Introductory Chapter: Electronics Cooling—An Overview

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1. Introduction

Recent development in semiconductor and other other mini- and micro-scale electronic technologies and continued miniaturization have led to very high increase in power density for high-performance chips. Although impressive progress has been made during the past decades, there remain serious technical challenges in thermal management and control of electronics devices or microprocessors. The two main challenges are: adequate removal of ever increasing heat flux and highly non-uniform power dissipation. According to a report of the International Electronics Manufacturing Initiative (iNEMI) Technology Roadmap [1], the maximum projected power dissipation from high-performance microprocessor chips will reach about 360 W by 2020. In fact, the micro- and power-electronics industries are facing the challenge of removing very high heat flux of around 300 W/cm^2 while maintaining the temperature below 85°C [2]. Furthermore, due to increasing integration of devices, the power dissipation on the chip or device is getting highly non-uniform as a peak chip heat flux can be several times that of the surrounding area.

Conventional cooling approaches are increasingly falling apart to deal with the high cooling demand and thermal management challenges of emerging electronic devices. Thus, high-performance chips or devices need innovative techniques, mechanisms, and coolants with high heat transfer capability to enhance the heat removal rate in order to maintain their normal operating temperature. Unless they are cooled properly, their normal performance and longevity can deteriorate faster than expected. In addition, the failure rate of electronic equipment increases with increasing operating temperature. Reviews and analyses on research and advancement of conventional and emerging cooling technologies reveal that microchannel-based forced convection and phase-change cooling (liquid) are among the most promising techniques that are capable of achieving very high heat removal rates [2–6].

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On the other hand, most of the cooling techniques cannot achieve the required performance due to the limitations in heat transfer capabilities of traditional coolants such as air, oil, water, and water/ethylene glycol/methanol mixtures, which inherently possess poor heat transfer characteristics, particularly thermal conductivity and convective heat transfer coefficient (HTC). For instance, in order to accommodate a heat flux of 100 W/cm^2 at a temperature difference of 50 K, it requires an effective HTC (including a possible area enlarging factor) of 20,000 W/m^2K, which is usually not possible through free and forced convections of these coolants [7]. Thus, there is always a desperate need to find cooling fluids with superior heat transfer performance. Consequently, there are several recently emerged fluids, which can potentially be used as advanced coolants. One such fluid is nanofluid—a new class of heat transfer fluids, which are suspensions of nanometer-sized particles in conventional heat transfer fluids such as water (W), ethylene glycol (EG), oils, and W/EG. Nanofluids were found to possess considerably higher thermal properties, particularly thermal conductivity and convective as well as boiling heat transfer compared to their base conventional fluids [8–12]. With highly desirable enhanced thermal properties, this new class of fluids can offer immense benefits and potentials in wide range of applications including cooling of electronics and other high-tech industries [12–14]. Recently, another novel class of fluids—termed "ionanofluids" was proposed by our group [15–16]. Ionanofluids, which are suspensions of nanoparticles in only ionic liquids, were also found to have superior thermal properties compared to their base ionic liquids [15–17]. In addition to their unique features like green fluids and designable for specific tasks, ionanofluids show great potential as advanced heat transfer fluids in cooling electronics.

In this chapter, an overview of various cooling methods and traditional coolants for electronic devices is presented first. Then, heat transfer properties and performances of new coolants are summarised, followed by their potential in electronics cooling.

2. Cooling methods

Despite impressive progress made on electronic cooling systems in recent years, the required high heat flux removal from the high-tech electronic devices remains inadequate and very challenging. There are a number of cooling methods widely used in electronic industries. Based on heat transfer effectiveness, the existing cooling modes can be classified into four general categories which are [18]:

- Natural convection,
- Forced convection air cooling,
- Forced convection liquid cooling,
- Liquid evaporation.

Based on the approximate range of heat flux removal rate of these methods, it is known that liquid evaporation is the best technique followed by the forced convections of liquids and then air [18]. However, forced air convection, which is widely used in cooling electronics such as CPU of computing devices, has very low heat removal rate (though higher than radiation and natural convection). As well known, besides heat removal mode, cooling fluids also play a major role in overall cooling performance.

