe illustrated in Fig. (1), using water as the working fluid and operated at  $150^\circ\text{C}$  would have a thermal conductivity several hundred times that of copper [44]. Heat pipes contain no mechanical moving parts and typically require no maintenance. The working fluids chosen depend on the temperature conditions in which the heat pipe must operate, with coolants ranging from liquid helium for extremely low temperature applications (2–4 K) to mercury (523–923 K) & sodium (873–1473 K) and even indium (2000–3000 K) for extremely high temperatures. The vast majority of heat pipes for low temperature applications use some combination of ammonia (213–373 K), alcohol (methanol (283–403 K) or ethanol (273–403 K)) or water (303–473 K) as the working fluid.

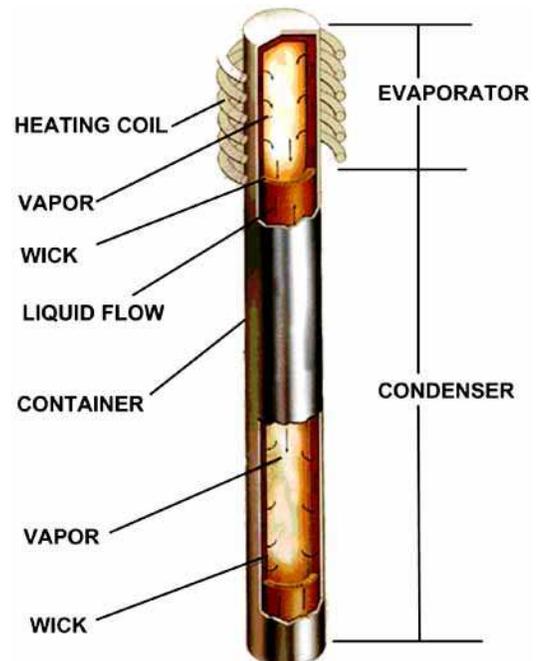


Fig. (6). Schematic of conventional heat pipe.

A loop heat pipe (LHP) which was developed to overcome the inherent problem of a conventional heat pipe has a separating vapor and liquid lines, as shown in Fig. (7), [45]. The isolation of the liquid path from the vapor flow will avoid liquid-vapor entrainment limitation and can transfer heat to a comparatively long distance for dissipation due to the co-current flow merits.

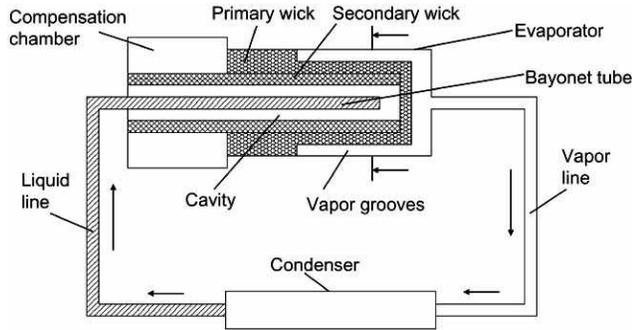


Fig. (7). A typical structure of a loop heat pipe [45].

Another special type of heat pipe widely used for electronics cooling now is the vapor chamber, which is a kind of flat heat pipe and mostly used as the base of a heat sink as seen in Fig. (8). The effective thermal conductivity of a heat pipe or a vapor chamber is between 5000-20000W/mK. If a heat pipe is attached to the base of a heat sink, the extra interface resistance from this bonding can degrade the effective conductivity. However, a vapor chamber can be a part of the base, eliminating this extra thermal resistance [46].

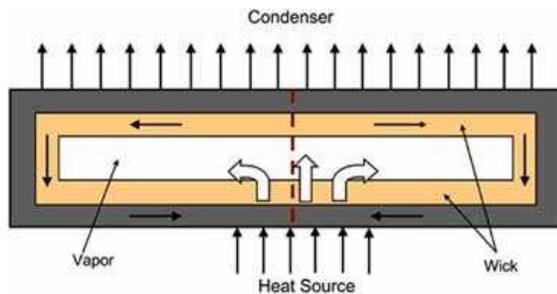


Fig. (8). Schematic of a vapor chamber [46].

