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A critical review of traditional and emerging techniques and fluids for electronics cooling

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ABSTRACT

Continued miniaturization and demand for high-end performance of electronic devices and appliances have led to dramatic increase in their heat flux generation. Consequently, conventional coolants and cooling approaches are increasingly falling short in meeting the ever-increasing cooling needs and challenges of those high heat generating electronic devices. This study provides a critical review of traditional and emerging cooling methods as well as coolants for electronics. In addition to summarizing traditional coolants, heat transfer properties and performances of potential new coolants such as nanofluids are also reviewed and analyzed. With superior thermal properties and numerous benefits nanofluids show great promises in fulfilling the cooling demands of high heat generating electronic devices. It is believed that applications of such novel coolants in emerging techniques like micro-channels and micro-heat pipes can revolutionize cooling technologies for electronics in the future.

1. Background

Recent advances in semiconductor and other mini-and micro-scale electronic technologies have resulted in very high increase in power density particularly for high performance chips. Despite impressive progress been made during the past decades, there are still serious technical challenges in thermal management of electronics devices or microprocessors. Two main cooling challenges are adequate removal of increased heat flux and highly non-uniform power dissipation. According to the 2004 International Electronics Manufacturing Initiative (iNEMI) technology roadmap [1], the maximum power dissipation and heat flux from the high performance microprocessor chips was projected to reach about 360 W and 190 W/cm^2, respectively by 2020 (Fig. 1). In fact, the heat flux generation of many high performance electronic devices are now much higher than the projections of that iNEMI roadmap. A study in 2007 [2] reported that many micro- and power-electronics industries were then facing difficult challenge of removing very high heat flux (around 300 W/cm^2) while maintaining the temperature below 85 °C. Additionally, due to increasing integration of devices (e.g., transistors) the power dissipation on the chip or device is becoming highly non-uniform as heat flux of a peak chip can be as high as several times that of the surrounding areas.

Furthermore, miniaturization of electronic component has resulted in medium-scale integration (MSI) in the 1960s with 50–1000 components per chip, large-scale integration (LSI) in the 1970s with 1000–100,000 components per chip, and very large-scale integration (VLSI) in the 1980s with 100,000–10,000,000 components per chip [3]. In 2006, chips were already manufactured that contained up to 100 million transistors per square centimetre and present super-powerful 10-core Xeon processors (Haswell-EP) have 5.5 billion transistors compared to 3.1 million for 32-bit processors of 1990s [4]. Semiconductor and microelectronic technologies still follow the classical Moore's law [5] progression towards shrinking feature size, increasing transistor density, faster circuit speeds, and higher chip performance. Fig. 2 presents the 2006 International Technology Roadmap for Semiconductors (ITRS) [6] projections on the key features of semiconductor components. This shows a continuous decrease in transistor size to 6 nm along with a rise in transistor density up to about 20 billion transistors/cm^2 by 2020. The chip size (at production) was also estimated to remain around 100 mm^2.

The design trend of modern electronics is based on the smaller and faster the better. However, this trend is also leading to high power densities and high operating temperatures, and low performance and longevity of the electronic devices. If heat is not removed at a rate equal to or greater than its rate of generation, components as well as the device temperatures keep increasing which in addition to significantly reducing the reliability and performance can lead to failure of the devices. In fact, the failure rate of electronic devices increases almost exponentially with increasing the operating temperature. According to a report on reliability prediction of electronic equipment prepared by

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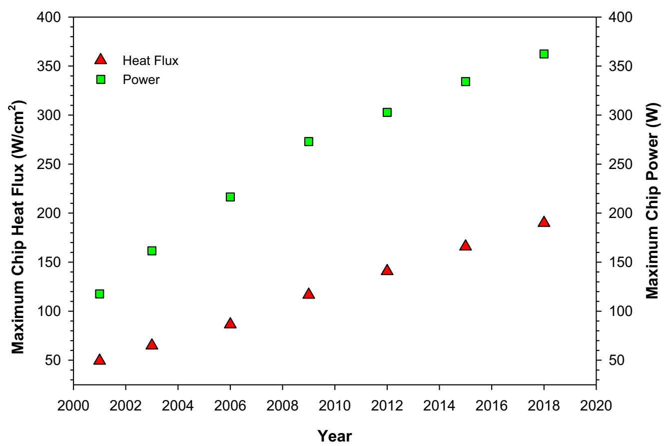

Fig. 1. Projections of maximum heat flux and power dissipation for microprocessor chips.

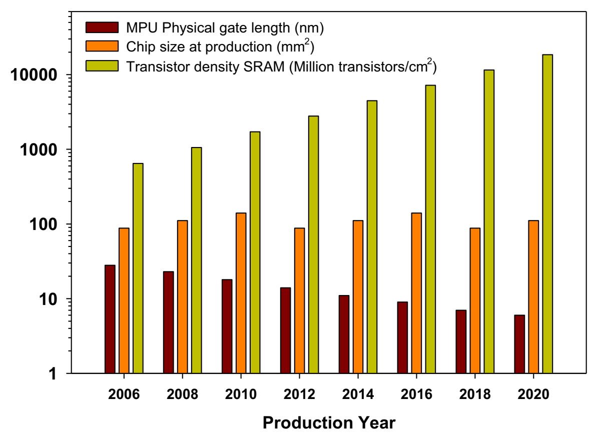

Fig. 2. The 2006 ITRS projections of chip size, transistor density and physical gate length of high-performance microprocessor chips [6].

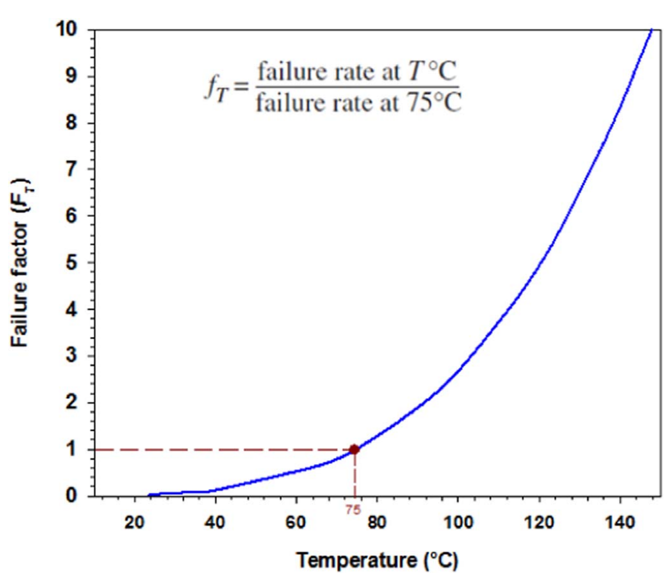

Fig. 3. Temperature dependence of failure rate of digital devices [7].

the U.S. Department of Defense [7], the failure factor, which is relative failure rate at any temperature over failure rate at 75 °C, increases exponentially with increasing the device temperature as demonstrated in Fig. 3. Pedram and Nazarian [8] also reported that more than 50% of all integrated circuit (IC) failures are related to thermal issues. Thus a rule of thumb is that the failure rate of electronic components can be halved for each 10 °C reduction in their junction temperature and the cooler the devices operate, the more reliable they are [3].

For many semiconductor technologies, the reliability of individual transistor is exponentially dependent on the operating temperature and the median time to failure in hours (MTF) can be estimated by the well-known Black's correlation [9], which has the form:

$$MTF = \frac{1}{AJ^2}\exp\left(\frac{E_A}{K_B T}\right) \tag{1}$$

where A is a constant, J is the current density (per cm^2), E_A is the active energy (in eV) which is approximately 0.68 eV for typical silicon failures, K_B is the Boltzmann constant and T is the absolute operating temperature (Kelvin). This equation (Eq. (1)) demonstrates that a modest increase in operating temperature could significantly increase the device failure rate.

