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Liquid metal cooling in thermal management of computer chips

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Abstract With the rapid improvement of computer performance, tremendous heat generation in the chip becomes a major serious concern for thermal management. Meanwhile, CPU chips are becoming smaller and smaller with almost no room for the heat to escape. The total power-dissipation levels now reside on the order of 100 W with a peak power density of 400–500 W/cm², and are still steadily climbing. As a result, it is extremely hard to attain higher performance and reliability. Because the conventional conduction and forced-air convection techniques are becoming incapable in providing adequate cooling for sophisticated electronic systems, new solutions such as liquid cooling, thermoelectric cooling, heat pipes, vapor chambers, etc. are being studied. Recently, it was realized that using a liquid metal or its alloys with a low melting point as coolant could significantly lower the chip temperature. This new generation heat transfer enhancement method raised many important fundamentals and practical issues to be solved. To accommodate to the coming endeavor in this area, this paper is dedicated to presenting an overall review on chip cooling using liquid metals or their alloys as coolant. Much more attention will be paid to the thermal properties of liquid metals with low melting points or their alloys and their potential applications in the chip cooling. Meanwhile, principles of several typical pumping methods such as mechanical, electromagnetic or peristaltic pumps will be illustrated. Some new advancement in making a liquid metal cooling device will be discussed. The liquid metal cooling is expected to open a new world for computer chip cooling because of its evident merits over traditional coolant.

Keywords chip cooling, liquid metal, liquid cooling, gallium and alloy, thermal management, convective cooling, high heat flux density, heat transfer enhancement

Received March 25, 2007; accepted May 17, 2007

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1 Introduction

Today's rapid IT development requires high PC performance capable of processing more data speedily. To fulfill this need, CPUs are assembled with more transistors, which are drawing more power and having much higher clock rates. This leads to an ever-larger heat produced by the CPU in the computer, which will result in a shortened life, malfunction or even failure of CPU [1]. Therefore, over the last four decades, the thermal management of electronics devices such as supercomputers keeps challenging system designers to develop feasible ways to keep the junction temperatures of electronic components below 85°C [2]. The 2005 International Technology Roadmap for Semiconductors (ITRS) indicates a continuing rise of high performance processors from a maximum power of 365 W in 2006 to 515 W by 2011 [3]. In addition, it predicts a decrease in the maximum allowable junction temperature from the current 100°C to 90°C by 2011. Furthermore, it is estimated that every 10°C increase above the normal junction temperature would reduce the device life by a factor of 2. All urgent needs provoke the tremendous efforts towards excellent thermal management solutions. In fact, heat removal has become one of the most challenging issues for the computer industry for many years. Conventional thermal management schemes such as air-cooling with fans, liquid cooling [4], thermoelectric cooling [5–8], heat pipes [9], vapor chambers [10], vapor compression refrigeration [11], impingement cooling [12,13] and micro-channel cooling [14] have either reached their practical application limits or are soon to become impractical for recently emerging electronic components. Therefore, while continuous efforts are made to improve the traditional schemes, exotic approaches are also tried as an alternative to those methods insufficient for cooling high power processors. In 2004, the chip manufacturer Intel partly canceled its new Pentium 4-based CPUs twice because of overheating issues. The last four decades of miniaturization has led to the doubling of the number of transistors on a chip every two years according to Moore's Law. It is projected that the next generation of computer chips will produce localized heat flux over 10 MW/m² [15].

Compared with air-cooling, liquid-cooling appears to be a much more efficient way of drawing heat away from the hot processor to the outside of the system. With forced flowing of convective water, the improvement over air-cooling was found to be more than a factor of 10 in the convective heat transfer coefficient. However, the use of water or other conventional liquids has some limitations. The low thermal conductivity of these fluids may lower their effectiveness as heat transfer fluids. Moreover, circulation of such fluids can be driven only by mechanical pumps that may be unreliable, occupy large space, and contribute to vibration or noise. Therefore, researchers are proposing to enhance the effective thermal conductivity by adding conductive nano metal particles such as copper or aluminum to the solution and suspension, which leads to the recent explosive investigation on nanofluids [16,17]. However, such improvement is still limited due to the used base fluids. Particularly, the mixed solution may easily be subject to additional troubles during thermal management such as susceptibility to fouling, particle deposition or conglomeration, degeneration of solution quality and flow jamming over the channels [17]. Besides, the low evaporation point of these liquids may imply potential dangers in preventing the device from burning out, since the liquids may easily escape to the ambient. In conclusion, it is absolutely necessary that new feasible ways be found to solve the problem of highly efficient thermal management.

2 Proposition of liquid metal coolant for chip cooling

As is well known, the thermal conductivity of a metal is much higher than that of a general liquid such as water, oil or more organic fluids. Thus, if a certain liquid metal or its alloys with a low melting point is adopted as the cooling fluid, a much higher cooling capacity than that of traditional fluids can be obtained. Starting from this basic point, Liu and Zhou [18] proposed for the first time to use a liquid metal or its alloys as the cooling fluid for the thermal management of the computer chip in 2002. The recent work by Miner and Ghoshal [19], Li et al. [20] further strongly supported this effort. Liquid metals used as coolant offer a unique solution to cool high density power sources and spread heat in a highly confined space. The two principal advantages lie in their superior thermophysical properties for extracting heat, and in the ability to pump these liquids efficiently with silent, vibration-free, low energy consumption rates, nonmoving and compact magneto-fluiddynamic (MFD) pumps because of its high electrical conductivity in a liquid metal [19,21]. So far, the liquid metal of gallium or its alloys are perhaps the best candidate. With about several dozen times larger thermal conductivity than that of water, liquid metals such as gallium or its alloys show a very good property in quickly transferring heat away. As a very promising coolant, a liquid metal has the following merits:

1) non-flammable, non-toxic, and environmentally friendly;

- 2) used as a replacement for mercury in existing applications;
- 3) low vapor pressure and thus causing no danger to human health;
- 4) low dissolution in water, therefore hard to invade the skin;
- 5) highly thermally conductive (more than an order of magnitude increase in the heat conductivity of water);
- 6) boiling point $> 200^{\circ}\text{C}$, eliminating power density as a limiting factor in cooling applications and eliminating the need to refill coolant;
- 7) electrically conductive activating efficient, non-moving electromagnetic pump;
- 8) true single-phase liquid cooling, and therefore low probability of leakage and accident.