In view of the patent development for heat pipes, Sony began incorporating heat pipes into the cooling schemes for some of its commercial electronic products in place of both forced convection and passive finned heat sinks in 1980s. During the late 1990s increasingly hot microcomputer CPUs spurred a threefold increase in the number of U.S. heat pipe patent applications. As heat pipes transferred from a specialized industrial heat transfer component to a consumer commodity, most development and production moved from the U.S. to Asia [44]. Every year, there is a huge of inventions and new applications about heat pipe. The patent review in this respect, the latest inventions from 2005 till

now on heat pipe, loop heat pipe and vapor chamber for electronics cooling will be summarized and the content will be divided to three categories: new concepts of applications; new materials and new structures; and new applications in the new emerging areas other than IT industry.

#### 4.1. New Concepts of Applications

Among the new patents for electronics cooling, different combinations; such as heat pipe + heat sink, vapor chamber + heat sink, thermoelectric cooler (TEC) + heat pipe + heat sink, TEC + vapor chamber + heat sink, vapor chamber + heat pipe + heat sink, and thermosyphon + heat pipe + heat sink, have been proposed. The representative patents for these various combinations are summarized as follows:

##### Heat Pipe or Vapor Chamber + Heat Sink

In the patent [47], a heat pipe directly integrated to a heat sink, as shown in Fig. (9), is constructed by forming a boundary structure by sealing together two formed plates: contact plate and cover plate. Contact plate and cover plate are sealed together at their peripheral lips and by conventional means, such as soldering or brazing, to form heat pipe. The interior of heat pipe is, however, constructed unconventionally. While contact plate is essentially flat with the exception of peripheral lip, cover plate includes multiple depressions. Depressions are formed and dimensioned so that, when contact plate and cover plate are joined, the flat portions of depressions are in contact with inner surface of contact plate. Depressions thereby assure that the spacing between contact plate and cover plate will be maintained even through pressure differentials between the inside volume of heat pipe and the surrounding environment might otherwise cause the plates to deflect toward to each other. The other process is same as the art of conventional heat pipe.

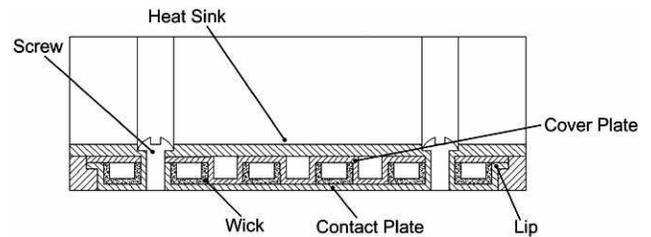
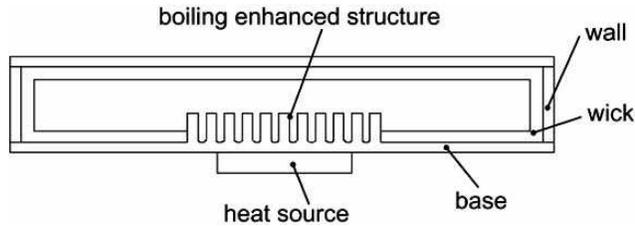


Fig. (9). Cross-sectional view of a flat plate heat pipe in direct contact with finned heat sink.

In the patent [48], a vapor chamber is proposed to improve the base conductivity of the heat sink, as shown in Fig. (10). Vapor chambers make use of same principle as heat pipe. If the area of the cooling surfaces is much larger than the evaporating surface, the spreading of heat can be achieved effectively since the phase change mechanism occurs near the isothermal condition. Consequently, the heat flux can be reduced inversely proportionally to the area ratio of heating surface to the cooling surface. In this invention, boiling enhancement features are adapted into the vapor chamber through a boiling enhanced multi-wick structure. With this structure, the condensate is collected from the



**Fig. (10).** A sectional side view of a vapor chamber implemented as a flat plate.

condensation sites using a wicking structure with a spatially-varying wicking power. Various boiling enhancement structures can be adapted at the heating zone to simultaneously provide wicking-power and boiling enhancement. In this manner, the boiling enhancement structure is not totally submerged inside a pool of liquid, and thus can operate in anti-gravity orientations. In addition, this boiling enhancement structure may act as a 3-D bridging wick, which may also provide a structure supporting function.