Besides failure of device, leakage power consumption is also highly dependent on the on-chip temperature profile. Higher temperature leads to larger power dissipation, which in turn increases the on-chip temperature. In many high performance designs, the leakage component is comparable to the switching component. For instance, Fallah and Pedram [10] demonstrated that 40% or even a higher percentage of the total power consumption in 90 nm process technology is due to the leakage of transistors. For a 15 mm die fabricated in a 100 nm process technology with a supply voltage of 0.7 V, the same group [8] later reported an exponential increase in leakage power with substrate temperature and the leakage power consumption increased up to 56% when die temperature was raised to 110 °C.

The reduction of size and the huge increase in the number of integrated components (e.g., transistor) and subsequent increase in power density (thus heat flux as well) yielded enormous challenges for developing efficient cooling at small temperature differences. The current cooling technologies for such high power density modules or systems are not adequate and greatly limit their performance in addition to raising the failure rates. For example, most of the power electronic modules are generally cooled by attaching them to an external heat-sink or cold plate, which is cooled by forced convection of air or circulated liquid. However, this conventional heat-sink cooling technique is not capable of adequately cooling such high power density modules or devices. Semiconductor engineers are therefore turning to new and more efficient cooling technologies. In recent years, two complementary ways of enhancing the effectiveness of cooling such modules have emerged [11]. While one method aims at decreasing the thermal resistance by removing and/or reducing the layers and thickness, the other method focuses on increasing the efficiency of the cold plate through elevating the heat transfer from the heat-sink body to the coolant. Nevertheless, these means are yet to make considerable impact in the cooling performances.

As discussed above, continued miniaturization and demand for high performance and reliability of electronic devices resulted in high increase in the heat flux generation and thus the operating temperature. However, conventional cooling approaches are increasingly falling apart to deal with the high cooling demand and thermal management challenges of modern 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. As mentioned before, unless these devices are cooled properly their normal performance and longevity can deteriorate faster than expected leading to their early or sudden catastrophic failures.

On the other hand, most of the cooling techniques cannot achieve the required cooling performance due to the limitations in heat transfer capabilities of traditional coolants such as air, oil, and water which inherently possess poor heat transfer properties particularly thermal conductivity and convective heat transfer coefficient. 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 heat transfer coefficient (including a possible area enlarging factor) of 20,000 W/m^2 K, which is usually not possible through free and forced convections of those coolants [12]. Thus, there is a desperate need to find cooling fluids with superior heat transfer capability. Consequently, there are few recently emerged fluids, which according to research findings, can potentially be used as advanced coolants in those electronic devices. One of such fluids is nanofluids-a new class of heat transfer fluids, which are the suspensions of nanometer-sized particles (typically < 100 nm) in conventional heat transfer fluids such as water (W), ethylene glycol (EG) and oils. Nanofluids were found to possess considerably higher thermal properties particularly thermal conductivity and convective as well as boiling heat transfer features compared to their base conventional fluids [13–18]. Besides desirable high thermal properties, these new fluids can offer immense benefits and applications in a wide range of areas including electronics [17,19–21]. Nanofluids are believed to be capable of meeting the cooling demands and challenges of high-tech electronic devices and appliances [21]. Recently another novel class of ionic liquids (ILs)-based nanofluids-termed "Ionanofluids" was coined by this group [22–24] and these fluids were also found to exhibit superior thermal properties compared to their base ionic liquids [22–25]. Together with the advantages of ionic liquids and superior properties, ionanofluids can also offer great potential as advanced heat transfer fluids in cooling electronic devices [25,26].

Apart from this background of electronics cooling, a critical review of various conventional and emerging methods as well as coolants for electronics cooling is presented. Then the heat transfer properties and performances of new cooling fluids are summarized followed by the presentation of research and development of their applications in electronics cooling. Finally future challenges of cooling technologies are highlighted.

2. Cooling techniques

2.1. Traditional cooling techniques

Although impressive progress has been made on electronic cooling systems in recent years, the high heat flux removal from the high-tech electronic devices remains very challenging and inadequate. Here available conventional cooling methods, their classifications based on heat transfer mechanisms and coolants used, as well as their cooling effectiveness are summarized.

Based on heat transfer effectiveness cooling modes can be classified into four general categories which are [27]:

1. Radiation and free convection,
2. Forced air-cooling,
3. Forced liquid cooling,
4. Liquid evaporation.

For the temperature difference between the heat transfer surfaces and the ambient of 80 °C the approximate ranges of heat removal rate (heat flux) for these methods are compared in Fig. 4 [27]. It can be seen that the liquid evaporation is the best technique followed by the forced convection of liquids. Whereas forced convection of air, which is widely used in cooling electronics such as CPU of computing devices, has very low heat removal rate (though higher than the free convection). On the other hand, despite very low heat transfer rate (in fact the lowest among others) natural convection is very popular mode in low heat flux applications due to very low cost, simplicity, and reliability. Besides types of heat removal methods, cooling fluids also play a major role for the overall cooling performance.

On the other hand, overall heat transfer coefficient is another key parameter, which also evaluates the cooling performance of fluids in any heat transfer mode. Table 1 presents typical ranges of heat transfer coefficients of most commonly used coolants (i.e., air and water) in all cooling modes. It is well-known that water possesses better heat transfer coefficient resulting higher cooling performance compared to

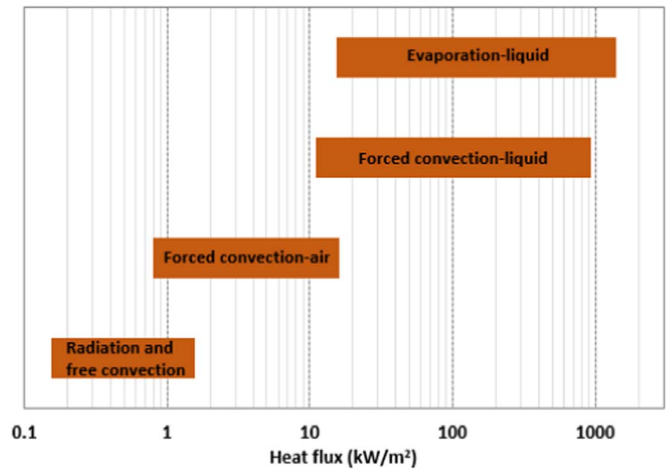

Fig. 4. Comparisons of heat transfer effectiveness of conventional methods.

Table 1
Range of heat transfer coefficients of air and water at different cooling modes.

Cooling modes	Heat transfer coefficient of air (W/m^2 K)	Heat transfer coefficient of water (W/m^2 K)
Free convection	5–100	100–1200
Forced convection (moderate flow speed)	10–350	500–3000
Boiling	–	3000–100,000

air. Table 1 also demonstrates that depending on cooling mode the heat transfer coefficient of water can be increased substantially.

In addition to above general categories, based on coolants used the cooling methods can also be classified into several types such as:

1. Air cooling,
2. Liquid cooling,
3. Refrigeration cooling.

On the other hand, direct liquid immersion (DLI) cooling also provides high heat transfer coefficient, which reduces the temperature rise of the chip surface above the liquid coolant temperature. In addition, this cooling also offers greater uniformity of chip temperatures compared to air-cooling. Some of the DLI cooling methods are very well-established and widely used in numerous thermal management systems [28,29] and do not need to discuss further. More details about thermal management of electronics using these cooling methods as well as various emerging ones can be found elsewhere e.g., [30–32].