This paper is aimed at providing a comprehensive review on the application and advancement of liquid metals or their alloys with low melting points as coolant, and to interpret their advantages and shortcomings.

3 Brief history for traditional liquid metal cooling

In fact, liquid metals have been used as coolant in nuclear reactors for a long time. In 1963, the first nuclear-powered submarine was launched with the liquid alloy of lead with bismuth as coolant [22]. The lead-bismuth coolant is generally corrosive for structural materials. In addition, such a liquid metal can easily contaminate the wall when running in a cooling loop. Figure 1 is a liquid metal cooling application using sodium as coolant that absorbs heat from the core in a fast breeder reactor [23].

Sato et al. [24] achieved an improvement of liquid metals through flow jet. Nowadays, liquid metal cooling has been widely used in nuclear-powered plants with many different metals having been tried. To reduce the amount of the long-term toxicity contained in the nuclear waste consigned to the geologic repository, the transmutation of waste blankets cooled with liquid metals is proposed to separate the uranium from the fraction of transuranic (TRU) elements and fission products in the light water reactor spent fuel [25]. Liquid metal cooling is also used in accelerators. Fast reactors typically use liquid metals as the primary coolant to cool the core and heat the water which is subsequently used to power electricity generating turbines. Sodium is a normal coolant for large power stations, but both lead and Na-K alloy have been used successfully for smaller generating rigs. Mercury has been used in some earlier fast breeder reactors. One advantage of mercury and Na-K alloy is that they both always take the liquid state at room temperature. They are convenient for experimental rigs but less important for full scale power stations. The advanced photon source (APS) at Argonne has pioneered the use of liquid metals as cooling fluids for X-ray optics in high intensity synchrotron beam lines [26]. Blackburn and Yanch [27,28] used a liquid metal jet

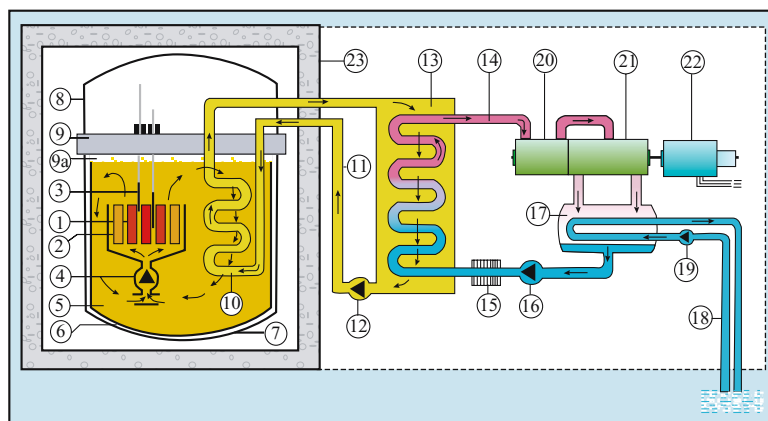


Fig. 1 Liquid metal (sodium) used as coolant in a fast breeder reactor

① Fissile material; ② Breeder material; ③ Control rods; ④ Primary Na pump; ⑤ Primary Na coolant; ⑥ Reactor vessel; ⑦ Protective vessel; ⑧ Reactor cover; ⑨ Cover; ⑩ Na/Na heat exchanger; ⑪ Secondary Na; ⑫ Secondary Na pump; ⑬ Steam generator; ⑭ Fresh steam; ⑮ Feed water pre-heater; ⑯ Feed water pump; ⑰ Condenser; ⑱ Cooling water; ⑲ Cooling water pump; ⑳ High pressure turbine; ㉑ Low pressure turbine; ㉒ Generator; ㉓ Reactor building [23]

impingement to improve the performance of their accelerator target for boron neutron capture therapy (BNCT). Another agency, Argonne [29] has been devoted to the development of liquid metal cooling for high heat load X-ray optics for the next generation of synchrotron facilities.

Compared with sodium cooled fast reactors, heavy liquid metal (lead or lead-bismuth) cooled fast reactors have adopted relatively open fuel lattices without wire spacers. Tak et al. [30] performed a sub-channel analysis for lead-bismuth cooled fuel assemblies with ducts and investigated thermal hydraulic characteristics with the emphasis on the turbulent mixing between sub-channels and interior assembly heat transfer using modified SLTHEN code.

Using liquid metal lithium as coolant in the mixed breeder blanket has the merits of excellent thermal properties, neutron moderation, tritium breeding effect and simple construction. Farabolini et al. [31] presented computations linking the tritium release rate to the characteristics of lithium-lead and helium cooling circuits. The effects of tritium permeation on the helium coolant in the blanket modules, lithium-lead circulation rate, tritium extraction unit efficiency, tritium permeation in the steam generator, helium coolant leak rate, helium purification unit maximum flow rate and efficiency, etc. were evaluated.