The boiling enhancement structure is protruded wick having a wicking power greater than that at the condensation site. As indicated in Fig. (10), the protruded wick can be in the form of fins so that the liquid can be wicked between the fins towards the tips of the fins. Besides fins, the protruded wick can also be an array of pins. Interlinking structures between fins or pins can also be used to increase the boiling surface area. Foam/porous structures can also be used in the protruded wick to provide the larger boiling surface area with the added heat diffusion in the porous media. With all of these structures, the objective is to provide a heat conduction path from the heating source toward a larger boiling surface, and to saturate this boiling surface (without total immersion) with condensate that is continually supplied by the complex wicking system.

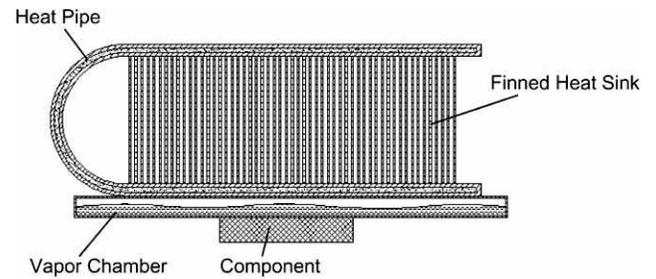
Similarly, a vapor chamber can serve as a heat spreader for the microelectronics die [49]. A thermoelectric module (TEC) serves to cool the vapor chamber and maintain proper functioning of the vapor chamber, thus keeping the microelectronic die cooled. A controller receives inputs from five temperature sensors, and utilizes these temperature measurements to control the current through the thermoelectric module and the voltage/current to a motor that drives a fan and provides additional cooling. The vapor chamber contacts the microelectronic die tightly and has a larger footprint than the die, serving as a heat spreader.

#### Vapor chamber + heat pipe + heat sink

ATI proposed a thermal management device utilizing varied methods of heat transfer augmentation to cool a heat generating component. In the proposed embodiment, at least one heat pipe is used to transfer heat from the condensation portion of a vapor chamber to a colder location on a finned heat sink which is also attached to the condensation portion of the vapor chamber [50], as depicted in Fig. (11).

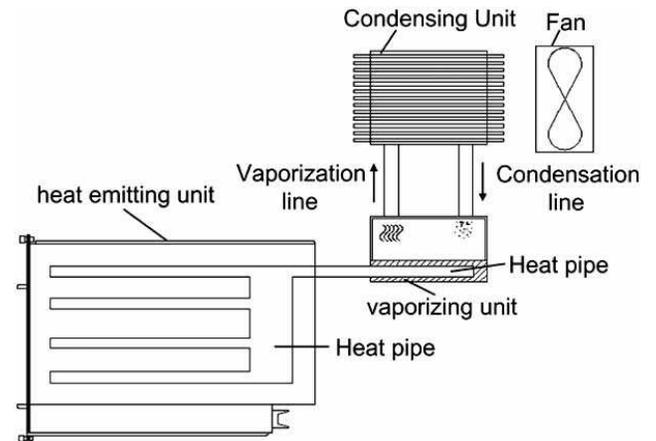
#### Thermosyphon + Heat Pipe + heat sink

A proposed patent [43] for cooling communication equipment using a heat pipe + thermosyphon overcomes the



**Fig. (11).** Cross-sectional view of the proposed cooling device [50].

low cooling capacity of the conventional fan + heat sink unit as shown in Fig. (12).



**Fig. (12).** Schematics of cooling unit for telecommunication equipment using a heat pipe and a thermosyphon [43].

A heat pipe mounted on a predetermined location of a heat emitting unit in a communication equipment transfers heat from the communication equipment. A vaporizing unit for vaporizing liquid inside the thermosyphon with the heat transferred via the heat pipe contacts a predetermined location of the heat pipe. A condensing unit to discharge the heat carried by the vapor to the environment is connected to the vaporizing unit through a vaporization line and a condensation line. A small capacity fan provides cooling air to the condensing unit. This thermosyphon does not need a separate power, but uses the heat generated by the unit. By way of employing the high density fin stack around the condensing unit [51], the size of such system can be reduced with the same heat discharge capability; or the capacity burden on the fan can be reduced.