The main features together with the advantages, disadvantages or limitations, and cost situations of these traditional cooling technologies in relation to electronics cooling are summarized and compared in Table 2.

Nevertheless, regardless of the methods used to cool the electronic devices or chips, transferring the heat to a fluid with or without phase transitions requires 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 dissipate the heat from the coolants.

2.2. Emerging cooling techniques

Based on effectiveness and material or process adapted in cooling electronics, emerging cooling methods can be classified into various types and some of them are as follows:

Table 2
Summary and comparisons of different traditional cooling technologies for electronics cooling.

Cooling technology	Main features	Advantages/effectiveness	Disadvantages/limitations	Cost situation
Free convection	– Most popular in low heat flux applications	– Low cost, simplicity and high reliability – Noise free	– Lowest heat removal rate – Large heat transfer area	Lowest cost among other technologies
Forced convection air-cooling	– When free convection of air is not sufficient, forced convection is used – Requires fan for air flow	– Most well-established cooling method – Widely used in data center cooling – Very reliable – Low maintenance – Simplicity in design and installation	– Low heat transfer coefficient (HTC) – Need additional means such as fan – Not noise free	Due to fan and installation, slightly higher cost than that of free convection
Forced convection liquid-cooling	– Involves sensible heating of flowing liquids – Requires pump for liquid flow – Water is most widely used coolants	– Higher HTC compared to air cooling – Most of the commercial heat exchangers belong to this mode	– Not widely used in electronics cooling especially small devices – Produces noise from fan or pump	Higher overall cost due to pump, fluids, installation and maintenance
Liquid evaporation	– With applied heat the coolant liquid changes to vapor – Uses enthalpy of vaporization	– Best traditional techniques with highest heat removal rate and HTC – Good at arid climates.	– Not good at cold and high humid weather conditions – Not suitable for small electronic devices – Possibility of pressure and temperature fluctuation	Relatively high cost due to high heating, fluids, installation, maintenance, and climate sustainability requirements

1. Heat pipes,
2. Heat pumps,
3. Microchannels,
4. Spray cooling,
5. Phase change material (PCM) based cooling,
6. Free cooling,
7. Thermoelectric cooling.

These cooling systems are also categorized into passive and active types. Passive cooling systems utilize capillary or gravitational buoyancy forces to circulate the cooling fluid, while active systems are driven by a pump or compressor for higher cooling capacity and improved performance.

As mentioned before traditional cooling approaches, consisting typically of external air-cooled heat sinks, are not capable of sufficiently cooling modern electronic devices and chips with high-power densities and such devices need innovative mechanisms and techniques to enhance the heat removal rate in order to minimize their operating temperature and maximizing their longevity. However, most of the emerging techniques such as thermosyphons [33], heat pipes [34], free cooling [35,36], electro-osmotic pumping [37], microchannels and micropumping [38–40], impinging jets [41], thermoelectric coolers [42], and PCM-based cooling [43–46] showed great potential for cooling those high-tech electronics. Thus, in recent years, these emerging techniques are receiving great attentions from researchers and electronic industries. In fact, few of these emerging techniques have already been used in commercial cooling of electronic devices. Few popular emerging cooling techniques have briefly been discussed here.

2.2.1. Heat pipes based cooling

Heat pipes, which work based on the phase change of working fluid inside the pipes, are very promising means of cooling electronic devices such as computer, laptop, telecommunication, and satellite modules [47–50]. Due to their extremely high effective thermal conductivity (up to several thousand times higher than even copper rod [51]) and very low effective thermal resistance (typically ranging from 0.05 to 0.4 °C/W [52]) heat pipes are one of the most viable means of cooling high heat flux generating electronic devices such as CPU. At present, there are many commercial cooling applications of heat pipes and because of high heat removal performance this cooling technique has attracted tremendous interest from the electronic industries. This can be evidenced from the huge number of industrial production of heat pipes. For instance, several millions of heat pipes are manufactured each month as cooling system for CPUs, laptops, and computers [49]. In fact, one of the highest volume applications of heat pipes is cooling Pentium processors of laptops [52]. Very recently, Chen et al. [53] reported a comprehensive review on design, fabrication and performance analysis of small heat pipes for electronics cooling. They also showed the potential of such small heat pipes in cooling small electronic devices and systems.

The most fascinating feature of heat pipes is that they don't have any moving parts and thus highly reliable with minimum maintenance. Heat pipes also offer numerous other advantages some of which include: no external energy or power consumption, noise free cooling, increased longevity hence low operation and overall cost, better application flexibility (due to simple and robust design and construction), small size and weight (suitable for modern electronic devices), work in any orientation, and sealed enclosure cooling thus no adverse effect to environment or the electronic devices.

There are several types of heat pipes used in electronic cooling applications, which are:

1. Flat heat pipes,
2. Cylindrical heat pipes,
3. Loop heat pipes,

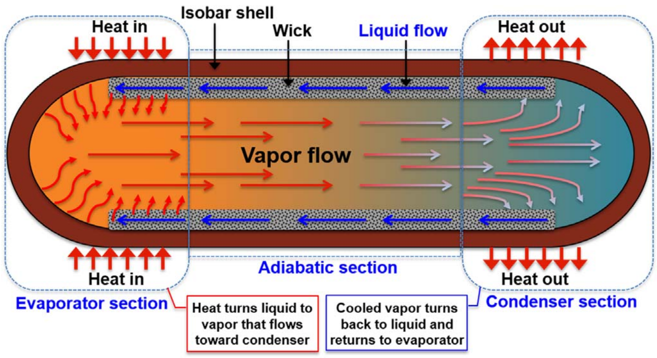

Fig. 5. Working principle and schematic of a heat pipe.

4. Micro-heat pipes,
5. Oscillating (also known as pulsating) heat pipes.

Heat pipe consists of metal envelope (e.g., pipe), wick, and cooling fluid. The envelope has three sections- evaporator, adiabatic, and condenser sections. The wick, which is mostly affixed at the inner wall of the pipe, is the most important part. It acts as capillary pumping, which drives the fluid from the condenser section to the evaporator even against the gravity. This allows the heat pipe to operate in any orientation. The grooved wick, sintered wick, and screen mesh wick are most commonly used wick types.

Fig. 5 demonstrates the working principle of a heat pipe, which is very simple and based on phase change heat transfer inside an enveloped metallic structure. When the evaporator section is heated from an external heat source (e.g., an electronic device or chip), it evaporates the liquid there. The vapor raises the pressure and results in having pressure difference along the axial direction which drives the vapor from evaporator to the condenser, where it condenses releasing the latent heat of vaporization to the heat sink and the vapor turns back to liquid. Meanwhile depletion of liquid by evaporation at the evaporator section causes the liquid/vapor interface to enter into the wick surface, and thus a capillary pressure develops there. This capillary pressure drives the condensed liquid back to the evaporator for re-evaporation. This way the liquid coolant circulates in a closed-loop envelope or pipe, while evaporation and condensation take place simultaneously for heat absorption and dissipation, respectively. Heat pipes involve two-phase passive heat transfer systems, which are capable of transferring (removing) large amount of heat with very small temperature drop. The high heat transfer performance of a heat pipe is achieved due to high latent heat of vaporization of working fluid.

