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REVIEW ARTICLE

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Liquid metal enabled combinatorial heat transfer science: toward unconventional extreme cooling

Abstract As a class of newly emerging material, liquid metal exhibits many outstanding performances in a wide variety of thermal management areas, such as thermal interface material, heat spreader, convective cooling and phase change material (PCM) for thermal buffering etc. To help mold next generation unconventional cooling technologies and further advance the liquid metal cooling to an ever higher level in tackling more extreme, complex and critical thermal issues and energy utilizations, a novel conceptual scientific category was dedicated here which could be termed as combinatorial liquid metal heat transfer science. Through comprehensive interpretations on a group of representative liquid metal thermal management strategies, the most basic ways were outlined for developing liquid metal enabled combined cooling systems. The main scientific and technical features of the proposed hybrid cooling systems were illustrated. Particularly, five abstractive segments toward constructing the combinatorial liquid metal heat transfer systems were clarified. The most common methods on innovating liquid metal combined cooling systems based on this classification principle were discussed, and their potential utilization forms were proposed. For illustration purpose, several typical examples such as low melting point metal PCM combined cooling systems and liquid metal convection combined cooling systems, etc. were specifically introduced. Finally, future prospects to search for and make full use of the liquid metal combined high performance cooling system were discussed. It is expected that in practical application in the future, more unconventional combination forms on the liquid metal cooling can be obtained from the current fundamental principles.

Keywords combinatorial heat transfer, liquid metal, high flux cooling, thermal management

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1 Introduction

The famous Moore’s law, which states that the integration density of a micro processor chip will double every 18–24 months, has kept powering the information-technology revolution since 1960s. Recently, however, Moore’s law is approaching its upper limit from both technological and economical aspects [1]. One of the main challenges lies in the fact that efficient cooling of electronic components is required more than ever, since more heat is generated in smaller spaces [2], which leads to the ever-increasing heat dissipation requirement (Fig. 1) [3]. Agostini et al. [4] has predicted that many micro- and power-electronics industries are facing difficult challenge of removing extremely high heat flux up to 300 W/cm^2, while maintaining the component temperature below 85°C.

Apart from the commonly focused chip cooling in the information-technology category, high performance heat removal technology is also critical for many other large power devices in order to guarantee their safe, reliable, and efficient operation, such as cooling of high power LEDs [5], laser diodes [6], radars [7], microwave devices [8], concentrating photovoltaic cells [9], and IGBT modules in power convertors [10] etc.

In accordance with the advancing of electronic technology, cooling science and technology is rapidly progressing to meet the increasing heat removal requirement. Among the strategies ever established, air cooling, including both natural convection cooling and forced convection cooling,

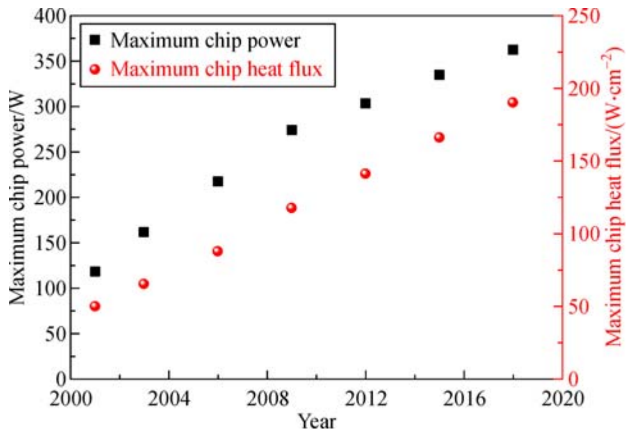

Fig. 1 Projections of maximum power and heat flux for microprocess chips (Adapted from Ref. [3] with permission from Elsevier, 2017)

is a widely adopted thermal management solution for electronics due to its advantages such as low cost, simplicity and reliability [11]. However, this technology is limited by its poor cooling capacity, which is generally suitable for the situations where heat flux is less than 10 W/cm^2. Heat pipe is a highly effective passive cooling technology which can realize long distance heat transfer with high rate and low temperature difference, and it can generally cope with heat dissipation rate up to several dozens of W/cm^2. At this stage, millions of heat pipes are manufactured each month which even dominate the market of CPU cooling of modern laptops [12]. As for higher heat flux, e.g., 10^2 W/cm^2 and even 10^{3}W/cm^2, heat pipe performs inability, and liquid cooling becomes the protagonist [4], including micro-channel [13] and mini-channel heat sinks [14], single phase [15] and two phase convection cooling [16], immersion cooling [17], impingement cooling [18], and spray cooling [19] etc.

In addition, there are two cooling technologies that can realize the refrigeration function and thus can cool the electronic components down to below ambient temperature, namely, thermoelectric cooling (TEC) and vapor compression cycle (VCC) cooling. TEC has advantages of compactness, light weight, reliability, vibration free and can be easily activated by DC electric sources. However, high cost and low efficiency restrict its popularization and application [20]. VCC is a promising solution for cooling high heat flux electronics, which possesses high heat transfer coefficient, low temperature coolant (lower than ambient temperature) and can cool multiple heat sources via a single refrigeration loop [21,22]. Concerns needing to be addressed for the wide applications of this approach are high cost, complexity and low efficiency especially under high temperature conditions.

For power devices which generate heat intermittently or have periodic thermal shock, phase change material (PCM) heat storage is a good option [23–26]. The basic principle in the thermal design of a PCM heat sink is that the melting point of the selected PCM must be below the unacceptable temperature point (e.g., about 85°C) of the device and beyond the ambient temperature (e.g., about 25°C). When facing a thermal shock, PCM automatically absorbs the heat and melts, with its temperature nearly remaining constant and thus preventing the power devices from overheating. After the thermal shock, the heat is dissipated from the PCM to the ambient, and the PCM solidifies and prepares for the next thermal shock. The thermal buffering effect of the PCM heat storage module can decrease the heat load of the cooling system by prolonging the heat dissipation time and thus simplify the system. In this sense, PCM can be termed as a smart cooling module.

In recent years, low melting point metals (or liquid metals) are attracting numerous attentions as a new class of material for electronics cooling, which exhibit powerful heat transfer capabilities mainly thanks to their intrinsic high thermal conductivity. In 2002, Liu and Zhou [27] proposed for the first time to use low melting point metal and its alloys as the cooling fluid for computer chip thermal management. Soon after, they demonstrated experimentally and theoretically that liquid metal cooling driven by either mechanical or electromagnetic pump can obtain superior thermal performances than the conventional water cooling under the same flow condition [28,29]. Miner and Ghoshal [30] from Nanocoolers Inc. (USA) advanced this technology and launched a liquid metal CPU cooling product in 2005 [31]. Their cooling device is driven by a magnetofluid dynamic (MFD) pump, and can cope with high heat flux (>200 W/cm^2) with convective heat transfer coefficient as high as 2×10^5 W/(m$^2\cdot$K).