#### TEC + Heat Pipe or Vapor Chamber + Heat Sink

This type of cooling unit, as exemplified by Fig. (13) [51], a plurality of heat pipes directly insert between the plates of the TEC unit. The heat pipes can be freely allocated, wherein the space around the heat exchanger can be used more efficiently with a high density fin stack around the heat pipes. Thus, the size of the system can be reduced with the same heat discharge capability.

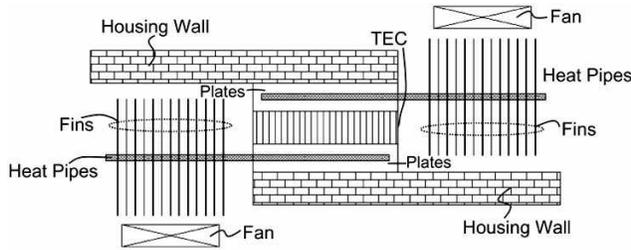


Fig. (13). TEC heat exchanger with heat pipe applied [51].

#### 4.2. New Materials and New Structures

As previously described, a sealed tube with wick structure on the inner surface is filled with working fluid which circulates inside the heat pipe with the aid of capillary force generated at the meniscus inside the wick. In this section, the patents about the working fluid, unique wick material and structure as well as other novel concepts for heat pipe developments are summarized.

##### Working Fluid

In patent [52], the proposed formula for working fluid contains any of  $C_4F_9C_2H_5$ ,  $C_6F_{13}C_2H_5$  and other compounds of the formula  $C_nF_{2n+1}C_mH_{2m+1}$ . The working fluid has a working temperature of  $-50^\circ\text{C}$  to  $200^\circ\text{C}$  without the danger of inducing a negative impact on environment, such as the disruption of ozone layer which accelerates the global warming. Another patent proposed an environment-friendly formula with a boiling point from  $20^\circ\text{C}$  to  $70^\circ\text{C}$ , which can be used for heat pipe [53]. Yujin Co. Proposed two methods for filling working fluid in a fine/micro heat pipe [54] and [55], different from the conventional vapor blown method.

##### Wick Material and Structure

Although the sintered wicks have demonstrated the adequate heat transfer characteristics in the prior arts, the minute metal-to-metal fused interfaces between particles tend to constrict heat conduction through the wick as described in [56]. The proposed invention [56] provides a capillary structure for a heat transfer device that comprises a plurality of particles joined together by a brazing compound such that fillets of the brazing compound are formed between adjacent ones of the plurality of particles. One or more vapor vents are defined through the capillary structure so as to provide enhanced vapor escaped passages through the capillary structure. In this way, while a network of capillary passageways are formed between the particles to aid the transfer of working fluid by capillary action, with the plurality of fillets provided to enhanced thermal conduction properties between the plurality of particles so as to greatly improve over all heat transfer efficiency of the device, the one or more vapor vents allow for a minimized pressure drop and therefore a minimized  $\Delta T$ , as depicted in Fig. (14).

As described in previous section, nanotechnology has found its wide applications to the wick structure in the two-phase devices for electronic cooling. As depicted in Fig. (15) [42], the heat dissipation system which comprises a vapor

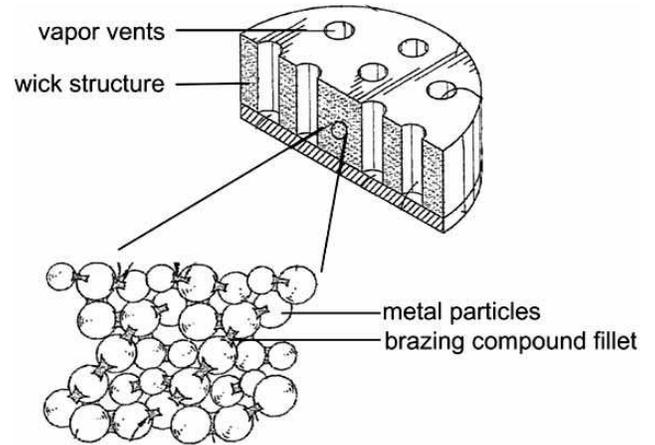


Fig. (14). A broken-way enlarged perspective view for the metal particles and fillets as wick structure [56].