High-performance electronic devices and chips need innovative techniques and systems design to enhance the heat removal rate in order to minimize their operating temperature and maximize longevity. Traditional cooling approaches, consisting typically of air-cooled heat sinks, are increasingly falling short in meeting the cooling demands of modern electronic devices with high-powered densities. Thus, in recent years, various techniques for cooling such electronics have been studied extensively and employed in various thermal management systems. These include thermosyphons [19], heat pipes [20], electro-osmotic pumping [21], microchannels [4, 5], impinging jets [22], thermoelectric coolers [23], and absorption refrigeration systems [24]. These cooling techniques can be categorized into passive and active systems. Passive cooling systems utilize capillary or gravitational buoyancy forces to circulate the working fluid, while active cooling systems are driven by a pump or compressor for higher cooling capacity and improved performance. As a passive cooling and given high latent heat of fusion, high specific heat, and controllable temperature stability of phase change materials (PCMs), PCMs-based heat sinks are relatively new techniques that can be used for transient electronic cooling applications [25].

Microscale cooling systems can sufficiently cool those high heat-generating electronic devices or appliances. For example, the heat transfer performances of microchannel based heat-sinks and micro-heat pipes are much higher compared to traditional heat exchangers. Because of the very compact, lightweight, suitable for small electronic devices, and superior cooling performance, microchannel-based cooling systems have received great attention from researchers and industries. The forced convective liquid cooling through microchannel heat sink is one of the promising and high-performance cooling technologies for small-sized high heat-generating electronic devices. Besides significantly minimizing the package size, this emerging cooling technology is also amenable to on-chip integration [4, 5].

Heat pipes-based electronics cooling is very popular and is recently receiving great attention from the researchers as well as industries and are already used in various electronic devices. Thus, a couple of chapters have particularly been devoted on this topic and it is not discussed here further.

On the other hand, direct liquid immersion cooling offers a very high HTC, which reduces the temperature rise of the chip surface. **Figure 1** compares the relative magnitudes (approximate) of HTCs of various commonly used coolants and cooling modes. The relative magnitude of HTC is directly affected by both the coolant and the mode of heat transfer (**Figure 1**). While water (deionized) is the most effective coolant, the boiling and condensation offer the highest HTCs.

Whatever methods are used to cool the devices or chips, transferring the heat to a fluid with or without phase transitions, it is necessary to dissipate the heat to the environment. This is mostly done with the forced convection of air, which is not sufficient particularly for high heat removal situations. Thus, it is also of tremendous importance to efficiently take away the heat from the coolants.