Over the past few decades, Liu's group continuously pushed forward liquid metal-based thermal management technologies and developed a series of cooling methods with different heat delivery strategies and concepts. In 2007, Ma and Liu [32] demonstrated a cooling device which can harvest the waste heat of a computer chip to power a thermoelectric generator (TEG) and thus drive the flow of liquid metal to cool the chip. This cooling device consumes no external energy and operates silently. In the same year, Ma and Liu [33] proposed the concept of nano liquid metal fluid combining high thermal conductivity nano particles with liquid metal, which suggested the fabrication of the ultimate coolant near room temperature with the highest thermal conductivity as a liquid in nature. In 2009, Deng and Liu [34] built a prototype of a hybrid liquid metal-water cooling system for heat dissipation of high power density microdevices, which utilized liquid metal convection loop as the primary heat sink and water convection loop as the secondary heat sink, and thus reduced the use of the amount of liquid metal and greatly decreased the initial cost of the cooling system. To further advance this technology, Deng and Liu [35] summarized the design and optimization principles for liquid metal cooling devices, especially the design of the MFD pump, and extended this technology to the field of cooling of high power LEDs [36]. In 2012, Deng and Liu [37] demonstrated the concept of a compact plate heat spreader based on room temperature liquid metal. Then, Luo et al. [38] constructed a prototype of the blade heat spreader and tested its performance, which could effectively spread the heat from the heat source to the whole blade and thus eliminated the hotspot effect. In the meantime, Aqwest Inc. (USA), supported by the funding from US Air Force, started to develop liquid metal heat sink for high power diodes since 2009 [39,40]. They also used this technology for cooling of high power electronic chips in inverters for hybrid electric vehicles (HEV) and plug-in HEV (PHEV) [41,42]. Besides, liquid metal based micro/mini-channel heat sink was also gradually concerned and investigated [43–49].

In 2011, Li and Liu [50] proposed the concept of water-free heat exchangers toward new industry by replacing the conventional working fluid water with liquid metal to enhance the heat transport efficiency. In the same year, Li and Liu [51–53] proposed and developed energy harvesting and cooling devices based on the thermosiphon effect of liquid metal. In 2012, Gao and Liu [54] prepared a gallium-based thermal interface material which had high compatibility and wettability and possessed thermal conductivity as high as 13.07 W/(m·K), much higher than the conventional thermal grease. In 2013, Ge et al. [55] proposed using low melting point metal as a new class of PCM for thermal energy storage and smart cooling of electronics, and successfully introduced this technology to USB flash [56] and mobile phone [57], which exhibited much superior performance than the conventional organic PCMs. Soon after, this technology was widely concerned and investigated [25,58–64]. In 2016, Tan et al. [65] demonstrated a new conceptual cooling device that integrated hybrid coolants (liquid metal droplet and alkaline solution) for chip cooling which was driven by the continuous electrowetting of liquid metal. Yang et al. [66] found that alternating electric field could actuate the oscillation behavior of liquid metal and thus induce the flow of surrounding solution with extremely low power consumption, which could be used for solution mixing or chip cooling. Tang et al. [67] developed a volatile fluid assisted thermo-pneumatic liquid metal energy harvester, which realized self-driving by the thermo-pneumatic force of low boiling point fluid and by using liquid metal as energy carrier fluid for energy harvesting. This self-driving device could also be used for heat dissipation.

Overall, liquid metal has been proven to be an excellent thermal management material, and many liquid metal based cooling systems have thus been enabled and investigated over the passed few years. However, the liquid metal is often very costly, and its specific heat capacity sometimes is lower than that of the conventional fluid such as water which limits its heat extraction capability. Clearly, combining the merits of liquid metal and that of existing coolants may be promising in future application. To put the liquid metal technology into more extensive practical applications, to make full use of the advantages of these cooling methods and improve their cost performance, and to deal with increasingly strict heat removal requirement in harsh and complex environments, it is urgent that more innovative liquid metal thermal management strategies should be developed. This paper is aimed at establishing a conceptual guidance and a basic way for developing liquid metal combined high performance cooling systems. The engineering modularity thought is adopted to classify the basic cooling element and construct a combined cooling system. General principles will be presented and typical examples will be provided.

2 Basic cooling system

2.1 Abstract division of a cooling system

Before proceeding with the construction of liquid metal combined cooling system, it is necessary to have a comprehensive understanding about the basic features of a common cooling system. For the convenience of combination, a cooling system is abstractly divided into five parts (Ref. [40]): heat source (hs), heat acquisition segment (ha), heat transport segment (ht), heat rejection segment (hr), and ambience. Specific heat transfer forms in these segments can be summarized in Fig. 2(a). It is worthy to note that in various specific cooling systems, some segments may be unnecessary and nonexistent.

Generally, heat is delivered through these segments in sequence: generated by the heat source, transferred to the acquisition segment, then delivered by the transport segment to the rejection segment, and finally dissipated to the ambience. Except for the TEC and VCC cooling methods which can realize apparent heat transfer against the temperature gradient direction by applying external energy (electric energy or mechanical energy) (Fig. 2(c)), an universal equation can be adopted to describe the heat transfer processes in these segments, as expressed in Eq. (1).

$$Q = \int_0^t q\mathrm{d}t = \int_0^t q''A\mathrm{d}t = \int_0^t hA\Delta T_\mathrm{m}\mathrm{d}t, \quad (1)$$

where Q, q and q'' are total heat needing to be dissipated, heat transfer rate, and heat flux, respectively; t, h, A, and ΔT_m are heat transfer time, equivalent heat transfer coefficient, heat transfer area and average temperature difference. Normally, the heat flux q'' decreases along these segments as well as the temperature, from the highest at the heat source to the lowest at the ambience. The total thermal resistance of a cooling system is an important index to evaluate its performance, which is given by

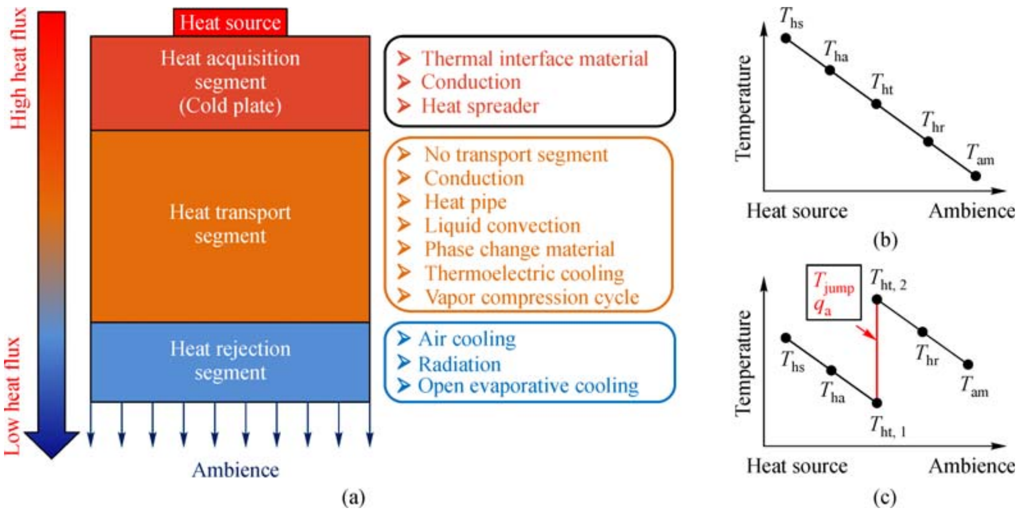

Fig. 2 Basic structure of a thermal management system
(a) Abstract division of cooling system; (b) schematic temperature variation along the segments in a common cooling system; (c) schematic temperature variation in thermoelectric cooling (TEC) or vapor compression cycle (VCC) cooling system

$$R_{total} = (T_{hs} - T_{am})/q, \tag{2}$$

where R_{total} is summation of the sub-resistances of these segments, namely

$$R_{total} = R_{hs\text{-}ha} + R_{ha\text{-}ht} + R_{ht\text{-}hr} + R_{hr\text{-}am}. \tag{3}$$

Definitions of these sub-resistances are similar to Eq. (2). It is worthy to note that, in the TEC or VCC cooling system, apparent temperature jump (T_{jump}) will occur in the TEC or the VCC module and additional heat (q_a) will be introduced by the module (Fig. 2(c)), which means that more heat will be dissipated to the ambience than the heat generated by the heat source. For other cooling methods, the amount of heat transferred through every segment is the same.