Based on total capillary pressure drop, the maximum heat transport capacity of a heat pipe can be determined from the following equation:

$$Q_{\max} = \frac{KA_w h_{fg}\rho_l}{\mu_l L_{\text{eff}}}\left[\frac{2\sigma}{R_{\text{eff}}} - \rho g L_{\text{eff}} \sin\phi\right] \tag{2}$$

where σ is the liquid surface tension, μ_l is the liquid viscosity, h_{fg} is the latent heat coefficient of liquid, R_{eff} is the effective pore radius of the wick structure, L_{eff} is the effective length of heat pipe, K is the permeability, A_w is the cross-sectional area of the wick, ρ_l is liquid density, g is gravitational constant, and ϕ is orientation angle with respect to the horizontal plane. Thus heat transfer of a heat pipe depends on geometry and orientation of heat pipe, microstructure of wick, and various properties such as h_{fg}, σ, μ, and ρ of working liquid.

Details about the heat pipe cooling systems, working principle, applications, opportunities and challenges can be found in the related books and articles in the literature e.g., [34,47–54].

2.2.2. Heat pumps cooling systems

Heat pumps transfer heat from a low temperature fluid to another high temperature fluid and use refrigerants as coolants. This cooling mode offers economical and environmental friendly alternative of recovering heat from different sources for use in various industrial, air conditioning systems, and commercial as well as building cooling applications. Heat pumps are usually used for moderate cooling needs and are not applied to electronics cooling, particularly high heat generating devices. In an effort to evaluate the performance of heat pump systems for electronics cooling applications, Kim et al. [55] performed numerical simulation using water/LiBr pair in a heat pump of dual micro-channel array evaporator. They demonstrated the feasibility of using miniature absorption refrigeration system for electronics cooling applications. However, their results were not validated with any experimental data. Details about advances in heat pumps and their applications can be found elsewhere [56] and will not be elaborated here.

2.2.3. Microchannels based cooling

Microscale cooling systems are capable of cooling high heat generating electronic devices and appliances. The heat transfer performance of a microchannel heat sink is much higher than that of any traditional heat exchangers. Thus, forced convective liquid cooling through microchannel heat sinks is one of the promising and high performance cooling technologies for high heat generating electronic devices. Besides significantly minimizing the package size, this emerging cooling technology is also amenable to on-chip integration [38,39].

In 1981, Tuckerman and Pease [57] first proposed microchannels as an advanced cooling solution after they achieved a very high heat flux of 790 W/cm^2 from an integral water-cooled microchannel (50 µm wide and 300 µm deep) with a temperature rise of 71 °C. Now electronics cooling has developed to a new high level because of microchannels-based cooling systems such as microchannel heat exchangers (MCHX) and heat sinks (MCHS). Since this pioneering work of Tuckerman and Pease [57], extensive research and development have been made and microchannels based cooling became a key technology for cooling many devices and systems particularly electronics with high power densities such as very large and ultra large scale integrations (VLSI and ULSI) [58–62]. Some representative studies on microchannels based cooling are summarized here.

For the purpose of cooling very high power chips such as microprocessors a single-phase silicone-microchannel cooler was designed and implemented by Colgan et al. [63]. It was demonstrated that such microchannel coolers can cool chips with average power density of 400 W/cm^2. Kandlikar and Upadhye [64] reported enhanced microchannel cooling by using off-set strip fins and a split-flow arrangement and cooling of over 300 W/cm^2 heat flux at 24 kPa was achieved with a flow of 1.5 l/min. Dix et al. [65] performed experimental and numerical investigations with a water cooled microchannel heat exchanger (MCHX) for electronic cooling applications. The performance of MCHX was optimized through changing channel geometries. They suggested that for maximum heat transfer performance it is necessary to consider the right balance between the surface area and pressure drop. Based on a numerical study on two-layer single phase flow microchannels Abdoli et al. [66] showed that such microchannel configuration is capable of removing heat from very high heat flux chips with hot spots.

In a different study, Atienza [67] considered inter-tier liquid as potential means to cool the high temperatures in 3D multi-processor system-on-chip (MPSoC) with hotspot. This cooling technology involves liquid (water) injection through microchannels between tiers of a 3D stack. A view of 3D stacked MPSoC architecture with interlayer microchannel cooling is presented in Fig. 6 [67]. It was concluded that microchannel-based liquid cooling is a promising technique to overcome the thermal challenges of 3D MPSoCs in high performance computing architectures.

Besides single-phase convection cooling, two-phase (boiling) liquid cooling in microchannels also emerged to be more promising cooling

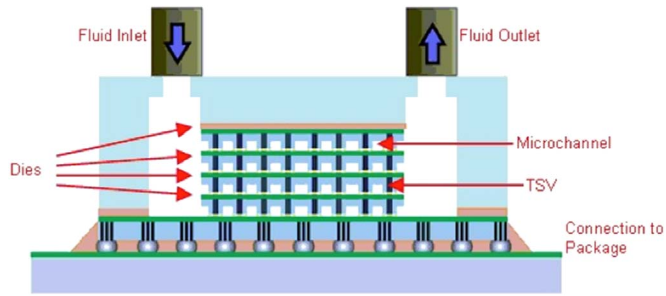

Fig. 6. Schematic arrangement of 3D stacked MPSoC architecture with interlayer microchannel cooling studied by Atienza [67].

technique for very high heat generating electronics. For example, Qu and Mudawar [68] conducted boiling experiment in a water-cooled microchannel heat sink containing 21 parallel channels and reported rapid increase in heat flux with small increments of wall temperature until the wall heat flux reached to a critical heat flux (CHF). Through silicon microchannels with nanostructured-wall significant enhancements in pool boiling heat flux (e.g., 120% over the non-nanostructured channel surface and more than 400% over a plain silicon surface) was reported in a study by Kandlikar's group [69].

An extensive review on development of microchannels based high heat removal technologies was done by Kandlikar [59]. A roadmap of challenges and opportunities of this emerging cooling technology for high heat generating devices was also laid out. Liquid coolant microchannels was anticipated to reach heat dissipation rate of as high as 1 kW/cm^2 at temperature difference (junction to ambient) of 50 °C. Recently, they [60] performed a critical review of the current state of research on heat transfer in microchannels. They also discussed the challenges and highlighted the future research needs in this area.

2.2.4. Thermoelectric cooling

A thermoelectric cooler (TEC) creates heat flux between the junctions of two different types of semiconductors through the Peltier effect, which is generally known as thermoelectric effect. The cooling instruments also called Peltier heat pump or thermoelectric cooler. It transfers heat from one side of the device to the other with consumption of electrical energy. TECs are compact and having no moving parts they offer great potential to enhance the cooling rate of electronic modules and other electronics [70]. TEC can also be integrated into electronic packages for their hotspots cooling [71]. Although the coefficient of performance of a TEC is lower than that of vapor-compression refrigeration (VCR) system [42], Zebarjadi [72] demonstrated that in order for electronics cooling applications the thermoelectric materials need to be of high thermal conductive and of large power factor. In a different study, Saengchandr and Afzulpurkar [73] reported a numerical analysis on combined thermoelectric module and heat pipe-based approach for cooling microprocessors and other computer chips. They claimed that their proposed cooling system was of sufficient capacity for cooling 200 W heat dissipation and the temperature of this combined cooling system was lower than existing cooling systems.

The cooling concept of a TEC is shown in Fig. 7. The simple working principle of TEC makes them popular in many applications. The main component of a TEC is an array of two dissimilar conductors namely P- and N- type semiconductors. First voltage is applied to the free ends of the two different conducting elements resulting in current (DC) flow through the P- and N- semiconductors. The flow of current across the junction of these two semiconductors generates a temperature difference. Because of this temperature difference, Peltier cooling causes heat to be absorbed from the vicinity of the cold plate and to move to the heat sink end of the device (Fig. 7).