As for the physical structures of liquid metals, Wang et al. [32] investigated the effects of the shear rate on the structural properties of liquid Al in the quenching process via molecular dynamics (MD) simulations. Their analyses in internal energy and pair correlation functions (PCF) revealed an increasing structural transition temperature as the shear rate is enhanced in the liquid. Cornell et al. [33] studied the structures of liquid gallium and mercury using nuclear magnetic resonance. The results are in qualitative agreement with the free electron theory. Schommers et al. [34] compared the effective pair potential with several methods including the so-called Singwi-Tosi-Land-Sjölander theory, the Weeks-Chandler-Anderson approach, the Percus-Yevick theory, the hypernetted chain

approximation and the Born-Green equation, based on the structure data of liquid gallium performed by Narton [35]. Koster [36] presented visualization data on density distribution in eutectic GaIn and observed that the roll cell recedes to be replaced by a chemically layered conductive melt that eventually solidifies with a rather uniform eutectic structure after solidification starts. Burton et al. [37] reported using gallium alloys as lubricant for high current-density brushes to wet a slip ring in contact with current collectors. Experiments found that both forms of gallium-wetted brush can offer low resistance, low heating, and good tribological properties. More studies were performed on the structural materials and polymers in the GaInSn eutectic. Such a material is close to the alloy found most promising as a lubricant [38]. Kolokol et al. [39] studied the microstructure of liquid-metal coolants by the methods of molecular dynamics and statistical geometry to engineer the structure of reactor materials and focused their attention on the topological features of the atomic configurations of melts for lithium, sodium and lead. Swalin [40] developed a small fluctuation theory of self-diffusion in liquid metals based on the movement of atoms of small and variable distances because of local density fluctuation, which has been confirmed by the existing data in liquid metals such as indium, gallium, sodium, zinc, mercury and can be represented by Einstein's equation. Keck et al. [41] measured the solubility of silicon and germanium in liquid gallium and indium over a wide temperature range and found that the logarithms of solubility have a linear relationship with the inversed absolute temperature while the heat of solutions are approximately proportional to the third power of the radii of the solvent atoms.

Liquid metals are also applied to reduce the electrical contact resistance at the interface due to its high conductance. Cao et al. [42] found that the contact resistance of the initial gold to gold resistance is around 0.3Ω , while that of gold contacted with a thin layer of liquid gallium alloy is only 0.015Ω . For eutectics of GaInSn, GaInZn and GaInSnZn,

Burton et al. [43] reported the measurements on viscosity and resistivity at room temperature. Contact resistance, friction and film thickness are calculated for tilted pads using these liquid alloys as lubricants. Their experimental findings show that the gallium alloys display the most favorable characteristics.

For a fast nuclear reactor, Savada et al. [44] proposed to use metallic fuel in the liquid phase and gallium coolant at high temperature with the inlet 1 700 K and the outlet 1 900 K. The combination of gallium coolant and Pu-Fe liquid metal fuels make it possible to create a compact reactor. Badyal et al. [45] presented inelastic neutron scattering measurements on liquid mercury at room temperature for wave numbers q in the 3–7 nm⁻¹ range, and found that the energy half width of the incoherent part of the dynamic structure factor is determined by a self-diffusion process.

Nisoli et al. [46] investigated the electron thermalization process both in solid and liquid metallic gallium nanoparticles with the radii in the 5–9 nm range by femtosecond pump-probe measurements. The results show that the temporal behavior of electron energy relaxation is similar in both phases, with a time constant from 0.6 to 1.6 ps (pico-second) by increasing the nanoparticle size, which can be interpreted in terms of a size-dependent electron-surface interaction model. The results bring new information on the role of the energy exchange with surface phonons in the electronic thermalization process which occurs in confined metallic structures.

Some developments in the recent research are explored in high-heat-flux thermal management [47–49]. Such trend makes it possible to identify the bottlenecks involved, and to motivate the lowering of thermal resistance through efficient heat removal to meet the increasing reliability and performance requirements in chips.

4 Liquid metal coolant in thermal management of computer chips

4.1 Some basics for liquid cooling

As a practical cooling fluid for computer chips, the liquid metal must have a low melting point, a low viscosity, a high thermal conductivity and a high heat capacity. Meanwhile, it must not be poisonous and caustic. The most important prerequisite is that the working liquid metal should remain in a liquid state when its cooling role is being performed under an appropriate temperature range for computer chips, which is generally below 100°C. It is generally held that the metal appears as a rigid block. With such an impression in mind, the fact is often ignored that those metals with extremely low melting points, several degrees centigrade below zero, actually stay in the liquid state around room temperature. In fact, compared with various liquid metals, it can be found that liquid gallium or its alloys can serve as a perfect candidate for the heat transfer medium, which has in fact been widely used

in the area of cooling synchrotrons [50] and nuclear reactors [44]. Smither et al. [26] conducted a set of finite element analysis calculations in three dimensions to determine the temperature distributions and thermal stresses in a single crystal of silicon with heat loads of 2–20 kW under different geometric arrangements and different cooling fluids including liquid gallium and sodium. Among the cases they tried, they found that the variation in temperature across the surface of the crystal and the distortion of the surface was at least a factor of two less for the gallium cooling case than that for the water cooling case and the water cooling was effective only under very high flow rates.

Unfortunately, less effort has ever been made to apply liquid metals to cool high power electronic components, especially computer chips up to now. An in-depth analysis on the thermal properties of gallium strongly suggests that, it suits very well with the cooling of computer chips owing to its low melting point, namely 29.78°C, which is around the room temperature. In fact, gallium can generally be kept in a liquid state at a temperature much lower than the room temperature due to its large sub-cooling point. It turns out to be an important merit for gallium to be used as the cooling fluid. The low melting point and very low vapor pressure of liquid gallium make it easy to handle. The high thermal conductivity of liquid gallium makes it an excellent cooling fluid. Further, the low kinetic viscosity of liquid gallium improves its capability in heat removal, especially at the liquid-solid interface and enhances its attractiveness as a new generation coolant. The normal (dynamic) viscosity of gallium is about 1.5 times that of water, which means that it can be pumped through small channels with relative ease. The surface tension of liquid gallium is much higher than that of water, which makes it immune to the presence of small cracks or channels in an imperfect seal which would be a serious leakage for water as a cooling fluid. Besides, liquid gallium is not toxic and relatively cheap. All these compelling properties warrant its future applications in the chip cooling area.