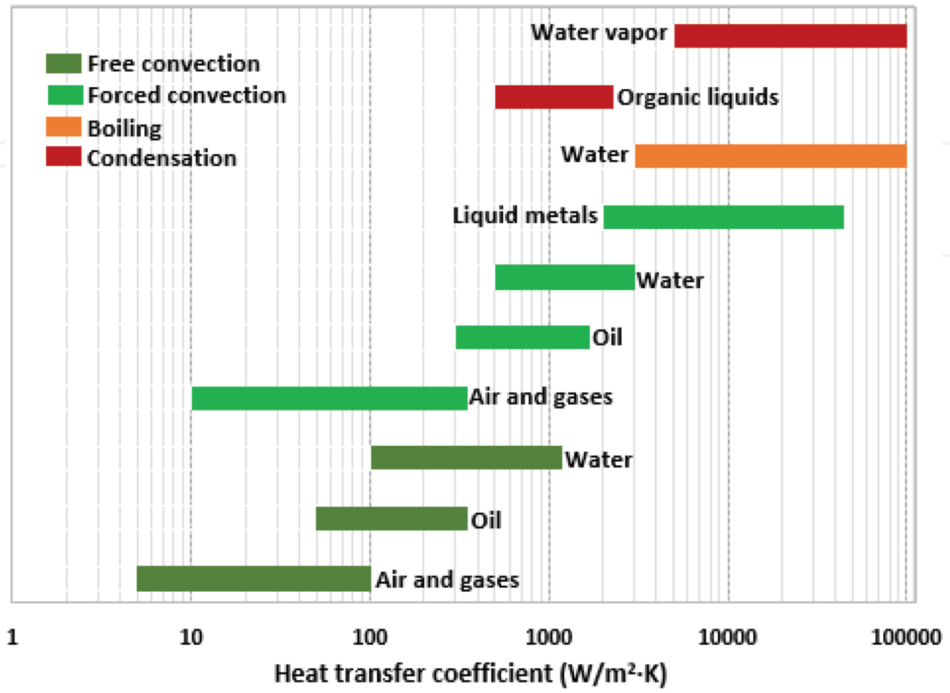

Figure 1. Range of overall heat transfer coefficients for different fluids and cooling modes.

3. Cooling fluids

3.1. Conventional coolants

There are a number of aqueous and non-aqueous conventional coolants which are used in various electronics cooling systems. As water possesses higher thermal conductivity and specific heat and lower viscosity compared to other coolants, it is the most widely used coolant for electronics. But water is not used in closed loop systems due to its high freezing point and the expansion upon freezing.

Nonetheless, it is important to select the best coolant for any specific device or cooling system. There are some general requirements for coolants and they may vary depending on the type of cooling systems and electronic devices. As well discussed in the literature [26], the liquid coolants for electronics cooling must be non-flammable, non-toxic, and inexpensive with excellent thermophysical properties and features, which include high thermal conductivity, specific heat and HTC, and low viscosity. Besides good chemical and thermal stability, coolants must also be compatible (e.g., non-corrosive) with the materials of the components of the cooling systems and devices. However, selection of a coolant for direct immersion cooling cannot be made only based on the heat transfer features. Chemical compatibility of the coolant with the chips and other packaging materials must be considered as well. The commonly used coolants for electronics cooling are mainly classified into two groups: dielectric and non-dielectric coolants.

There are several types of dielectric coolants, which are aromatics, aliphatics, silicones, and fluorocarbons-based fluids. Aromatics coolants such as diethylbenzene (DEB), toluene, and benzenes are the most commonly used coolants. Aliphatic hydrocarbons of paraffinic and isoparaffinic types (including mineral oils) and aliphatic polyalphaolefins (PAO) are used in a variety of direct cooling of electronics. Silicones-based coolant is another popular type of coolant widely known as silicone oils, e.g., Syltherm XLT. The fluorocarbons series of coolants such as FC-40, FC-72, FC-77 and FC-87 are widely accepted in the electronics industries.

Non-dielectric liquids are also used for electronics cooling because of their better thermal properties compared to their dielectric counterparts. They are normally aqueous solutions and thus exhibit high heat capacity and thermal conductivity. Water, EG, and mixture of these two (W/EG) are very popular and widely used as electronics coolants. Other popular non-dielectric coolants include propylene glycol (PG), water/methanol, W/ethanol, NaCl solution, potassium formate (KFO) solution, and liquid metals (e.g., Ga-In-Sn). Mohapatra and Loikits [26] evaluated that among the various coolants, KFO solution possesses highest overall efficiency. Comparisons of various properties and characteristics of all types of available coolants can help selecting the right coolants.

3.2. Potential new coolants

As mentioned before, the cooling demands of modern electronics devices or systems cannot be met by those conventional coolants due to their inherently poor thermal properties which greatly limit the cooling performance. Here, the newly emerged heat transfer fluids like nanofluids and ionanofluids, which have highly desirable superior thermal properties and are suitable for even microsystems, can be the cooling solutions. These new fluids can also offer immense benefits and potential applications in a wide range of industrial, electronics, and energy fields [12–14, 17]. Results of key heat transfer features including thermal conductivity, convective and boiling of these new coolants are briefly summarized in the following subsection.