The primary purpose of designing a cooling system is to efficiently remove the heat generated by the heat source (electronic components) to the ambience and thus prevent the heat source from overheating. Under the prerequisite that the maximum temperature of the heat source is acceptable, the manufacture feasibility, robustness, maintenance, power consumption, cost, weight, volume, vibration, and noise of the system should also be considered and compromise among these restricts is needed. Under a given heat dissipation rate and a specific ambient temperature condition, the overall thermal resistance of the system should be as low as possible. Generally, in a rational design of a cooling system, the thermal resistances in different segments should be at the same order of magnitude, which means no “thermal short plank” exists. If there exists a significantly large thermal resistance in a certain segment of a cooling system, that segment should be emphatically concerned and optimized. In the following subsections, all of these segments will be introduced in detail to show how they function and relate to each other. Since the heat source and the ambience are generally given conditions and cannot be changed, only the heat acquisition segment, heat transport segment, and heat rejection segment will be discussed.

2.2 Heat acquisition segment

Heat acquisition segment is defined here as the one that contacts directly with the heat source. In some cooling systems, the heat acquisition segment is usually called cold plate. The main heat transfer mechanism in a cold plate is usually conduction. Since the area of heat source is small, the heat flux in this segment is generally very large. Therefore, extended surface is needed to reduce the heat flux, which is called heat spreading. Contact thermal resistance unavoidably exists on the interface between the heat source and the cold plate. The total thermal resistance of the acquisition segment is the summation of these resistances, namely

$$R_{hs\text{-}ha} = R_{cont} + R_{cond} + R_{spread}. \tag{4}$$

It is worthy to note that thermal contact resistance exists on every contact interface in a cooling system, while the contact resistance in the heat acquisition segment needs to pay more attention to, since the heat flux in that segment is the largest and thus the temperature rise across the interface will be significant. The existence of thermal contact resistance is due principally to the surface roughness effects on the contact interface. Contact spots are interspersed with air gaps (or vacuum) which have a poor heat transfer capability. The contact resistance can be reduced by increasing the contact spots (or decreasing the gaps’ area), which can be realized by decreasing the roughness of the mating surfaces or increasing the joint pressure [68]. In addition, filling the gaps with materials (thermal interface material, TIM) which possess a relatively high thermal conductivity can also help reduce the contact resistance. Thermal conductivity, wettability, and thickness of the TIM are the factors that may influence the contact resistance. Generally, under the prerequisite that the rough surfaces are well covered and the interface gaps are well filled with TIM, the thinner the TIM layer and the higher the thermal conductivity of the TIM, the lower the contact resistance is. The conventional organic thermal grease generally possesses a thermal conductivity in the magnitude of 10^{-1}–10^{0} W/(m·K), while that value for liquid metal based TIM (LMBTIM) is up to 10^{1} W/(m·K) [54], which makes it an excellent candidate as TIM, especially for the high heat flux condition.

Lee et al. [69] theoretically gave the expression of the spreading resistance of a plate spreader, which indicated that higher thermal conductivity of the cold plate leads to lower spreading resistance. The conduction resistance is also inversely proportional to the thermal conductivity of the cold plate material. Hence, the highly conductive material such as copper or aluminum plate is usually chosen as the cold plate material. Heat pipe, which has a high equivalent thermal conductivity (10^{4} W/(m·K)), can be filled into the cold plate to further decrease the spreading resistance [70]. Sometimes, vapor chamber can be used directly as a heat spreader which may have a better performance than that of a copper plate under specific geometric and heat conditions [71–73].

Liquid metal heat spreader (Fig. 3) can also be used in the acquisition segment, which can achieve comparable performance to that of a vapor chamber [39,40]. The difference between a LM heat spreader and a vapor chamber is that the former realizes heat transport and spreading by single phase convective flow while the latter by evaporation/condensing cycle. Generally, a vapor chamber can achieve good temperature uniformity. The temperature uniformity of a liquid metal heat spreader is affected by many factors such as the flow channel configuration and the flow velocity of liquid metal. Clearly, a proper geometric construction and a higher flow velocity will lead to better temperature uniformity. So far, to the best of the authors' knowledge, there is no detailed quantitative comparison about the temperature uniformity and equivalent thermal conductivity of the two heat spreaders, and further investigations are needed in the near future to comprehensively compare the thermal performances of them. One of the main advantages of the LM heat spreader is that it has no heat transfer limitations and can stably operate within a wide temperature range under any heat flux situations, while the performance of the vapor chamber may degrade under high heat flux conditions due to many inherent limitations [74].

2.3 Heat rejection segment

Heat rejection segment is the one responsible for dissipating the heat to the ambience. Air is the most commonly encountered ambience for devices on the ground. Natural or forced air convective flow through the rejection segment takes the heat away to the ambience. Due to the relatively poor heat transfer capability of air, many air cooling enhancement techniques have been developed [11], which can be classified into two categories: surface extension and heat transfer augmentation. The former enhances the cooling performance by increasing the heat transfer area, mainly including utilization of fin (plate fin [75] or pin fin [76]) and porous surface (carbon or metal foam [77,78]). The latter enhances the cooling performance by augmenting the heat transfer coefficient via flow interruption (such as boundary layer restarting or swirled flow), including louver or slit fin [79] vortex generator [80], cannelure or grooved surface [81], converging-diverging structure [82], etc.

Radiation heat transfer is reasonably neglected for most ground electronics when their temperature is relatively low and the temperature difference is small. However, in outer space, radiation becomes the only heat dissipation mechanism. The radiation heat transfer can be enhanced by increasing the reflectivity and emissivity of the heat

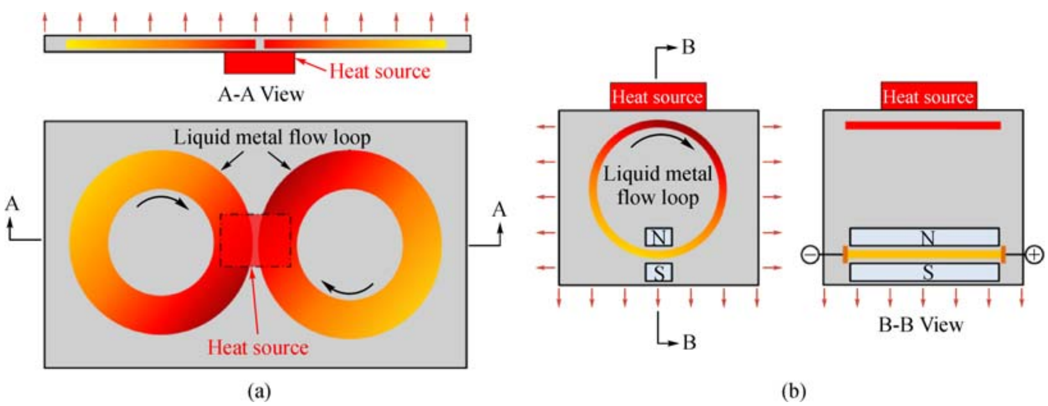

Fig. 3 Liquid metal heat spreader
(a) Plate heat spreader; (b) annular heat spreader

transfer surface [83]. Radiative coating of high emissivity material is a widely used method [84].

The heat dissipated by the rejection segment is the summation of air convection and radiation, calculated by

$$q = \eta h A_{\mathrm{hr}}(T_{\mathrm{hr}} - T_{\mathrm{am}}) + \varepsilon A_{\mathrm{hr}}\sigma(T_{\mathrm{hr}}^4 - T_{\mathrm{am}}^4), \qquad (5)$$

where η, A_{hr} and ε are the fin efficiency, surface area, and surface emissivity of the rejection segment, and σ is Boltzmann constant.

Sometimes, spray cooling is used for electronics thermal management, which absorbs heat from the heat rejection segment (or directly contact with the heat source surface) by evaporating the working fluid [19]. Different from the two-phase channel flow cooling, the vaporized working fluid in spray cooling enters the ambience after it finishes its heat absorption function and no longer condensates for later use as that does in a close loop. This method is called open evaporative cooling here, and is classified into the heat rejection segment.