Thermal management of high power density processors is central to the development of computing and communications systems [4]. Limiting system operating temperature is necessary to suppress reliability degradation mechanisms in most electronic devices. Non-ideal scaling CMOS devices have resulted in computing applications requiring cooling beyond what can be offered by finned heat sink structures, heat pipes, and forced water cooling. Consequently, alternatives such as single- and two-phase fluid cooling systems are being implemented more widely. In most fluid cooling systems, the low thermal conductivity of working fluids (e.g. water) necessitates micro channels for effective heat transfer from the source, and results in greater hydrodynamic pressure drops in the fluidic loop and increased electrical power dissipation in water pumps. The available water pumps have poor reliability and often have mechanical limitations (such as orientation-dependent performance, moving parts and

noise). In the case of electro osmotic pumps, high electrode potentials can result in dissociation of water molecules. Highly conducting fluids such as liquid metals offer a unique solution to cooling high density power sources and spreading heat in small form-factor applications. The two principal advantages lie in their superior thermophysical properties of sucking heat away from a hot chip and the ability to pump these electrically conductive liquids efficiently with silent, vibration-free, non-moving, magnetofluidynamic (MFD) pumps.

4.2 Thermal properties of liquid metals

A number of studies dedicated to eutectic and near-eutectic alloys revealed that the behavior and properties of liquid metals or their alloys are ambiguous and contradictory [51,52]. Almost all the properties of liquid metals vary with the temperature. Even at the same temperature, different heating or cooling processes will have different effects on the properties of liquid metals. Plevachuk et al. [53] revealed discrepancies between heating and cooling curves of temperature dependencies of some electro physical and structural-sensitive properties. Except for bismuth, gallium is the only element which expands on cooling, with a volume increase of 3.2% during solidification. A lot of experiments were performed for the properties of liquid metals such as tungsten [54], lead-bismuth alloy, gallium, and other liquid metals or their alloys. Table 1 lists the typical properties which are gathered from a wide range of different literatures.

4.2.1 Thermal conductivity

Metals often have much higher thermal conductivity than nonmetal materials. Table 1 shows the physical properties including the thermal conductivity of several typical metals in the liquid state. It is easy to notice that the thermal conductivity of liquid metals is generally several dozen times higher than that of water whose thermal conductivity is about 0.6 W/(m·°C).

Table 1 does not include those metals whose melting points are above 300°C because it is impractical for them to perform

possible opto-electronic cooling tasks. The first three metals in the table, mercury, cesium, and gallium are the ones that remain in the liquid state at or around room temperature. Liquid rubidium has all the necessary features of an excellent coolant but it is extremely expensive and reactive. Gallium and cesium have quite acceptable melting points, just above room temperature, and good thermal conductivity. So far, gallium can be regarded as superior over cesium because of its low working temperature range, much higher specific heat per unit volume, much lower vapor pressure at room temperature, and much less reactive nature when exposed to oxygen and water. The other three ones, tin, lithium, and indium are also excellent coolants. Lithium especially has two outstanding merits, very high thermal conductivity and very high specific heat per unit volume, to fulfill the task of heat transfer. However, the only difficulty encountered is their relatively high melting points. In spite of this, they can still possibly serve as one of the components to make alloys with low melting points. The next two, sodium and potassium, as active alkali metals, are also very good cooling fluids. Although their operating temperature ranges are smaller than the previous candidates, the alloy of sodium and potassium has been widely used in the fast breeder reactor. One of their outstanding properties is that their eutectic alloys can reach a melting point as low as -11°C. If there were better options, they could serve as prime candidates of cooling fluids in chip thermal management with proper treatment. The major adverse issue is that they are quite reactive towards air and water and thus imply a possible fire hazard. This entails special safety considerations if they are really adopted as coolants.

The low vapor pressure is very important if one is working in a high vacuum environment. Generally, mercury is not in the candidate list because of its very high vapor pressure (1.68×10^{-3} mmHg). A leakage in a mercury cooling loop would be serious even at room temperature, which becomes even worse at an elevated temperature. Such kind of metals could easily contaminate the whole system. And, if any mercury vapor were to reach any part of the human body, tremendous efforts should be made to immediately get rid of

Table 1 Thermal properties of typical metals with low melting point [29,55,56]

Liquid metals	Melting point/°C	Evaporation point/°C	Evaporation pressure/mmHg	Specific heat /kJ·(kg·K) ⁻¹	Density/kg·m ⁻³	Thermal conductivity /W·(m·°C) ⁻¹	Surface tension /N·m ⁻¹
Mercury	-38.87	356.65	1.68×10^{-3a}	0.139 ^{a)}	13 546 ^{a)}	8.34 ^{a)}	0.455 ^{a)}
Cesium	28.65	2 023.84	10 ^{-6d)}	0.236 ^{d)}	1 796 ^{d)}	17.4 ^{d)}	0.248 ^{d)}
Gallium	29.8	2 204.8	10 ⁻¹²	0.37 ^{m)}	5 907 ^{m)}	29.4 ⁿ⁾	0.707 ^{m)}
Rubidium	38.85	685.73	6×10^{-6}	0.363 ^{m)}	1 470 ^{m)}	29.3 ^{m)}	0.081
Potassium	63.2	756.5	6×10^{-7}	0.78 ^{m)}	664 ^{m)}	54.0 ^{m)}	0.103 ^{d)}
Sodium	97.83	881.4	10 ⁻¹⁰	1.38 ^{d)}	926.9 ^{d)}	86.9 ^{d)}	0.194 ^{d)}
Indium	156.8	2 023.8	$< 10^{-10}$	0.27 ^{m)}	7 030 ^{c)}	36.4 ^{c)}	0.55 ^{m)}
Lithium	186	1 342.3	10 ⁻¹⁰	4.389 ^{b)}	515 ^{b)}	41.3 ^{b)}	0.405 ^{b)}
Tin	232	2 622.8	$< 10^{-10}$	0.257	6 940 ^{c)}	15.08 ^{b)}	0.531 ^{m)}