Among the advantages of TEC over vapor-compressors include: no moving parts, high reliability, environmental friendly and safer due to

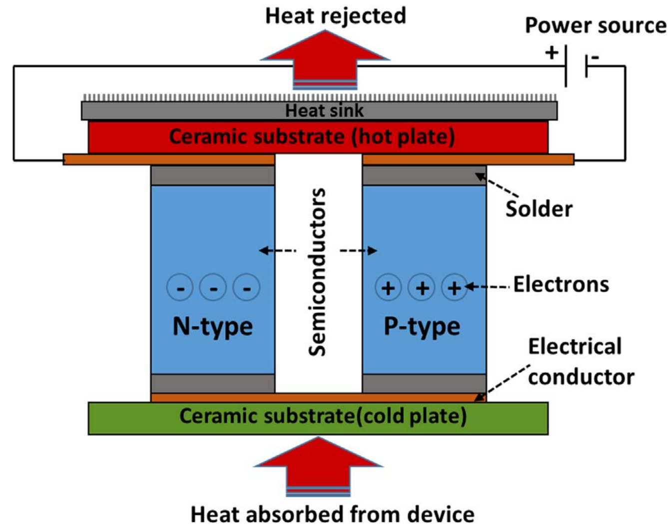

Fig. 7. Thermoelectric cooling concept and schematic.

absence of any refrigerants, small size, and feasibility of cooling below ambient temperature. Thin film TEC also offers great benefits mainly due to their dramatic enhancement in cooling power density [74]. Some components in electrical systems and computer such as microprocessors and power amplifiers are cooled by this cooling technique.

2.2.5. Free cooling

Free cooling is an economic cooling approach (also known as economizer cycle), which uses low external natural air temperature to cool mainly data centers or server systems [35,36,75]. It mainly uses natural cool and humid air into any electronic enclosure (such as data center) to cool it down. Water is also used in this cooling. If the environmental air temperature is much lower than that of the data center, heat can naturally transfer to environment from the data center. Free cooling is classified into two groups- direct cooling and indirect cooling.

Based on the cooling flow direction and system used, there are also three categories of free cooling which are: airside free cooling, waterside free cooling, and heat pipe free cooling.

Although airside and waterside cooling are well-known, the heat pipe free cooling is a new type of cooling systems recently getting popular to cool data center. It works the same as the usual heat pipe technology. Details about all these free cooling types are provided in a review article by Zhang et al. [35]. Since free cooling is not usually used in any other electronic devices or systems, it will not be discussed further.

2.2.6. PCMs-based cooling

As an emerging passive method PCMs-based cooling has received great attention in recent years. This is very promising cooling approach as it can take the heat from the devices and appliances and can store which can be used in other purposes such as heating homes or offices. Having numerous advantages including high latent heat of fusion, high specific heat, controllable temperature stability, and small volume change during phase change PCMs have been studied for various applications including electronics cooling [33,43–46,76,77]. If the heat output occurs during the phase transition PCMs can absorb very large quantity of heat without raising temperature.

A new design of heat sink with PCM for cooling of microprocessors was proposed by Jaworski and Domanski [79] and its thermal characteristics and performance were also studied numerically. They showed that a small amount (mass) of PCM in the heat sink can significantly increase its capability to stabilize microprocessor temperature indicating high potential of PCM-based heat sink for electro-

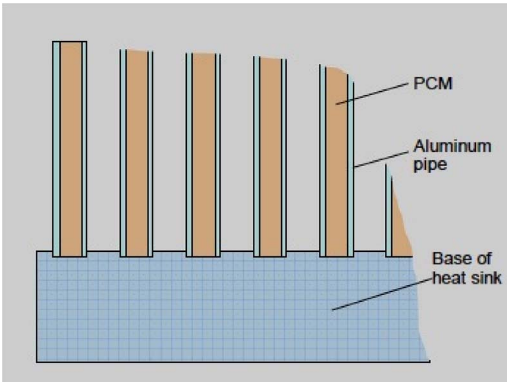

Fig. 8. Schematic design of PCM-based heat sink [79].

nics cooling. The schematic design of a simple PCM-based heat sink is depicted in Fig. 8.

Performances of the PCM-based thermal management systems for electronic devices along with the thermal properties of PCMs can be found in a recent review paper [78]. Nevertheless, more extensive studies are to be conducted and the areas of applications of PCMs in cooling electronics need to be explored further.

Progress and comparisons of various heat flux removal techniques can be found in reviews on cooling technologies reported in the literature e.g., [2,80]. Nevertheless, microchannels based forced convection and phase-change based liquid cooling are among the most promising technologies that are capable of achieving very high heat removal rates [38,40,49,60].

3. Conventional and emerging coolants

There are numerous traditional aqueous and non-aqueous coolants, which are used in various electronics cooling systems. Properties and selection criteria of these coolants are discussed in this section. As a new and emerging type of coolants, nanofluids showed great potential as superior coolants for electronic devices compared to traditional coolants. Heat transfer properties including thermal conductivity, convective and boiling heat transfer of nanofluids have also been briefly reviewed and analyzed here.

3.1. Conventional coolants

There are numbers of cooling fluids widely used in various cooling applications. Relative magnitudes (approximate) of heat transfer coefficients of various commonly used coolants and cooling modes are compared and presented in Fig. 9. As known and demonstrated (Fig. 9) the relative magnitude of heat transfer coefficient is affected by both the coolant and the heat transfer mode. Among these conventional coolants water is the most effective coolant and the boiling and condensation modes offer the highest heat transfer coefficients.

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 known and discussed in the literature [81,82], the liquid coolants for electronics must be non-flammable, nontoxic, and inexpensive with excellent thermophysical properties and features which include high thermal conductivity, specific heat, and heat transfer coefficient as well as 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 as well as the devices. In addition, high flash point, boiling point and auto-ignition temperature are desired together with low freezing point. It is noted that the selection of a coolant for direct immersion cooling cannot be made only based on the heat transfer features. Chemical compatibility

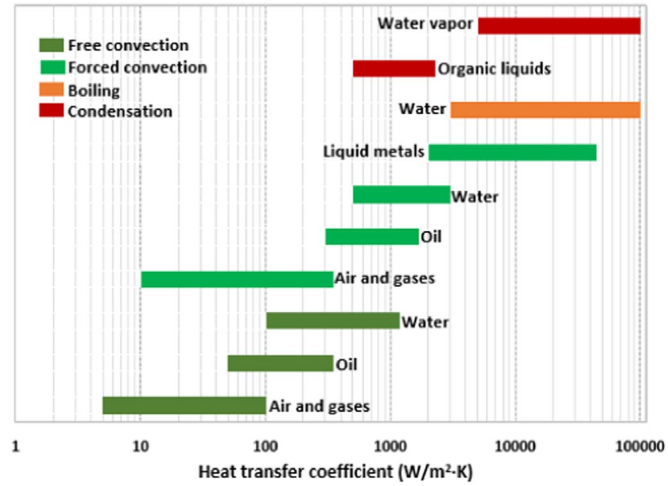

Fig. 9. Range of overall heat transfer coefficients for different fluids and cooling modes.

of the coolant with the chips and other packaging materials must be considered as well.

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. However, water is not used in closed loop systems due to its high freezing point and the expansion upon freezing.

The commonly used conventional coolants for electronics cooling are mainly classified into two groups: (I) dielectric and (II) non-dielectric fluids.

(I) Dielectric coolants

There are several types of fluids in this group of coolants, which are Aromatics, Aliphatics, Silicones, and Fluorocarbons based fluids.

Aromatics based liquids: Due to cheaper and better performance, alkylated aromatics are most commonly used coolants. Examples of some aromatics coolants are diethyl benzene (DEB), toluene, benzenes, and xylene.