2.4 Heat transport segment

Heat transport segment is the one connecting the acquisition segment and the rejection segment. It is responsible for transporting heat from the acquisition segment to the rejection segment. The transport segment may utilize a single transport method or a combined transport method. Single transport methods include conduction, heat pipe, liquid convection, PCM, TEC, and VCC, as shown in Fig. 4. In this subsection, these single transport solutions will be briefly introduced, and their combination will be discussed in the next subsection.

In some cooling systems, there may be no transport segment, namely, the acquisition segment and the rejection segment are directly connected. Heat is directly dissipated by the rejection segment from the acquisition segment to the ambience. Typical examples are air cooling fin heat sink [85,86] and vapor chamber heat sink [72,73,87] (Fig. 4(a)). In some cases, the space near the heat source is very limited and there is no room for placing the cooling system. Heat conduction can be used to deliver the heat from the acquisition segment to the remote radiator (Fig. 4(b)). Heat pipe can also realize this target and have a better performance [88] (Fig. 4(c)).

Liquid convection (Fig. 4(d)) is a powerful solution for dealing with high heat flux situations, and water is the most commonly used working fluid due to its easy access, low cost, and stability. Single phase mini-channel water cooling heat sink is widely investigated since it has a stable and high thermal performance while with moderate

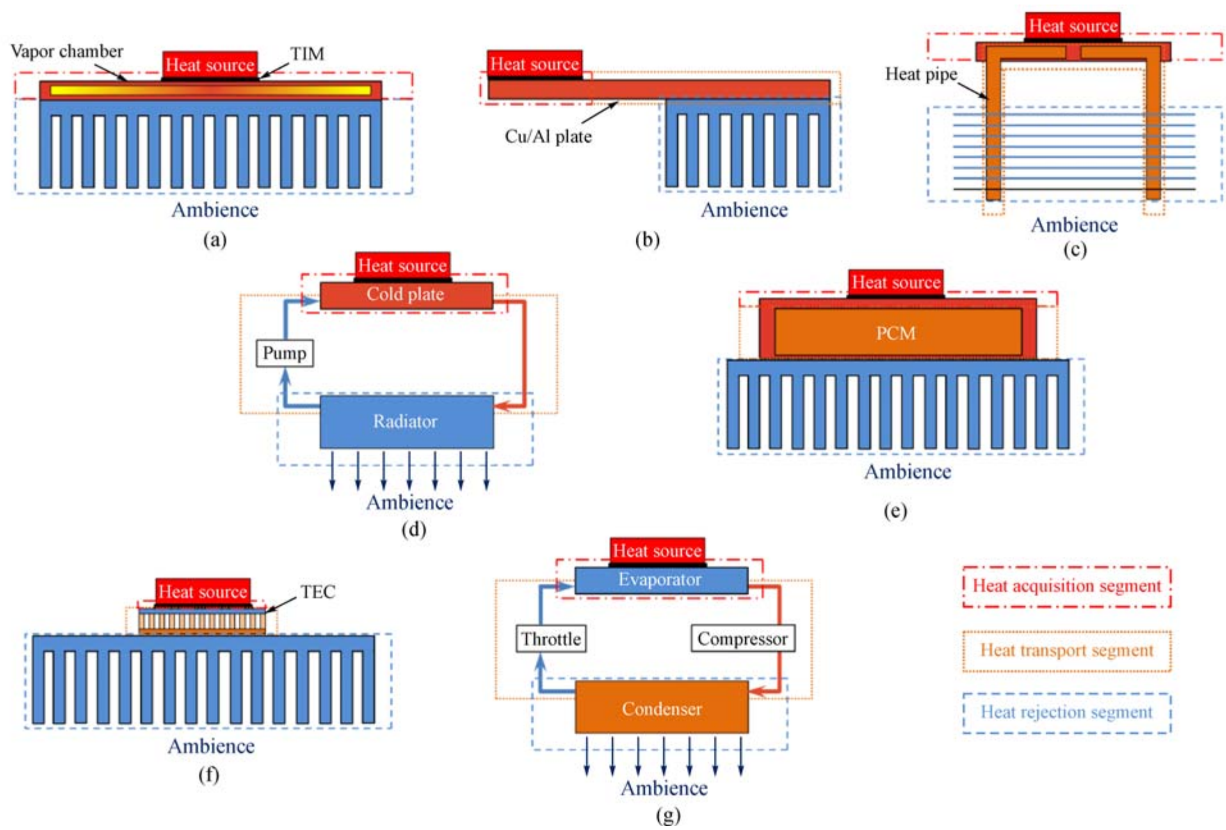

Fig. 4 Schematic diagrams of common single cooling systems

(a) Vapor chamber heat sink; (b) conduction heat sink; (c) heat pipe heat sink; (d) liquid convection cooling; (e) PCM cooling; (f) thermoelectric cooling (TEC); (g) vapor compression cycle (VCC) cooling pressure drop [14,89]. It has been analytically proved that for laminar pipe flow and fully developed heat transfer condition, the ratio of heat transfer coefficient of liquid metal cooling and water cooling is simply given as the ratio of their thermal conductivities, namely [30]

$$\frac{h_{\mathrm{lm}}}{h_{\mathrm{water}}} = \frac{k_{\mathrm{lm}}}{k_{\mathrm{water}}}. \tag{6}$$

The main thermal resistance in a liquid convection segment is convective resistance, which is given by

$$R_{\mathrm{cov}} = \frac{1}{hA_{\mathrm{cov}}}. \tag{7}$$

For a typical liquid metal coolant $Ga_{68}In_{20}Sn_{12}$, its heat transfer coefficient is about 27 times that of water[1)], which indicates that liquid metal has much superior convective heat transfer capability and thus has lower convective resistance.

PCM cooling is suitable for situations where the power devices generate heat intermittently or have periodic thermal shock. The implementation of a PCM thermal buffering module prolongs the total time t for heat dissipation from the on load time to the whole period (including both on load time and off load time), which will lead to a lower heat load (Eq. (1)) and thus the cooling system can be much simplified and more compact and efficient. Conventionally, organic PCMs (typically paraffin) are widely used for thermal management of power devices. The main drawback of paraffin PCMs lie in their low thermal conductivity, which seriously hinders the heat conduction inside the PCMs and thus decreases the performance of the module. Many heat transfer enhancement technologies have been developed to improve this situation [90], mainly including configuration of high thermal conductive paths (such as internal fins [91–93], heat pipes [94], wire mesh plate [24] and metallic foam [95]) and high conductive nano-particle inclusion [96,97], etc.). The low melting point metals (LMPMs) possess high thermal conductivity inherently, generally about two orders of magnitude larger than that of organic PCMs [55], which renders them excellent heat extraction capability as a PCM, as will be discussed in detail later.

The TEC [98] and VCC [99] cooling methods are schematically presented in Fig. 4(f) and (g), which have a refrigeration function and can provide low temperature (even lower than the ambient temperature) for the electronics.

3 Liquid metal combined cooling system

There are four types of applications of liquid metal in cooling systems, namely liquid metal based thermal interface material, liquid metal heat spreader, liquid metal convection cooling, and LMPM PCM. The former two are classified into the heat acquisition segment, while the latter two are in the transport segment. Combination of a cooling system mainly happens in the transport segment, therefore, LMPM PCM combined cooling systems and liquid metal convection based combined cooling systems will be illustrated in detail in this section.