Note: a) 25 °C; b) 200 °C; c) 160 °C; d) 100 °C; n) 50 °C; m) at melting point.

it and to tackle with the hazard thus caused. The use of mercury is forbidden in most accelerator environments. Unless specifically requested, mercury is not in recommendation.

Gallium, with its high thermal conductivity, high volume specific heat, large working temperature range, and very low vapor pressure, is an ideal candidate as chip coolant. Gallium has the additional attractive feature of being relatively non-toxic. Its pure metal and most of its compounds formed in nature are not soluble in water and will, therefore, not be absorbed through the skin. Recently, it was found gallium even has antimicrobial activity and thus can be used as antibiotics in medicine [57]. This finding can eliminate the worry of being hurt by liquid gallium or its alloys when used as coolant. These characteristics combined with its very low vapor pressure make gallium much safer to handle than most of the other liquid metals.

It is well known that the total thermal conductivity of metals or alloys include lattice contribution and electronic contribution. The thermal conductivity due to electronic contribution $\lambda_{\text{electronic}}$ can be calculated by using Wiedemann-Franz-Lorenz relation [58]

$$\lambda_{\text{electronic}} = L\sigma T \quad (1)$$

where L is the Lorenz number, equaling $2.45 \times 10^{-8} \text{ W} \cdot \Omega \cdot \text{K}^{-2}$. σ is the electrical conductivity and T the absolute temperature. It is found that for most metals, the electronic contribution is more predominant than the lattice contribution in the whole temperature range and therefore the thermal conductivity can be approximated as $\lambda = \lambda_{\text{electronic}} = L\sigma T$.

Overall, the structural stability and many physical properties of liquids are directly or indirectly related to the state of valence electrons in liquid matter. Therefore, the study of electrical transport properties is very important because it reveals the change of valence electrons [59]. Wang and Li [60] presented a review of the theoretical study of the electrical resistivity and thermopower of liquid metals and alloys. In fact, because diffusion and convection in melts play an important role in most technological processes involved with the liquid state, the measurement of thermal conductivity often turns out far from satisfactory. Such experiments in liquid metals or liquid alloys suffer from the additional transport induced by gravity-driven flow. Therefore, some research groups performed similar experiments under microgravity conditions such as aboard a space vehicle [61].

4.2.2 Surface tension σ

The surface tension of water is 0.072 N/m, lower than that of many liquid metals, which can be partially reflected by Table 1. This merit makes it possible to reduce or avoid leakage in cooling systems. The surface tension of liquid metals can be measured with a vacuum electrostatic levitation furnace above or below the melting temperature [62]. Lee et al. [63] have performed experiments to investigate the temperature dependent surface tension of several alloys such as liquid Sn-Ag, In-Ag and In-Cu alloys, etc.

Hardy [64] measured the surface tension of liquid gallium using the sessile drop technique with an Auger spectrometer. The surface tension in mN/m is found to decrease linearly with the increase of temperature and may be represented as $708 - 0.66(T - 29.8)$, where T is the temperature in centigrade. This result is of importance because gallium has been suggested in this review as a best base fluid for nano liquid metal and component of alloys with low melting points. In addition, the surface tension is of technological significance in the processing of compound semiconductors involved with gallium.

4.2.3 Heat capacity c

Any theory concerning melting, freezing or convective heat transfer needs to take the liquid state explicitly into account. Liquid metals and their alloys can serve as model systems since they are rather close as describable as the real-world representatives of idealized hard-sphere systems. A basic thermodynamic quantity in this respect is the specific heat capacity [65].

The heat capacity of water is 4 200 J/(kg · K). That of liquid metal gallium is 370 J/(kg · K). Although the heat capacity per mass of many metals is much smaller than that of water, the specific heat per unit volume is close to that of water, for example, 4 200 kJ/(m³ · K) for water and 2 158 kJ/(m³ · K) for liquid gallium. The merit that gallium has high specific heat per unit volume among liquid metals allows it to be a promising coolant in chip cooling applications.

4.2.4 Boiling temperature

The boiling points of many metals are generally very high. This guarantees a low working pressure for the liquid metal used as coolant at normal temperature. The low working pressure in the coolant loop improves reliability and safety and simplifies the design and fabrication of equipment, and further substantially makes it easy to operate the equipment. Compared with water cooling, liquid metals have much less possibility of burning out, which thus significantly reduces leakage. Also, because of its high boiling point, the coolant can be guaranteed as a truly single phase fluid, avoiding abrupt changes of pressure while flowing. This is highly desirable for stable chip cooling.

4.2.5 Sub-cooling point

Gallium can generally be kept in a liquid state at a temperature much lower than room temperature, due to its large sub-cooling point [1]. Figure 2 presents an experimentally measured typical curve of the gallium temperature transients during the cooling and heating process. It shows that metal gallium remains in the liquid state even when the temperature has already been reduced to as low as 0.89°C in the cooling process. In fact, it is surprising that Ga encapsulated in carbon nanotubes may remain in the liquid state even below

–80°C [66]. Micrometer-sized [67] or submicrometer-sized [68] liquid gallium can indeed be undercooled down to 150 K. Great temperature difference between the solidifying point and melting point guarantees it a perfect coolant for convective cooling.