Aliphatics based liquids: Aliphatic hydrocarbons of paraffinic and iso-paraffinic type (including mineral oils) are used in a variety of direct cooling of electronics. Aliphatic polyalphaolefins (PAO)-based fluids are also used in some electronics cooling applications.

Silicones based liquids: This is another popular type of coolant widely known as silicone oils (e.g., Syltherm XLT). The main advantage of this class of coolants is their properties such as viscosity and freezing point, which can be controlled by changing the chain length.

Fluorocarbons based fluids: The fluorinert series of electronic liquids such as FC-40, FC-72, FC-77 and FC-87 are widely accepted in electronics industries. These liquids are inert, stable, non-flammable, and non-reactive. FC-72 and FC-77 are most commonly used for electronic cooling applications.

(II) Non-dielectric coolants

Non-dielectric liquid coolants are often used for electronics cooling because of their better thermal properties as compared to their dielectric counterparts. They are normally aqueous solutions and thus exhibit high thermal conductivity and heat capacity as well as relatively low viscosity. Water (W), ethylene glycol (EG), and mixture of these two (W/EG) are very popular and widely used as coolants for many electronic devices. Some 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 [81] evaluated that among various coolants KFO solution possesses the highest overall efficiency.

Table 3 presents several key properties of various commonly used

Table 3
Properties of various common liquid coolants (thermophysical properties at room temperature).

Liquids	Boiling point at 1 atm (°C)	Freezing point (°C)	Flash point (°C)	Thermal conductivity (W/m K)	Specific heat (kJ/kg K)	Viscosity (mPa s)	Density (kg/m^3)
Water (W)	100	0	–	0.613	4.18	0.89	1000
Ethylene glycol (EG)	198	−11	125–138	0.26	2.84	19.83	1109
W/EG (50/50 v/v)	107	−37.8	–	0.37	3.285	3.8	1087
W/PG (50/50 v/v)	106	−35	–	0.36	3.40	6.4	1062
W/methanol (60/40 w/w)	79	−40	26	0.4	3.56	2.0	935
Aromatic (DEB)	78	< −80	57	0.14	1.7	1	860
Aliphatic (PAO)	346	< −50	> 175	0.137	2.15	9	770
Silicone (Syltherm XLT)	–	−111	42–55	0.11	1.6	1.4	850
Fluorocarbon (FC-72)	56	−90	–	0.054	1.09	0.65	1680
Fluorocarbon (FC-77)	97	< −100	–	0.06	1.17	1.13	1800
W/KFO (60/40 w/w)	–	−35	–	0.53	3.2	2.2	1250
Dynalene HC−30	112	−40	–	0.52	3.1	2.5	1275
Dynalene HC-50	118	−55	–	0.505	2.7	3.2	1340
Ga-In-Sn	–	−10	–	39	0.365	2.2	6363

dielectric and non-dielectric coolants. Comparisons of properties of these coolants (Table 3) can help selecting the right coolants. Data of these properties and other characteristics of variety of coolants can also be found in the literature [81–83].

3.2. Emerging cooling fluids

As mentioned before, the cooling challenges of modern high heat generating electronic devices cannot be completely fulfilled by the above-mentioned conventional coolants due to their inherently poor thermal properties, which greatly limit their cooling performance. On the other hand, increasing the thermal properties of these coolants by dispersing even micro-sized metallic or nonmetallic particles in them cannot make them suitable for those electronic devices and cooling systems because they can clog and damage the flow channels besides rapid settling of these particles inside the channel. Here comes nanofluids-a new class of heat transfer fluids, which is the suspension of nanoparticles (NP) in conventional coolants [17,19]. With no aforementioned limitations and having superior thermal properties nanofluids can suitably be used and can meet the cooling demands of modern and small electronic devices [17,21]. This new class of fluids can also offer immense benefits and potential applications in a wide range of industrial, electronics, and energy fields [17,19,20].

The impact of nanofluids is great given the cooling performance of heat exchangers or other cooling systems is vital in many industries. Results of key heat transfer properties and features related to cooling performance including thermal conductivity, convective and boiling of nanofluids are summarized in the following subsections.

Another recently innovated class of fluids is ionanofluids which is ionic liquid-based nanofluids. Studies showed that ionanofluids also posses superior thermal properties particularly thermal conductivity and heat capacity compared to their base ionic liquids [22–24]. 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 as coolants for electronic devices and packages.

3.3. Thermal properties and features of new coolants (nanofluids)

3.3.1. Thermal conductivity

Since thermal conductivity is one of the most important properties of any cooling fluid, researchers have mostly focused on this key property of nanofluids. Nanofluids were also found to exhibit superior other thermophysical properties such as thermal diffusivity and viscosity than those of base fluids [13,84–87]. Extensive research works have been performed on the thermal conductivity of nanofluids, which was found to be considerably higher than that of their base fluids [13,14,18,19,84,88–106]. Fig. 10 demonstrates significant enhancements of thermal conductivities of wide variety of nanofluids as a function of concentration of nanoparticles and the enhanced thermal conductivities increase further with increasing concentration of nanoparticles. However, results from different research groups are not very consistent which can also be evidenced from Fig. 10. There are also controversies regarding heat transfer mechanisms [107]. Nonetheless, thermal conductivity of nanofluids has been the mostly studied topic and thus no further discussions on the results and factors behind this thermal property are made here. As high thermal conductivity is the most desired feature of any cooling fluid, with such significantly high

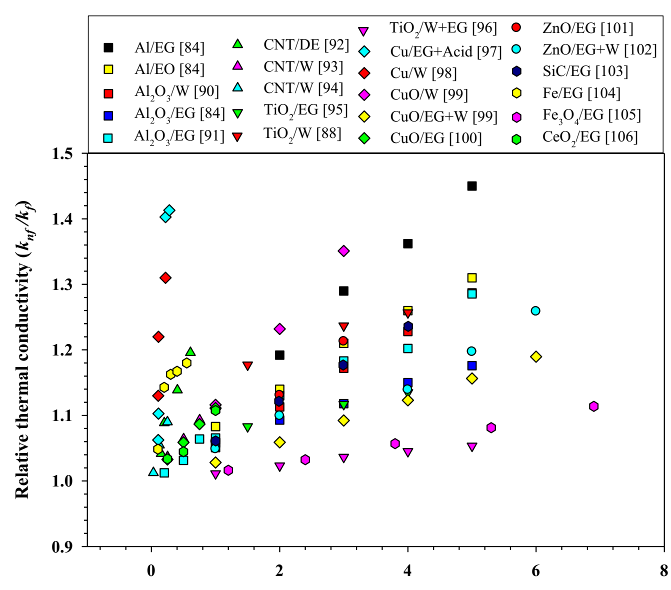

Fig. 10. Enhancement of thermal conductivity of various types of nanofluids as a function of concentration of nanoparticles.

thermal conductivity nanofluids are believed to be able to meet the cooling demand of high-tech electronics devices and systems.

3.3.2. Convective heat transfer performance

Evaluating convective heat transfer performance of nanofluids is very important in order for their application as coolants in electronics and other systems which employ flowing of coolants. Compared to the studies on thermal conductivity, investigations on convective heat transfer of nanofluids in various channels or heat exchange systems are still scarce. Previously author reviewed convective heat transfer of nanofluids [15] and thus this feature is not discussed in details. Instead research findings on this area is summarized and its importance in electronics cooling is highlighted.

Studies revealed that nanofluids exhibit enhanced heat transfer coefficient (HTC) compared to their base conventional fluids and the enhanced HTC further increases considerably with increasing loading of nanoparticles as well as Reynolds number (*Re*) or flow rate [15,108–110]. The enhancement of HTC is even more significant at turbulent regime. Some of the key experimental studies on this heat transfer mode of nanofluids in various flow systems are briefly summarized here.