3.1 LMPM PCM combined cooling system

3.1.1 LMPM PCM cooling

There are two situations where PCM heat storage module is suitable for. One is that the heat source works intermittently (intermittent thermal shock); the other is that the heat source works continuously with transient peak load (peak thermal shock). For the first situation, a PCM cooling system is configured; while for the second, a basic heat sink is needed and PCM assists in eliminating the thermal shock. The cooling capability of a PCM can be evaluated by its figure of merit (FOM) [25,62,100], which is defined as

$$\mathrm{FOM} = \sqrt{k\rho\Delta H}, \tag{8}$$

where k, ρ, and ΔH are the thermal conductivity, density, and fusion latent heat of the PCM. The higher the FOM of a PCM, the better it performs in thermal control. Table 1 lists the FOMs of some typical PCMs used in thermal management, the melting point of which ranges from 28.2°C to 60.2°C. It can be seen that LMPMs (gallium, $Bi_{49}In_{21}Pb_{18}Sn_{12}$ and $Bi_{31.6}In_{48.8}Sn_{19.6}$) possess FOMs two to three orders of magnitude larger than that of the conventional organic PCMs, which implies the much superior heat extraction capability of LMPMs. Yang et al. [62] have shown that LMPM can cope with ultra-high thermal shock like 100 W/cm^2 (1 s) with a maximum device temperature rise of 21°C, which is extremely difficult to deal with by the conventional PCMs.

Figure 5 depicts the concept of LMPM PCM combined series cooling system for cooling of intermittent heat source. The PCM can be used as the primary heat sink (Fig. 5(a)) or the secondary heat sink (Fig. 5(b)). In the first combination form (Fig. 5(a)), intermittent heat is first absorbed by the PCM in the form of latent heat and then dissipated to the ambience via the secondary heat sink. The heat transport segment of the secondary heat sink can be conduction, heat pipe, liquid convection, TEC, or VCC cooling. The use of the PCM module can reduce the heat load of the secondary heat sink and thus reduce its size, cost and power consumption, etc.

In some situations, a PCM module may have difficulty in coping with the high thermal shock of the heat source, and thus a high performance active cooling loop needs to be configured as the primary heat sink. Under this condition, the volume or weight of the heat rejection

1) America Indium Corporation. Physical property data for indalloy alloys. 2003

Table 1 FOMs of some typical PCMs used for thermal management [62]

PCM	Melting point T_m/°C	Thermal conductivity k/(W·m^{-1}·°C^{-1})	Density ρ/(kg·m^{-3})	Latent heat ΔH/(kJ·kg^{-1})	FOM $k\rho\Delta H$ /(10^6 W^{2}s·°C^{-1}·m^{-4})
Octadecane [60]	28.2	0.148	770	243.52	28
Gallium [61]	29.78	33.68	6094.7	80.16	16454
n-Eicosane [101]	36.5	0.157	770	237.4	29
Paraffin RT44 [102]	41–45	0.2	760	255.0	39
Octadecanol [59]	55.6	0.175	894	239.7	38
$Bi_{49}In_{21}Pb_{18}Sn_{12}$ [59]	58.2	10.1	9307	23.4	2200
$Bi_{31.6}In_{48.8}Sn_{19.6}$ [64]	60.2	14.5	8043	27.9	3254

segment may be restricted due to specific application limitations. Since the size of the rejection segment is generally positively related to its heat load, a PCM heat storage module can be configured between the transport segment and the rejection segment to lower the heat load and thus reduce the size of the rejection segment, as illustrated in Fig. 5(b).

It is worthy to note that sometimes internal high conductive paths or nano-particles could be filled into the PCM to enhance the heat transfer inside. These enhancement methods are not considered as combination here but regarded as a PCM module only. Figure 6 displays two examples of the LMPM PCM combined series cooling system. Figure 6(a) is a PCM/heat pipe heat sink and Fig. 6(b) is a liquid cooling/PCM heat sink. Similarly, other combined cooling systems can also be developed based on the concept shown in Fig. 5.

3.1.2 LMPM PCM against thermal shock

In situations where PCM is used to eliminate thermal shock, there are generally two transport segments which work in parallel, as exhibited in Fig. 7. Under normal operation condition, the heat is delivered by the basic transport module such as conduction, heat pipe, liquid convection, TEC, or VCC. When facing a thermal shock, the basic transport module cannot withstand such a high heat flux and the excess heat is absorbed by the PCM module via melting the PCM. After the thermal shock, the heat stored by the PCM is rejected to the basic transport module or transferred directly to the rejection segment and then dissipated to the ambience; the PCM solidifies and prepares for the next thermal shock. Figure 8 is an example of this kind of cooling system, namely a heat pipe/LMPM PCM cooling system which can withstand thermal shock. More examples of this kind of combination can be referred to in Refs. [91,103–107].

In fact, the basic transport module can be designed according to the peak heat load and thus the PCM module is not needed. However, the peak load may lead to a very large or complicated cooling system and greatly increase its volume and cost. The implementation of a PCM module can easily solve this problem.

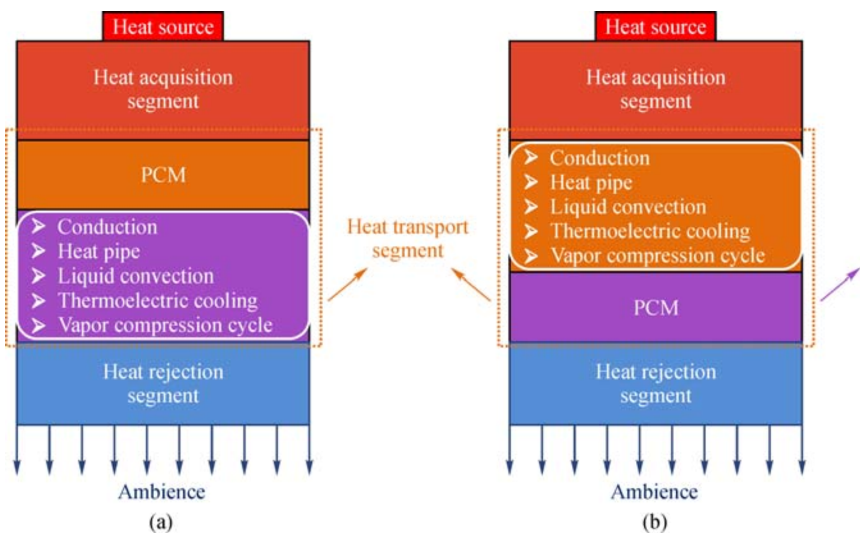

Fig. 5 LMPM PCM combined series cooling system for intermittent heat dissipation
(a) LMPM PCM as primary heat sink; (b) LMPM PCM as secondary heat sink

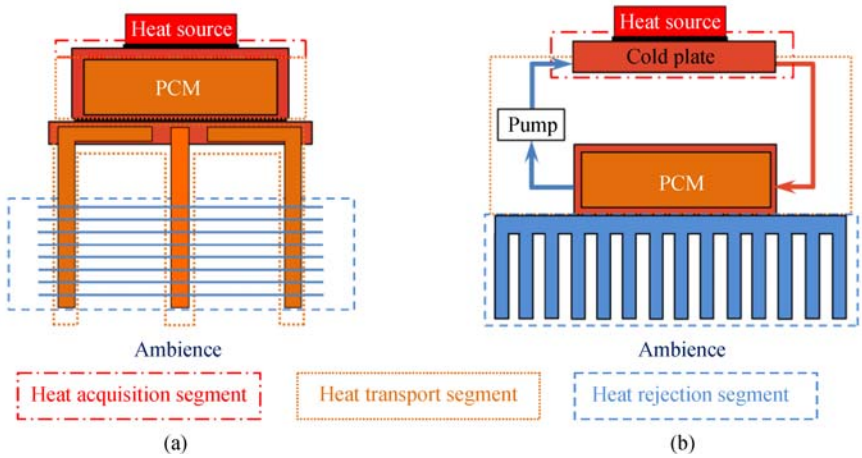

Fig. 6 Examples of LMPM PCM combined series cooling systems for intermittent heat dissipation
(a) LMPM PCM/heat pipe heat sink; (b) liquid cooling/ LMPM PCM heat sink