3.2.1. Summary of thermal properties and performance

Extensive research has been performed on the thermal conductivity of nanofluids and studies showed that nanofluids possess considerably higher thermal conductivity compared to their base fluids [8, 12, 27–28]. However, results from different research groups are not very consistent and sometimes also controversial particularly regarding the heat transfer mechanisms [29]. Nanofluids also exhibit superior other thermophysical properties than those of base fluids [8, 27, 30–32]. With significantly high thermal properties, nanofluids can meet the cooling demand of high-tech electronics devices.

Evaluating the convective heat transfer performance of nanofluids is very important in order for their application as coolants in electronics. There have been large number of studies on convective heat transfer of nanofluids and nanofluids are found to exhibit enhanced HTC compared to their base fluids at any flow conditions. The enhanced HTC (*h* or *Nu*) further increases considerably with increasing concentration of nanoparticles as well as Reynolds number (*Re*) or flow rate [9, 33–34]. The enhancement of HTC is even more significant at turbulent regime. Based on the findings of convective heat transfer, it is considered that nanofluids can perform better cooling compared to conventional fluids in electronics cooling systems.

Another very important and efficient mode of cooling is boiling or phase change of fluids in various heat exchange systems. There is an increasing research focus on this key-cooling feature of nanofluids. Studies on boiling heat transfer of nanofluids revealed an undisputed substantial increase (up to few times of base fluids) in the boiling critical heat flux of nanofluids [9, 35–36]. Research also demonstrated that the boiling performance of nanofluids can be enhanced further with nanoparticle concentration and various other factors such as deposition of nanoparticles on heater wall, roughness of wall surface, and addition of surfactant [35–38]. Given the superior convective and boiling heat transfer performances, these new fluids can considerably increase the HTC and can act as better coolants than water or other conventional coolants.

Like nanofluids, ionanofluids also exhibit superior thermal properties, particularly thermal conductivity and heat capacity compared to their base ionic liquids [15–17]. Besides good thermal stability, thermophysical properties of ionanofluids can be adjusted by changing the ionic composition and structure of base ionic liquids. Early research revealed that these new nanofluids showed great potential to be used as advanced coolants for electronics cooling [16–17].

3.2.2. Potential of new fluids in electronics cooling

In recent years, extensive research works have been performed on the application of microchannel cooling systems (e.g., heat sinks) for electronics cooling [4, 5, 39]. Since the convective HTC is inversely proportional to the hydraulic diameter of the channel, very high heat transfer performance can be achieved by using microchannel at any flow regime. The forced convective heat transfer of cooling fluids through microchannel heat sinks is among the more promising technologies, which can offer very high heat removal rates [4, 5, 21, 39]. Nevertheless, the main limitation of cooling performance actually raised from the low heat transfer capability of the coolants used. In this regards, nanofluids with superior heat transfer performance can potentially boost the heat removal performance of microchannel cooling systems even further and be able to remove high heat flux of high-tech electronics devices.

Nanofluids have directly been employed in cooling systems of electronic or computing devices to evaluate the performance of these new fluids [40–42]. Results were very promising as the application of nanofluids in those cooling systems resulted in better cooling performance compared to traditional base fluids [39–43]. Thus, applications of nanofluids in conventional and emerging techniques such as microchannels and heat pipes can be the next-generation electronics cooling systems. A detailed discussion and analysis on the potential benefits and applications of nanofluids in cooling electronics can also be found in an ongoing study by the author [44].

4. Conclusions

Advances in electronics and semiconductor technologies have led to a dramatic increase in heat flux density for high-performance chips and components, whereas conventional cooling techniques and coolants are increasingly falling short in meeting the ever-increasing cooling need of such high heat-generating electronic devices or microprocessors. Despite good progress been made during the past decades, there remain some serious technical challenges in thermal management and cooling of these electronics. High-performance chips and devices need innovative mechanisms, techniques, and coolants with high heat transfer capability to enhance the cooling rate for their normal performance and longevity. With superior thermal properties and cooling features, nanofluids offer great promises to be used as coolants for high-tech electronic devices and industries. The emerging techniques like microchannels with these new fluids can be the next-generation cooling technologies.

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