Xuan and Li [111] studied convective heat transfer of Cu/W nanofluids and Nusselt number (*Nu*) of this nanofluid was found to increase significantly with the volumetric concentration of Cu nanoparticles. For instance, *Nu* of their nanofluid was increased by about 60% at 2 vol% of Cu nanoparticles. Wen and Ding [112] investigated the heat transfer behavior of nanofluids at the tube's entrance region under laminar flow conditions and the local HTC was observed to vary with nanoparticle volume fraction as well as with *Re*. Heris et al. [113] studied convective heat transfer of CuO and Al_2O_3/W-based nanofluids under laminar flow conditions through an annular tube. Their results showed that HTC increases with particle volume fraction as well as Peclet number. Vajjha et al. [114] determined convective heat transfer and friction factor of three different nanofluids dispersing Al_2O_3, CuO and SiO_2 nanoparticles in EG/W mixture (60/40 by mass) in turbulent flow regime. Results showed significantly high convective heat transfer performance of these nanofluids compared to base fluid (EG/W) and the HTC increases further with increasing concentration of these nanoparticles and *Re* as well. For example, a maximum 120% increase in convective heat transfer coefficient (*h*) was reported for 10 vol% of Al_2O_3, nanoparticle in EG/W mixture. Kumaresana et al. [115] performed experiments on heat transfer characteristics of EG/W (30/70 by volume) mixture-based multi-walled carbon nanotubes (MWCNT) nanofluid in a tubular heat exchanger. The HTC of this nanofluid was found to increase to a maximum of 160% at only 0.45 vol % MWCNT.

Faulkner et al. [116] was the first to conduct convective heat transfer experiments in a microchannel system having hydraulic diameter of 355 μm using CNT/W–nanofluid. At CNT concentration of 4.4% a considerable enhancement in *h* of this nanofluid was observed. Later, Jung et al. [117] studied heat transfer performance of Al_2O_3/water-based nanofluid in a rectangular microchannel under laminar flow condition. They demonstrated that the *h* increased by more than 32% for 1.8 vol% of Al_2O_3 nanoparticles and the *Nu* increases with increasing *Re* in the flow regime of $5 > Re < 300$. Recently, Sivakumar et al. [118] studied heat transfer characteristics of microchannel heat sink using different nanofluids including CuO/EG in laminar flow condition. At 0.3 vol% of CuO nanoparticles the *h* of this nanofluid increased astonishingly high from 4050 to 42,000 (W/m^2 K) for increasing *Re* from 100 to 1300 only.

Results from some key studies on convective heat transfer are summarized and presented in Table 4, which demonstrates significantly enhanced convective heat transfer performance of nanofluids compared to their base fluids which are conventional heat transfer fluids. Based on an early review of nanofluids for electronic packaging, Lai et al. [119] concluded that nanofluids based convective heat sinks are very promising for electronics package cooling.

From this brief summary of findings on convective heat transfer of nanofluids it can be conferred that these new fluids can perform better heat transfer as compared to conventional fluids in any flow conditions and systems including electronics cooling. However, their convective cooling performances in various electronic devices need to be assessed extensively.

3.3.3. Boiling heat transfer performance

Boiling is very efficient mode of heat transfer in various energy conversion and heat exchange systems as well as cooling of high energy density electronic components. It is long known that addition of solid particle in fluid can alter its boiling heat transfer performance [128]. Recently there is an increased research focus on this key-cooling feature (boiling) of nanofluids. Das et al. [129] reported a survey of limited studies on particle concentration dependence of pool boiling of nanofluids. They demonstrated that the enhancement in boiling heat transfer coefficient (BHTC) is mainly at lower particle concentrations. Reviews on nanofluids boiling heat transfer studies [15,16,129–132] conferred that despite some inconsistent results there is undisputed substantial increase (up to few times of base fluids) in the boiling critical heat flux (CHF) of nanofluids. It was also reported that the boiling performance of nanofluids can be enhanced further with increasing nanoparticle concentration and changing various other factors including deposition of nanoparticles on heater wall, roughness of wall surface, and addition of surfactant [133–135]. Nevertheless, the enhanced boiling heat transfer performance of nanofluids demonstrates that they can be used as advanced coolants in numerous applications including electronics cooling.

Representative results [133,134,136-141] on boiling critical heat flux of various nanofluids are presented in Fig. 11, which confirms substantial increase in CHF of nanofluids with loading of nanoparticles. It also shows that the CHF of some nanofluids increased until certain concentration and then decreased with further increase the loading of nanoparticles. This indicates that for each of these nanofluids, there might be a critical concentration beyond which nanofluids may not perform better in boiling heat transfer.

4. Application of new fluids (nanofluids) in electronics cooling

Because of very compact, lightweight and superior cooling performance, extensive research works have been performed on the application of microchannel-based cooling systems (e.g., heat sinks) in electronics cooling [38,39,61,108,142]. Since the convective heat transfer is inversely proportional to the hydraulic diameter of the channel, very high heat transfer performance can be achieved by using microchannel in any flow regime. However, the main limitation of microchannel cooling performance actually comes from the low heat transfer capability of conventional cooling fluids. In this regards, nanofluids with superior heat transfer capability can considerably increase the heat removal performance of microchannel cooling systems.

Number of research efforts have been made where nanofluids were directly employed in cooling systems of commercial electronic or computing devices to evaluate the cooling performance of these new fluids. The results of these studies were promising as nanofluids in those cooling systems resulted better cooling performance as compared to conventional cooling fluids.

Nguyen et al. [143] numerically investigated heat transfer performance of two nanofluids (γAl_2O_3/W and γAl_2O_3/EG) for cooling microprocessors of high heat output. The convective heat transfer coefficient of these nanofluids was reported to increase substantially with nanoparticle volumetric loading and/or the flow rate (*Re*), which resulted in considerable decrease in the maximum junction temperature of the microprocessors. Later, the same group [144] conducted

Table 4
Summarized key results on forced convection heat transfer studies of nanofluids.

Nanofluids and Reference	Geometry/flow nature	Findings
Cu/W [111]	Tube/turbulent	A large increase in *h* with Cu vol% and *Re*.
Al_2O_3/W [112]	Tube/laminar	*h* increases with Al_2O_3 vol% and *Re*.
CNT/W [120]	Tube/laminar	*h* increased by 350% at 0.5 wt% and *Re*=800.
Al_2O_3/W and CuO/W [113]	Tube/laminar	*h* increases with NP vol% and *Pe*. Al_2O_3 shows higher increment than CuO.
Al_2O_3/W [117]	Rectangular microchannel/laminar	*h* increased 15% for 1.8 vol% of Al_2O_3.
TiO_2/W [121]	Minichannel/laminar	*Nu* increased 13% at 0.8 vol% of TiO_2 and *Re*=1100.
Al_2O_3/W and ZrO_2/W [122]	Tube/turbulent	*h* increased significantly with NP loading.
SiO_2/W+EG (60:40 w/w) [123]	Tube/turbulent	*h* increased up to 40% at 10 vol% of SiO_2 and *Re*=3200
Al_2O_3/W [124]	Tube/laminar	*h* increased only up to 8% at *Re*=730 for 0.3 vol% of Al_2O_3.
Al_2O_3, ZnO, TiO_2 and MgO/W [125]	Tube/laminar	*h* increased up to 252% at *Re*=1000 for MgO/water.
MWCNT/W [126]	Tube/laminar and turbulent	*h* increased up to 40% at 0.25 wt% of MWCNT.
Al_2O_3, CuO and SiO_2/EG+W (60:40) [114]	Tube/turbulent	At *Re*=10,000, *h* was 29% greater for SiO_2, 40% for Al_2O_3, and 43% for CuO nanofluids over the base fluid.
Al_2O_3/W and W+EG (50/50 v/v) [127]	Tube/laminar	At *Re*=1700 and 0.7 vol% of Al_2O_3, *Nu* of W and W/EG increased about 14% and 15%, respectively.
CuO/EG [118]	Microchannel/laminar	For 0.3 vol% of CuO, *h* increased from 4048 to 42,022 for increasing *Re* from 100 to 1300.