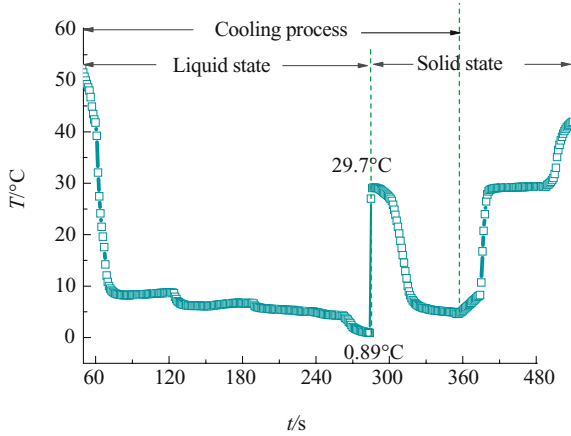


Fig. 2 Gallium's temperature in the process of solidifying

Many researches have been devoted to the structural analysis [69–71] of liquid metals. The molecular dynamics (MD) or Monte Carlo simulation is a favorable tool in investigating the liquid structure theoretically [72–77]. X-ray diffraction and neutron diffraction are two experimental methods to obtain the information of structures in liquid metals [55,78].

4.2.6 Viscosity

The viscosities of different pure metals and alloys can be described by the Arrhenius equation, which is shown in Eq. (2). The Arrhenius equation is one of the best formulas used to describe the viscosity data of metallic melts in a certain temperature range

$$\eta = A \exp\left(\frac{E_V}{RT}\right) \quad (2)$$

where E_V denotes the activation energy as an energy barrier for the movement of atoms in liquid metals; R is the gas constant; A is a constant, and T is the absolute temperature of the samples. The activation energy of the viscous flow can be determined from the experimental values of the dynamic viscosity. Zhou and Chen [79] gave an overview of the viscosity of liquid metals. It may be regarded that the viscosity of metal fluid might be a problem for flowing, but the truth is that dynamic viscosity is rather comparative. For example, the dynamic viscosity of water is 1.002 mPa·s at 20°C, while that of liquid gallium is only slightly higher, being 1.2 mPa·s at 77°C [80].

In short, high thermal conductivity, high volume specific heat, low kinematic viscosity, very low vapor pressure and appropriate working temperature range make liquid metals, especially gallium or its alloys, a very promising heat transfer

medium. A liquid metal coolant is able to absorb heat more rapidly, thus cooling down chips faster. This property makes it an excellent coolant in some nuclear reactors, which are mainly cooled with liquid sodium or potassium, and in the manufacture of high-quality machine components, such as gas turbine blades, where the components are rapidly cooled to 660°C with molten aluminum to prevent the formation of defects. The day may certainly come when liquid metals are used as coolant in the computer chip industry.

4.3 Advantages of liquid metal cooling over other liquid cooling

Advantages of using liquid metals for the thermal management of computer systems can be summarized as follows:

- 1) high heat transport capability;
- 2) high heat flux densities;
- 3) low thermal resistance;
- 4) less safety consideration because of single-phase flowing;
- 5) environmentally friendly;
- 6) small, flexible geometric solutions and easy miniaturization;
- 7) ability to cool multiple heat sources;
- 8) light weight, orientation-independent solutions;
- 9) MHD-drivable due to being electric conductive;
- 10) high reliability due to non-moving parts in pumps.

A special feature of liquid metal cooling worth mentioning is that the system has no moving parts. The fluid passes through a magnetic field with a pair of electrodes stuck to the liquid metal that serves to introduce a DC electric current. The electric current through the magnetic field then generates the Lorenz force on the liquid metal itself which pumps the liquid metal coolant circulating around the cooling loop.

As pointed out in Ref. [26], in those cooling cases examined to date where water cooling has been replaced by liquid gallium cooling, there has been a considerable improvement, often by a factor of three to five, in the convective heat transfer coefficient.

5 Typical alloy with low melting point

5.1 Ga-In alloy

As is shown above, the melting point of gallium is around 29.7°C, which is slightly higher than needed. It is expected that a perfect coolant should always stay in the liquid state over the temperature range from zero to 100°C so as to guarantee a safe initiation and smooth and proper working conditions. The fact that the melting point of an alloy may reach a lower melting point than any metal constituting the alloy sparks the interest in finding typical alloys with low melting points.

To further reduce the working temperature of liquid metals, low-melting-point alloys can be a good choice. In

fact, low-melting metals as powders have been used intensively for various microelectronic applications as the solders and components of conductive adhesives [81–84]. Kathuria [85] studied the three-dimensional microstructure by selective laser sintering of low-melting-metal powders. A most widespread technology of low-melting metallic powder fabrication is an ultrasonic atomization process [86,87], which is the usual way to choose a low-melting-point metal as one of the components.

Gallium alloys can easily be made to form eutectic material that melts below room temperature, as shown in Table 2. In this respect, the gallium-indium alloy has the important advantage of being unfrozen at room temperature. The main difficulty with the use of indium-gallium mixture is that it is much more difficult to clean up if it is spilled on the surface of a device. With pure gallium, what has to be done is only to pour cold water on it, freeze it, and then pick the gallium up as a solid lump. Considering the above merits of liquid metals in electronics cooling, liquid metal gallium or its alloys can be expected to play more roles despite the shortcomings that the mixture of indium and gallium does not freeze as easily but tends to smear and stick to the surface of most materials [91].