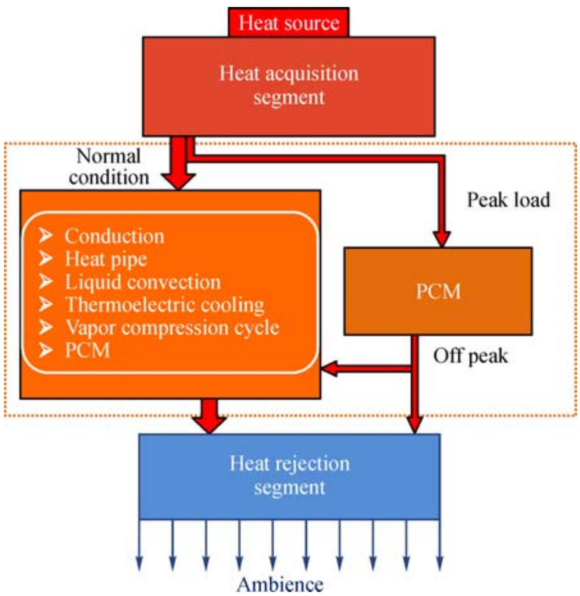

Fig. 7 LMPM PCM combined parallel cooling system against thermal shock

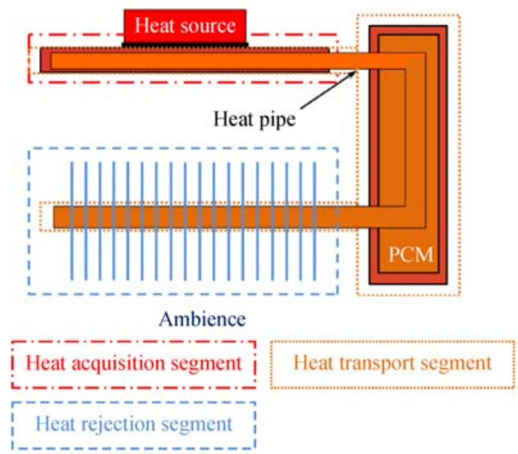

Fig. 8 Heat pipe/LMPM PCM cooling system against thermal shock

3.2 Liquid metal convection based cooling systems

Liquid convection cooling is an important active cooling method for high power heat dissipation. As mentioned before, the excellent convective cooling capability of liquid metals mainly benefits from their intrinsic high thermal conductivity, as listed in Table 2. It can be calculated from Table 2 that liquid metal generally possesses heat transfer coefficient which is an order of magnitude larger than that of water. Another advantage of using liquid metal as heat transfer fluid is that it has very high boiling point. For example, the boiling point of gallium is 2403°C, which means that it can work within a very wide temperature range without performance degradation or other issues (such as leakage or even explosion) caused by evaporation.

Yang et al. [49] have shown that in mini-channel heat sink, liquid metal exhibits much superior flow and thermal performance than water, namely, liquid metal cooling can realize lower overall thermal resistance with less pumping power consumption. Besides, liquid metal can be driven by the MFD pump, which is generally more efficient than a mechanical pump used for driving water convection [30,31,35,110]. However, the main issues that restrict its wide use lie in the high price and heavy weight of liquid metal. Besides, the driving and corrosion prevention cost significantly increase with the increase of the amount of liquid metal used. Combination cooling system may be a good way to relieve these issues to some degree via reducing the amount of liquid metal used. Liquid metal convection can be used as the primary heat sink to take the heat away from the heat acquisition segment and then

Table 2 Comparison of the thermophysical properties of water and liquid metals

Material	Density $\rho/(\mathrm{kg \cdot m^{-3}})$	Heat capacity $c_p/(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$	Viscosity $\mu/(10^{-3}\ \mathrm{kg \cdot m^{-1} \cdot s^{-1}})$	Thermal conductivity $k/(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$	Melting point $T_m/°C$
Water[a] [108]	998	4182	1.003	0.6	0
Hg [109]	13564	139	1.56	8.7	–38.9
$Na_{27}K_{73}$ [109]	868	982	0.91	21.8	–11
$Ga_{61}In_{25}Sn_{13}Zn_1$ 1)	6500	—	—	15	7.6
$Ga_{68}In_{20}Sn_{12}$ 1)	6363	366	2.22	16.5	10.7
$Ga_{80}In_{20}$ [34]	6335	404	—	26.6	16
Ga [61]	6095	398	1.75	33.7	29.8

Note:[a]—at 20°C

transfer the heat to a secondary heat sink which is responsible for delivering the heat to a remote rejection segment. Liquid metal does not have to flow to the heat rejection segment and thus its amount is reduced. This reduction could be much significant for the situations where the heat rejection segment is remote to the heat source. This kind of combination is also suitable for situations where the secondary heat sink cannot withstand the high heat flux condition or may be much more energy consuming or inefficient when high heat flux is applied. Liquid metal convection can cope with the high heat flux in the acquisition segment and then the heat is transferred to a secondary heat sink with much reduced heat flux. Deng and Liu [34] have given a typical example in which a liquid metal/water hybrid cooling system is constructed and tested (Fig. 9). The thermal performance of the hybrid cooling system is very close to that of the absolute liquid metal cooling, while the amount of liquid metal charged is reduced from 44.79 mL to 11.75 mL and thus the initial coolant cost is greatly lowered, from $113 to $30. Conduction, heat pipe, liquid convection, TEC, or VCC can serve as the secondary heat transport module to deliver the heat to the rejection segment. A PCM module can also be used for temporary heat storage (thermal buffering). These combinations are conceptually presented in Fig. 10(a) and Fig.11(a).

For applications involving refrigeration, namely TEC, or VCC module serve as the primary heat transport segment, a high performance secondary heat sink is requisite. For example, Hu et al. [98] experimentally studied a water-cooled thermoelectric cooler for CPU cooling under severe environment. Chein and Chen [111] developed a thermoelectric cooler integrated with a secondary microchannel heat sink for water refrigeration. Generally, the hot end temperature in TEC, or VCC module has a great influence on their efficiency, and lower hot end temperature leads to a higher efficiency. Hence, high performance liquid metal convection may be suitable for the hot end cooling in these situations (Fig. 10(b) and Fig.11(b)).

The combinations above are all in series forms. Liquid metal convection can also be combined in parallel with other cooling methods (Fig. 10(c) and Fig.11(c)). Mei et al. [112] developed a hybrid mini-channel heat sink, in which liquid metal and water flowed in parallel. Figure 12 demonstrates the schematic diagram of this hybrid heat sink, in which water flows in the left half part and liquid

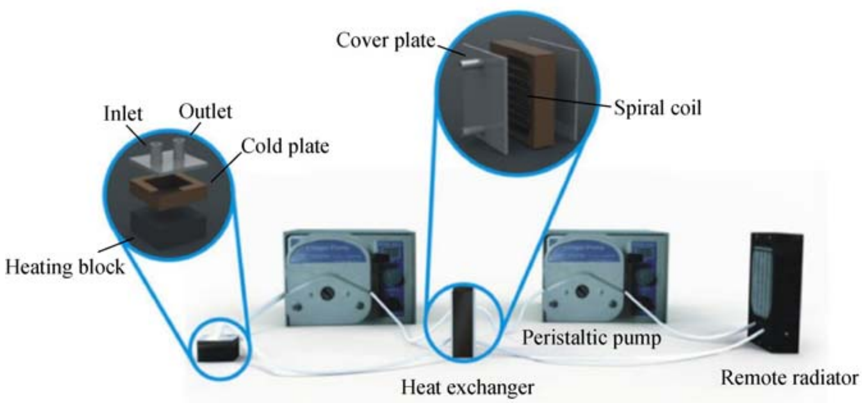

Fig. 9 Setup of hybrid liquid metal/water cooling system (Adapted from Ref. [34] with permission from Springer, 2010)