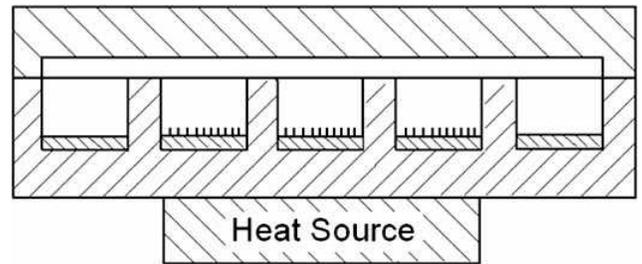


Fig. (15). Cross-sectional view of a nanostructured heat pipe.

chamber, a heat sink, a heat source and a nanostructure array extending from the heat source adopts the nanostructured composite wick.

As indicated in Fig. (16), the nanostructured composite wick comprises a channel, a plurality of nanostructures, wherein the nanostructures have a differentially-spaced apart gradient along the length of the channel so as to promote capillary fluid flow. The formation of the wick can be one or a combination of the following processes; namely depositing a solid film on a substrate and then electrochemically etching the solid film forming arrays of nano-pores; and/or electrochemically growing nanowires or nanotubes in the nano-pores and annealing the nanowires to form polycrystalline wires. The calculated overall thermal resistance based on silicon and Cu are respectively  $0.0467$  and  $0.0251 \text{ cm}^2\text{K/W}$ .

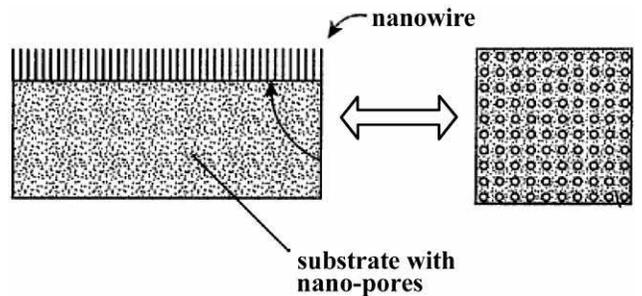


Fig. (16). Schematic diagram illustrating synthesis of Cu nano wire array with controlled density and wire diameter.

Quite similar to the cooling device proposed by patent [42] that uses microfabrication technique, the patent [57] employed a micro heat pipe with nanostructured wick on the order of approximately 10 to 400 nm with spacing between the nanoelements in the approximate range of 20 to 600nm as shown in Fig. (17). The proposed nanostructured bristle wicks [57] enable more efficient heat exchange in the heat pipe. By way of defining the boiling surface area ratio (BSR) as the ratio between the effective surface area with the wicking material for evaporation and the unit area that the wicking material occupies along the interior surface of heat pipe, the typical BSR for such device [57] falls in the range of approximate 18 to 125. As a comparative example, the conventional sintered metal powder with a 1mm thick coating generally has a BSR about 0.035.

Heat transfer data were measured for the prototype heat pipes with one inch in diameter [57]. By using the nanobristle array organized by nanowires as the evaporator, the thermal resistance is reduced to the range of 0.06-0.08 Ccm<sup>2</sup>/W within the desired heat flux of 100-200 W/cm<sup>2</sup>. Also the nanobristle heat pipe show a significant 25-30% reduction in thermal resistance over the sintered metal powder heat pipe as compared in Fig. (18).

**Novel Concept**

Another new method for miniaturization of heat pipe or loop heat pipe is introduced by patent [58]. This invention is a MEMS-based LHP or CPL using CMOS grade silicon and microlithographic techniques to achieve a planar configuration. The major working material is silicon which is particularly compatible for the cooling and packaging needs for electronic devices. This micro LHP uses a new coherent porous silicon (CPS) wicks. The CPS wicks can minimize the packaging stress and improve the strength-to-weight ratio. Also the burst-through pressures can be controlled as well as the diameter of the coherent pores can be controlled on a sub-micron scale. This two phase planar operation can provides a sound heat transfer capacity (20-60 W/cm<sup>2</sup>). Cooling performances of such two-phase device are dependent upon the CPS wick. As an alternative approach, the nanofluid enhanced heat pipe [59] exhibits high heat transfer performance, while being small-sized and light-weighted. Such a heat transfer device is realized by having organic fine particles contained in a working fluid through the optimizations of particle size, mixing ratio, composition