Table 2 Typical low-melting gallium alloys and alkali-metal alloys [88–90]

Alloy	Melting point/°C	Alloy	Melting point/°C
GaIn ₁₅ Sn ₁₃ Zn ₁	3	GaIn ₂₅ Sn ₁₃	5
Ga _{62.5} In _{21.5} Sn ₁₆	10.7	Ga _{69.8} In _{17.6} Sn _{12.6}	10.8
GaSn ₆₀ In ₁₀	12	GaIn ₂₉ Zn ₄	13
Ga ₇₅ In ₂₅	16	GaSn ₁₂	17
GaZn ₁₆ In ₁₂	17	GaZn ₃	25
GaSn ₈	20	K ₇₈ Na ₂₂	−11.1

So far, liquid metal gallium or its alloys can be regarded as the best coolant because of its excellent thermophysical properties. For example, gallium alloys and other metals such as bismuth, tin, indium and zinc generally have lower melting points. A gallium alloy with 8% of tin will melt at 20°C, while a gallium alloy with 25% of indium will melt at 16°C. Additional combination of useful metals can produce more liquid metal candidates, with a wide variety of melting points. For miniature interconnection applications, innovative material systems based on gallium alloys offer potentially attractive alternatives over commonly used bonding materials, such as solders and conductive adhesives, without reliability and environmental drawbacks. A gallium alloy is a mechanically alloyed mixture of a liquid metal and metallic powders. They are formed at room temperature and finally cured to solid intermetallic interconnects. Baldwin et al. [91] demonstrated the feasibility and applicability of gallium alloys as flip-chip on laminate interconnect materials.

5.2 Na-K alloy

Liquid sodium has been used as a coolant and heat transfer medium in the liquid metal fast breeder reactor. The question

of safety immediately arouses concern since sodium metal is an extremely reactive chemical and would burn (sometimes even explode) in contact with air or water. It is true that liquid sodium must be protected from contact with air or water at all times, and kept in a completely sealed system. However, it has been found that the safety issues are not significantly greater than those with high-pressure water and steam in light-water reactors.

Sodium is a solid at room temperature but liquefies at 98°C. It has a wide working temperature range since it will not boil until 892°C. That brackets the range of operating temperatures for the reactor so that it does not need to be pressurized as does a water-steam coolant system. It has large specific heat so that it is an efficient heat transfer fluid.

The melting point of eutectic NaK-77.8 (indicating the percentage of potassium as 77.8%) is as low as $(-12.65 \pm 0.01)^\circ\text{C}$, which is perhaps the lowest melting point of NaK alloys. NaK-78 has the melting point of -11°C . Schormann et al. [90] reported on Na-K alloys for the preparation and reduction of various monoalkyl aluminum (III) compounds. For computer chip cooling, Na-K alloys should be carefully compacted in cooling modules, which has eliminated the possibility of any contact with air or water. In this respect, the similar route of making heat pipes may be a good reference.

5.3 Wood's metal

Wood's metal (bismuth 50%, lead 25%, tin 12.5% and cadmium 12.5%) has a much lower melting point of 71°C, so it seems impractical to use it as a coolant in chip cooling. However, fortunately, the melting point of Wood's alloy can be reduced with the increase of indium by 1.45°C per 1 wt-%. The alloy will have a melting point of 43°C when 19.1% of indium is added.

The advantage of Wood's metal lies in the fact that it can intrude into voids and stress-induced micro cracks while the specimen is held at a desired stress level and then solidified to preserve the geometry of the induced micro cracks. For example, by substituting Wood's metal for mercury as the intruding liquid, Lange et al. [92] adopted scanning electron microscopy and imaging techniques to treat the sample after intrusion for the characterization of the pore size distribution of cement-based materials. The important application may be realized in electronic packaging.

5.4 Nano liquid metal

Aiming to realize the idealistic heat transfer performance, Ma and Liu [93] proposed to further significantly magnify the conductivity of liquid metal coolant by adding nano particles with superior conductivity to liquid metals or their alloys. This may lead to the emergence of the highest thermally conductive fluid. Precisely speaking, a nano liquid metal is somewhat different from the above mentioned alloys. Probing into its physical properties requires additional work.

By Using several most-accepted theoretical models for characterizing the nano fluid, including Maxwell [94], Hamilton-Crossor [95], Lu-Lin [96] and Bruggeman [97], the thermal conductivity enhancement of the liquid-metal fluid due to the addition of more conductive nano particles was predicted.

The calculated results indicate that the effective thermal conductivity is much higher than that of the base liquid metal fluid as shown in Fig. 3 [93].

Considering both the high thermal conductivity of the base fluid and the large volume fraction, this novel nanofluid made from the liquid metal shows a very promising future for the thermal management application in super CPU chip cooling or the situations which seriously require high heat flux removal, either as flowing coolant or thermal interfacial materials.

6 Ways of driving liquid metal coolant

In water-cooling systems, mechanical pumps and peristaltic pumps are always used to circulate water. Generally speaking, liquid metals can also be driven by pumps as those routinely used as liquid coolant currently. The only problem is that conventional pumps may not be the best choice. For example, it is difficult for liquid metals to be driven by mechanical pumps because of their much higher density. Some other problems also occur such as liquid metal embrittlement in mechanical pumps, etc. There are several special ways to drive liquid metals. The magneto-hydro-dynamic (MHD) pump (also called EM pump or MFD pump) is one of such candidates. It can drive the coolant without producing any noise because it has no moving parts. However, the existing design may make the running of the MHD pump rather difficult such that it may require a pretty high electrical current which, as a result, would generate a large amount of heat. Therefore, the lowering of the driving electrical current should be carefully addressed. Recently, new ways have been

figured out to drive the metal coolant, which is to use the electro-wetting effect to drive discrete droplets of a liquid metal alloy in a cooling integrated card [98].