1) America Indium Corporation. Physical property data for indalloy alloys. 2003

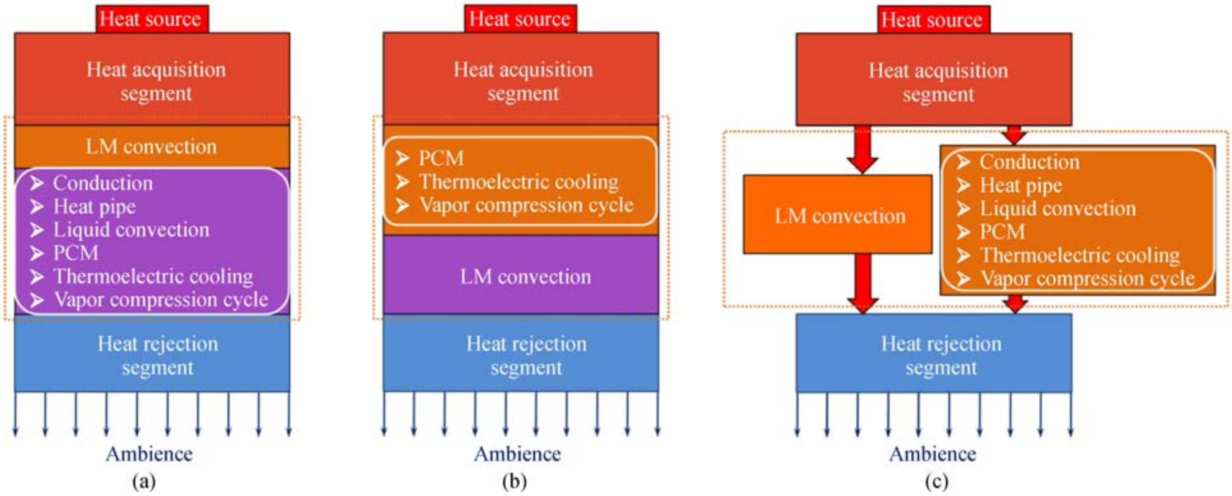

Fig. 10 Liquid metal convection combined cooling systems
(a) Liquid metal convection as primary heat sink; (b) liquid metal convection as secondary heat sink; (c) liquid metal convection combined parallel cooling system

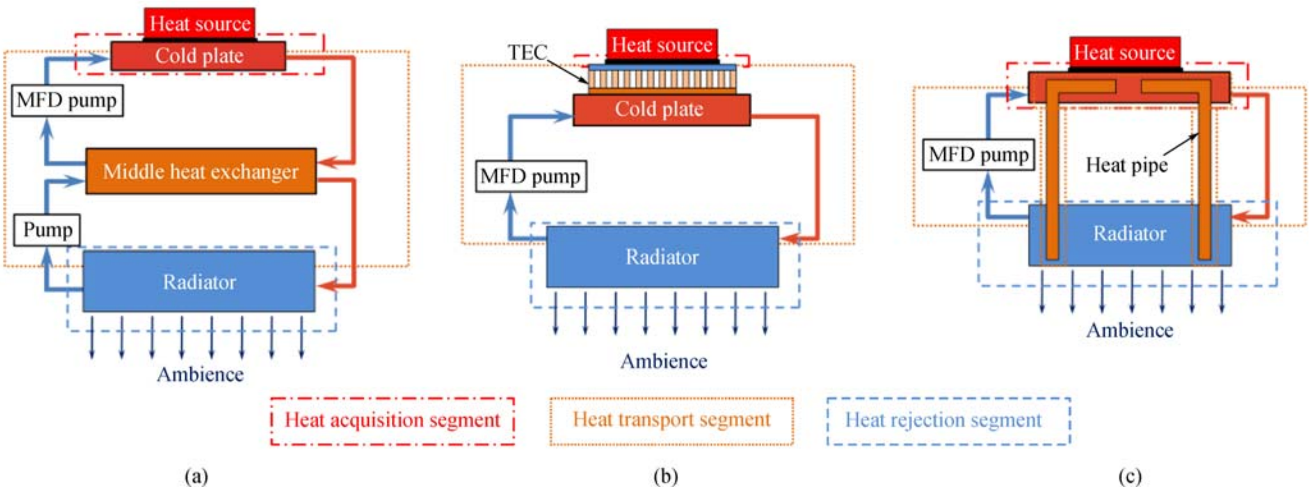

Fig. 11 Examples of liquid metal convection combined cooling systems
(a) Liquid metal convection/water convection cooling system; (b) TEC/liquid metal convection cooling system; (c) liquid metal convection/heat pipe parallel heat sink

metal flows in the right half part. Experimental results indicated that the hybrid mini-channel heat sink had a better cooling performance than pure water cooling heat sink (Fig. 12(c)). By utilizing hybrid mini-channel heat sink based on liquid metal and water, it was expected that it could be made more inexpensive and practicable for liquid metals to be used in large power electronics cooling areas.

Liquid metal convection can be conveniently started and stopped to quickly response to heat load variation of the heat source and thus prevent it from overheating. Liquid metal convection cooling can also serve as a backup solution for conditions when the other cooling method mal functions. For example, Fig. 13 shows a liquid metal convection/heat pipe parallel cooling system which is suitable for situations where the heat load of the heat source fluctuates significantly over time [113]. The heat pipe cooling module can only withstand moderate heat load, and liquid metal convection starts to work when facing a peak load. If a single liquid metal convection cooling system is configured, it may increase the initial cost.

3.3 All liquid metal combined cooling system

Here, an all liquid metal combined cooling system is configured, as depicted in Fig. 14. In the heat acquisition segment, liquid metal based TIM is used on the contact interface; a liquid metal heat spreader is adopted to reduce

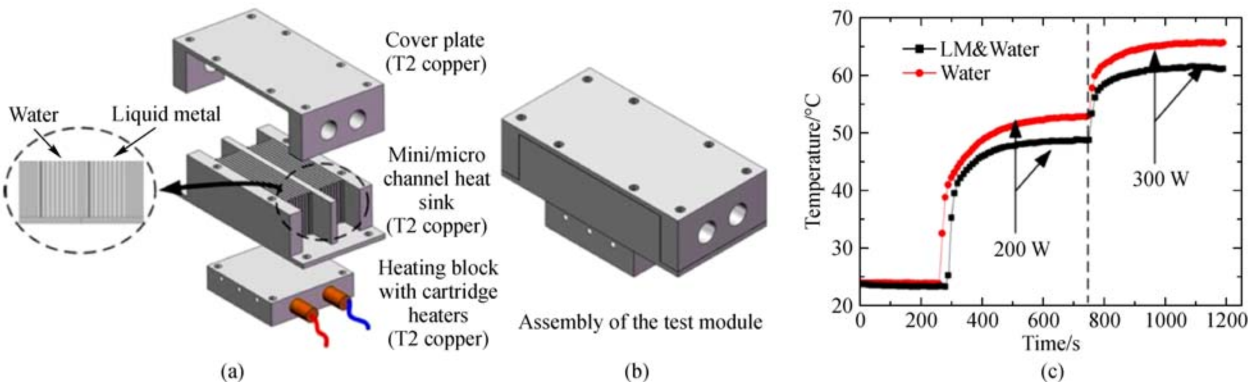

Fig. 12 Schematic diagram of a hybrid mini-channel heat sink
(a) Schematic of hybrid liquid metal/water mini-channel heat sink; (b) assembly of the module; (c) comparison of the thermal performance of water cooling and hybrid liquid metal/water cooling [112]