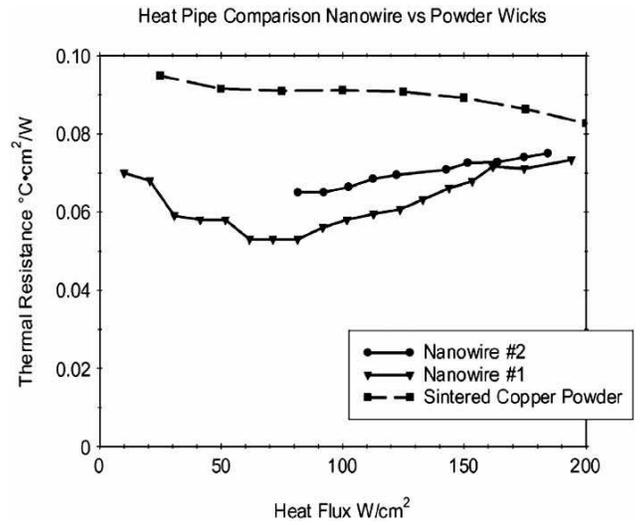


Fig. (18). Thermal resistance against input heat flux for heat pipes with nanobristle array wicks.

and surface characteristics. Specifically disclosed in [59] is a heat pipe wherein the working fluid containing 0.001-5 wt% of organic fine particles having an average particle diameter of 1-1000 nm in a hermetically sealed container

A loop heat pipe assembly may require a lengthy condenser section for adequate heat transfer. However, the lengthy condenser section may be too long to fit within a maximum packaging volume, as a requirement for shipping and handling. Thus, a need exists for a component of a heat pipe assembly that assumes a compact volume for packaging, and that deploys to a length that would exceed the packaging volume limitation. The proposed invention [60] is a component of a looped heat pipe assembly that has bendable sections, as shown in Fig. (19), which allow the component to assume a number of dimensional configurations. The invention allows a heat pipe of large size to fit in a package.

As seen in Fig. (19), the embodiment of each condenser bendable section is made bendable by a hollow tubular bellows providing annular vapor line. The bellows is flexible in addition to being bendable. Each open end of the bellows couples with the outer tube of a corresponding condenser rigid section with a hermetic seal to provide a continuous

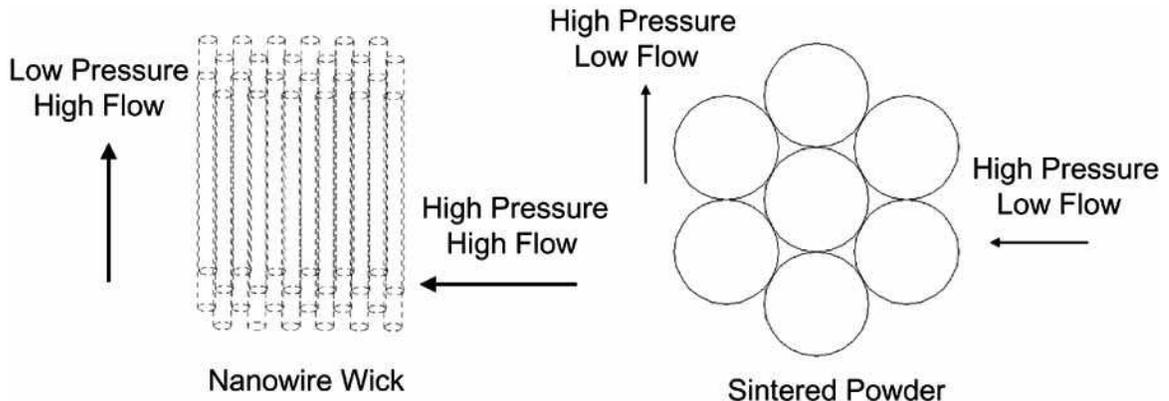
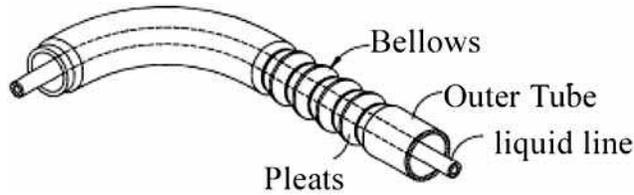


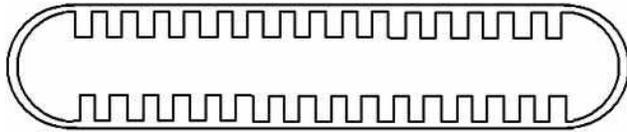
Fig. (17). Comparison of fluid flow in nanowire and sintered powder heat pipe wicks.