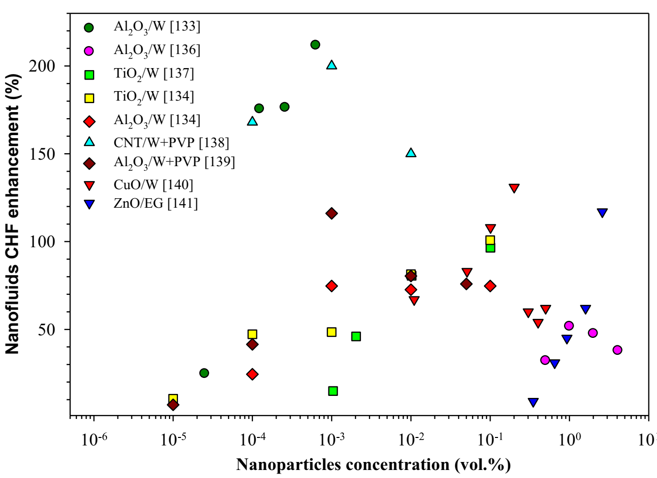

Fig. 11. Boiling critical heat flux of various nanofluids as a function of concentration of nanoparticles.

another similar study evaluating the cooling performance of nanofluids (Al_2O_3/W) in commercial water block system used for CPU cooling. For a certain flow rate (0.06 kg/s) the maximum block temperature was reduced from 40.9 °C to 37.3 °C due to increasing nanoparticle volumetric concentration from 0 (pure water) to 6.8%. Thus nanofluids showed enhanced cooling performance in this cooling system and the enhancement further increased with increasing nanoparticle loading.

Roberts and Walker [145] investigated heat transfer performance of Al_2O_3/W nanofluids in a commercially available electronics cooling system, which was a water block used for liquid cooling of a CPU. The convective heat transfer coefficient in the straight heated tube was found to increase up to 18% over that of the base water. They concluded that nanofluids can be used in commercial and industrial cooling based applications.

For the purpose of cooling electronics, a combined experimental and numerical study with aqueous silica-nanofluids in microchannel heat sink was performed by Escher [146]. For a constant *Re*, they reported an increase in *Nu* with increasing nanoparticle concentration.

The effect of the flow rate of three nanofluids (i.e., SiO_2, Al_2O_3 and TiO_2 nanoparticles dispersed in different compositions of a mixture of water and EG) in the cooling process of microchips was studied by Rafati et al. [147]. The enhanced cooling of the microchip (i.e., a considerable reduction of the operating temperature of processor) was observed due to using nanofluids. An increase in the flow rate of nanofluids resulted in noticeable decrease in the processor temperature.

Ijam and Saidur [148] performed mathematical analysis of two nanofluids as coolants in minichannel heat sink at turbulent flow regime. Their analysis showed that instead of water using aqueous SiC and TiO_2 nanofluids in microchannel heat sink a maximum 12.77% enhancement of heat flux could be achieved.

The heat transfer performance of aqueous and EG-based Al_2O_3 and CNT nanofluids in a CPU cooling system was experimentally evaluated by Nazari et al. [149]. Results were compared with the cooling performances of these base fluids (W and EG) and the CPU temperature was found to decrease about 20% and 22% for using Al_2O_3 and CNT nanofluids, respectively. Turgut and Elbasan [150] also studied thermal performance of the same Al_2O_3/W nanofluids in a similar commercial electronic (CPU) cooling unit as previously reported by other researchers [144,145]. Their results showed about 2.7 °C decrease of system temperature due to adding 1 vol% of Al_2O_3 nanoparticle in water. In recent years, there is a growing research interest on the application of nanofluids in heat pipes based cooling and numbers of numerical and experimental studies have been reported in the literature [151–154]. Among the early researchers in this area, Tsai et al. [155] and Ma et al. [156] demonstrated that the cooling performance of an oscillating heat pipe can significantly be improved by charging nanofluids into it. Yulong et al. [157] also found that changing Al_2O_3/EG+W (50/50 by vol.) nanofluid in an oscillating heat pipe significantly increases the heat transfer performance and the enhancement depends on the shape and volume fraction of nanoparticles.

Nanofluids have also been used in thermosyphon heat pipes. For example, Gabriela et al. [158] performed experiments with aqueous iron-oxide (γ-Fe_2O_3) nanofluids in an inclined thermosyphon heat pipe. They observed that addition of 5.3% (by volume) of nanoparticles in water improved the cooling performance considerably and concluded that this nanofluid has great potential as working fluids for thermosyphon heat pipes. Yang and Liu [159] employed functionalized nanofluid in thermosyphon and showed that the evaporating heat transfer coefficient can be enhanced.

Yousefi et al. [160] studied heat transfer performance of a CPU cooling heat pipe using nanofluids. Employing a 0.5 wt% Al_2O_3/W nanofluid in a CPU heat pipe the thermal resistance was found to decrease considerably (22%). This indicates that this nanofluid can perform better as compared to its base fluid (i.e., water) in cooling CPU.

Liu and Li [151] summarized available studies on the application of nanofluids in heat pipes. Their survey revealed that most of studies reported considerable enhancement in heat transfer (cooling) of heat pipes using nanofluids. The relative reduction of the total thermal resistance for various heat pipes with nanofluids was also reported.

Another review on nanofluids in heat pipes also showed that nanofluids can considerably enhance the thermal efficiency and can reduce the thermal resistance of heat pipes as compared to traditional fluids [152]. The results from the literature studies indicate that application of nanofluids in heat pipes has great potential in the filed of electronics cooling.

All these studies demonstrated that nanofluids perform better heat transfer (cooling) in electronic cooling systems.

5. Concluding remarks

Despite good progress been made during the past decades electronic and semiconductor industries are still facing some serious technical challenges to deal with the thermal management of their high performance electronics products and devices. This is mostly related to conventional cooling approaches and coolants, which are increasingly falling short in meeting the ever-increasing cooling demand of high heat generating electronic devices and microprocessors. However, most of the electronics devices and appliances employ these conventional cooling techniques. Thus, high performance electronics products (e.g., chips, devices etc.) need innovative mechanism, techniques, and coolants with high heat transfer performance in order to sufficiently remove their generated heat for expected performance and durability. Studies revealed that the heat pipes and the forced convection in microchannels-cooling systems are the most promising technologies for electronics cooling.

On the other hand, as a new class of coolants nanofluids exhibit significantly higher thermal features such as thermal conductivity, convective and boiling heat transfer compared to their base conventional fluids. These demonstrate that nanofluids are better coolants than their conventional counterparts. In addition, results from the limited studies on application of nanofluids also confirmed that this emerging class of fluids performed better as coolants for electronic devices compared to conventional coolants. Nevertheless, it is still of great importance to apply nanofluids in wide range of electronics cooling systems and to assess their applicability and performance.

The emerging cooling techniques like microchannels systems together with these novel fluids can substantially increase their heat removal performance and can meet the cooling needs of those high-heat generating electronic devices. Thus nanofluids - based microchannels can be a next generation electronics cooling technology. However, more extensive studies are to be performed for their realization and commercial scale applications in electronics industries.

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