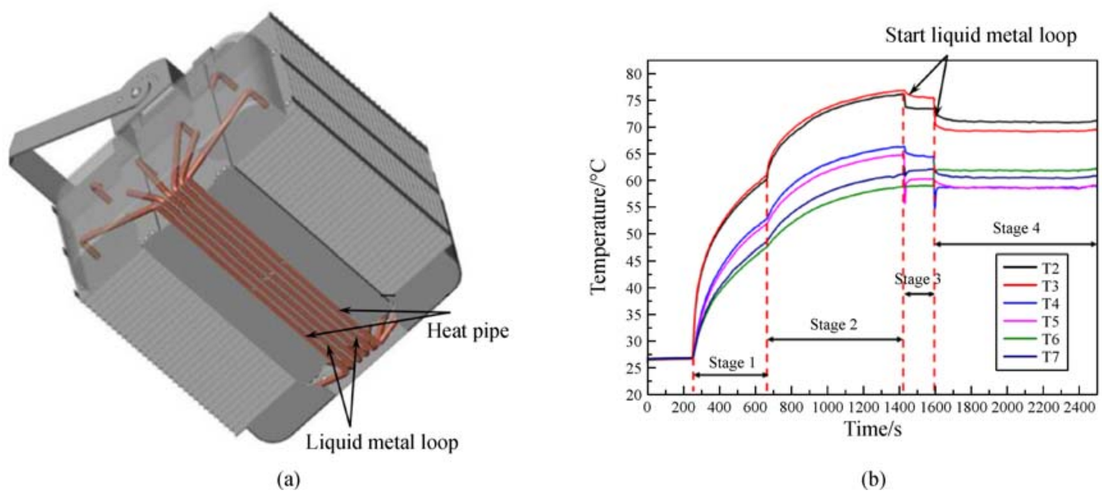

Fig. 13 Liquid metal convection/heat pipe parallel cooling system suitable for sustaining significant fluctuation of the heat load of the heat source
(a) Heat pipe cooling system combined with liquid metal convection loop; (b) thermal performance of the combined cooling system facing thermal shock (Adapted with permission from Ref.[113])

the heat flux and thus reduce the heat load of the transport segment. In the heat transport segment, a basic liquid metal convection cooling loop is configured and a LMPM PCM module is set to cope with the thermal shock in periodic peak load condition.

3.4 Other alternative combinations

In addition to combination with conventional cooling technologies, the cooling function of liquid metal can also be combined with some other functions, such as electricity transmission, since liquid metal is also a good electric conductor. The electrical conductivity of pure gallium is 6.8×10^6 S/m, about a ninth of that of copper which is a widely used excellent conductor. Flowing liquid metal may serve as wire in a functional circuit while, at the same time, taking away the heat generated by the circuit. For example, Chen [114] proposed a new radiofrequency ablation method based on liquid metal, in which liquid metal served as electrode and thermal control fluid simultaneously. The experimental results showed that, this new type of probe could produce a larger tissue ablation area, and effectively prevent the tissue carbonization caused by high temperature around the probe via flowing of liquid metal.

From the viewpoint of material, liquid metal based combined material is also worthy of exploration. To name just a few, liquid metal and water (or other liquid) may work together as a coolant for convective cooling or as a combined PCM for thermal energy storage. Since liquid metal has high thermal conductivity and water has high specific heat capacity and high fusion latent heat, the

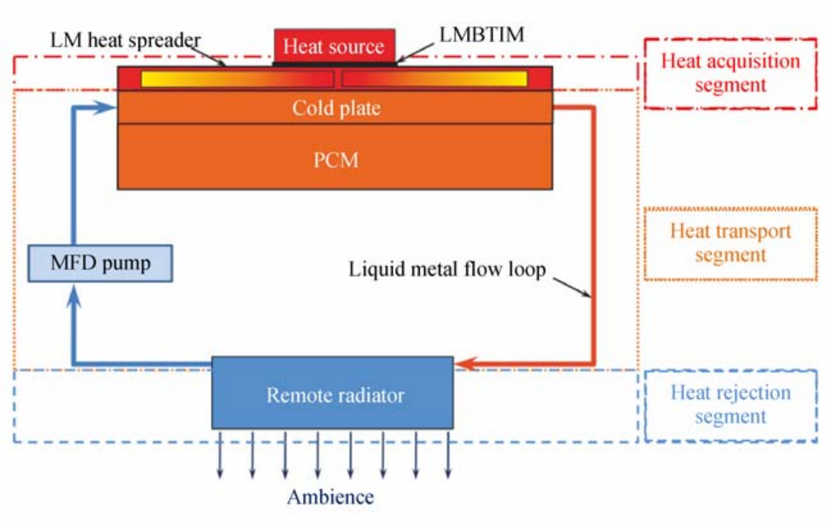

Fig. 14 All liquid metal combined cooling system

mixture of them may exhibit a higher performance. Low melting point metal and paraffin may be mixed as a new PCM, since low melting point metal has a better heat transfer capability and paraffin is cheaper and has a higher fusion latent heat. Low melting point metal can also be dispersed on another material (e.g. polydimethylsiloxane, PDMS) to get a form-stable PCM. However, more works are needed in the near future to test their working performance.

4 Conclusions

Liquid metal has excellent performance when used as a class of powerful thermal management material, and liquid metal based cooling technologies can be easily combined with many other commonly used cooling methods, such as conduction, heat pipe, liquid convection, PCM, TEC, and VCC cooling. Involvement of liquid metal cooling technologies renders a cooling system more flexibility and provides it with a great potential in dealing with more complex and critical cooling requirements. Liquid metal based thermal interface materials can be used to effectively reduce contact resistance. A liquid metal heat spreader can eliminate hotspot effect and reduce heat flux without heat transfer limitations which occur in vapor chamber. LMPM PCM combined cooling system can deal with intermittent heat dissipation conditions and prevent the heat source from overheating when facing a thermal shock. Liquid metal convection combined cooling methods may help improve the cost performance of a cooling system and make it more capable of handling complex cooling situations. Some other alternative combinations, such as heat transfer combined with electricity transmission and liquid metal based combined material, are worthy of exploration. This paper only provides an overall conceptual guidance for configuration of liquid metal combined cooling system, more novel types of combination may be developed based on the abstractive conceptual principles provided in this paper, and more experimental works are to be conducted in the near future to make new devices which can make full use of the superiority of these methods and thus help advance the industrialization of liquid metal based cooling technologies.

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Notations

A	Heat transfer area/m^2
c_p	Specific heat capacity/(J·kg^{-1}·K^{-1})
H	Heat transfer coefficient/(W·m^{-2}·K^{-1})
ΔH	Fusion latent heat/(J·kg^{-1})
K	Thermal conductivity/(W·m^{-1}·K^{-1})
Q	Heat transfer rate/W
q''	Heat flux/(W·m^{-2})
R	Thermal resistance/(K·W^{-1})
T	Temperature/K
$\mathrm{T_m}$	Melting point/°C
ΔT_m	Average temperature difference/K
t	Time/s
Greek letters	
η	Fin efficiency
μ	Viscosity/(kg·s^{-1}·m^{-1})
ρ	Mass density/(kg·m^{-3})
σ	Boltzmann constant

Abbreviation

FOM	Figure of merit
LM	Liquid metal
LMPM	Low melting point metal
MFD	Magnetofluid dynamic
PCM	Phase change material
TEC	Thermoelectric cooling
TEG	Thermoelectric generator
TIM	Thermal interface material
VCC	Vapor compression cycle

Subscripts

a	Additional heat
am	Ambience
cond	Conduction
cont	Contact
conv	Convection
ha	Heat acquisition segment
hr	Heat rejection segment
hs	Heat source
ht	Heat transport segment
spread	Spreading

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