**Fig. (19).** Enlarged view of a hollow bendable fluid transport section.

vapor line. For the inside liquid line, the tube is made, for example, of polytetrafluoroethylene (PTFE) formed into bendable tubing. Thermal insulation properties of the tube provide insulation against thermal interaction between the vapor and the condensate.

A simple manufacturing method of miniaturized flat plate heat pipe is proposed in [61]. This invention provides a fine structure of flat plate heat pipe formed of a flat pipe having a predetermined through-hole therein and a plurality of grooves extending from an inner surface of the through-hole in a longitudinal direction. The working fluid flows by a capillary force produced from the plurality of grooves taking the various forms. Figure 20 typifies the flat heat pipe fitted with U shaped plurality of grooves.



**Fig. (20).** Sectional view of flat heat pipe having a plurality of grooves [61].

## 5. CURRENT & FUTURE DEVELOPMENTS

The increased power density for electronic chipsets and assemblies has urged the developments of cooling units for high power electronic components toward the two-phase systems which employ various heat transfer augmentation designs. In addition to the wide range of heat transfer augmentation methods developed for the single-phase convection, the efficient wick structures for two-phase components as well as the methods for reducing the thermal contact resistances have utilized the nanotechnology to improve the thermal physical properties and/or the surface topology for capillary actions. The emerging design proposals with various combinations of the interdependent cooling components such as vapor chamber +heat sink, thermoelectric cooler (TEC) + heat pipe + heat sink and thermosyphon + heat pipe + heat sink have led the future developments of electronic cooling concepts toward the system development. In this respect, the interdependency between the cooling components in an electronic cooling system involving two-phase devices and the performance improvements for the worst components in an electronic cooling system have drawn the current research attentions for future developments. Current techniques developed for electronic cooling systems also keep finding their alternative applications to the optical and electronic communication systems where the high cooling power density is essential for their normal operations.

## 6. CONCLUSIONS

The hybrid technology for cooling devices such as the combination of phase-change process with nanofluid and the utilization of carbon nanotubes for wick structure or for thermal contact layer has emerged as the current trend of patent developments for thermal managements of electronic systems. Although the air-cooled radiator is a subject of long term development, this device which convects heat to the surrounding ambience appears to be essential for all different types of electronic cooling systems. Design concepts for optimizing the cooling effectiveness of the subassembly in an electronic cooling system shall shift from the increased cooling area by using fins or pins toward the more effective conductive and convective measures due to the ever mounting needs for miniaturization of electronic devices. In this respect, the nanotechnology has found its applications to reduce the thermal contact resistance between two subassemblies with temperature differences, to increase the capillary limit of interfacial device by improving the microstructures of wicks and/or inner surfaces in two phase components and to upgrade the thermal physical properties of working fluid. Cooling performances of the thermally driven, self-circulating phase change devices depend greatly on their orientations in respect to gravity, which can be combined with the forced liquid cooling system in order to upgrade their cooling performances. With the future needs to develop the forced liquid convective system involving phase change processes, the optimization of condenser design is urged.

## NOMENCLATURE

$R_{cond}$	=	Combined conductive resistance of heat exchanger and radiator ( $\text{Km}^2\text{W}^{-1}$ )
$R_{conv}$	=	Convective resistance of radiator, vapor chamber or heat pipe ( $\text{Km}^2\text{W}^{-1}$ )
$R_i, R_{ci}$	=	Thermal resistances of interfacial device and contact resistance ( $\text{Km}^2\text{W}^{-1}$ )
$\phi$	=	Heat flux ( $\text{Wm}^{-2}$ )
$T_a$	=	Ambient temperature (K)
$T_j$	=	Maximum junction temperature at the thermal contact (K)

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