6.1 MHD pump

Because of its high conductivity, a liquid metal can be driven by an MHD pump which exploits the Ampere force arising from the application of direct current normal to the magnetic field in the region of the fluid between two permanent magnets. Advantages of adopting an MHD pump lies in the ability to pump these liquids efficiently with a silent, vibration-free, low energy consumption rate of the nonmoving and compact MHD pump. The working principle of an MHD pump is shown in Fig. 4.

With evident advantages over rival technologies such as water cooling, a liquid metal coolant can be driven by an MHD pump which requires no moving parts, and thus produces no noise and consumes little power. In some situations, the driving of a liquid metal can be done by the waste heat, which leads to the technique in the sense with zero net energy input [100]. Furthermore, the fact that the system has no moving mechanical parts eliminates such tough issues as leakage, wearing out or sticking.

At present, an MHD pump (such as that of NanoCoolers) still needs large current (15–30 A) and low voltage, which meets with some difficulties in practical use. First, the high electrical current is hard to obtain in a computer closet. Second, the electrical circuit will generate large amounts of heat because of large current according to the Joule heating law.

Ma and Liu [100] realized the working of the MHD pump with DC current less than 1 A and demonstrated the feasibility of using waste heat to drive a thermoelectric generator (TEG) and thus the flowing of liquid gallium. The advancement enables the MHD pump to come into real application, as shown in Fig. 5(b).

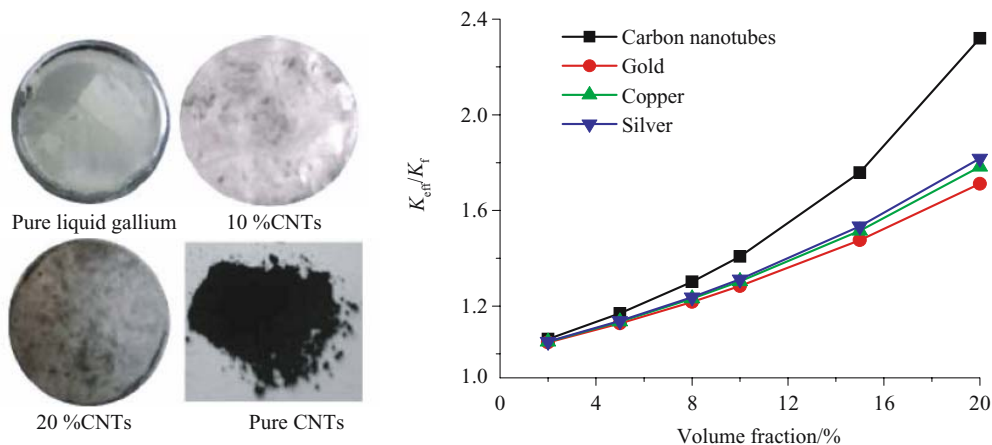


Fig. 3 Thermal conductivity enhancement ratio as a function of volume fraction for different nano-particles in liquid-gallium suspensions [93]

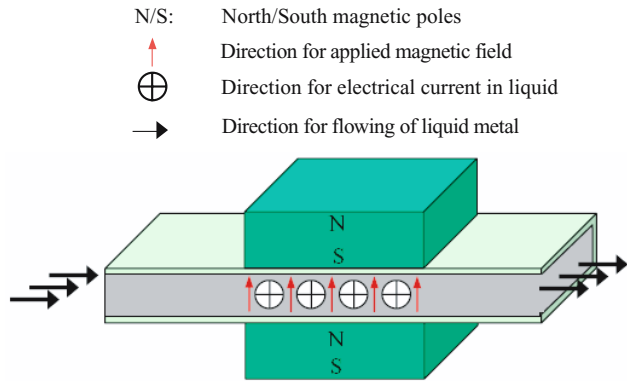


Fig. 4 Principle of MHD pump

6.2 Peristaltic pump

Li et al. [1] used a peristaltic pump to drive the liquid metal to cool the simulating chip. In their test, the copper plate steady state temperature, cold plate surface temperature, radiator inlet temperature and outlet temperature of liquid metal gallium were compared with those of water. The driving force of the coolant to flow in the tube comes from the peristaltic pump. In this way, a liquid cooling system circulating either a liquid metal or water through the cold plate attached to the heating plate was thus constructed. As a liquid metal or water passes through the cold plate, heat is transferred from the hot processor to the cooler liquid. The hot liquid metal or water then flows out to a fan-cooled radiator and transfers the heat to the ambient air. The cooled liquid metal or water then travels back through the system to the CPU to continue the heat dissipation process again. The liquid metal cooling driven by a peristaltic pump is shown in Fig. 6.

6.3 Electro-wetting pump

Electro-wetting refers to an electrostatically induced reduction in the contact angle of an electrically conductive liquid droplet on a surface as shown in Fig. 7 [98]. Electro-wetting on a single planar surface offers flexibility for interfacing to liquid handling instruments, utilizing droplet inertial dynamics to achieve enhanced mixing of two droplets upon coalescence, and increasing droplet translation speeds. Emerling et al. [101] presented experimental results and

discussed design issues associated with the grounding-from-below approach.

Kim et al. [102] described the first micro-electro-mechanical systems (MEMS) demonstration device that adopts surface tension as the driving force. A liquid-metal droplet can be driven in an electrolyte-filled capillary when the surface tension with electric potential is locally modified.

Adoption of electro-wetting is based on two facts. The first is that by use of liquid metals or low-melting-point alloys at room temperature (instead of water or air), the heat transfer performance of a cooling system can be enhanced significantly. The second is that electro-wetting is an efficient, low power consumption, and low voltage actuation technique for pumping liquids at micro-scales.

As already mentioned before, liquid metals have much higher surface tension (in excess of one order of magnitude) than most non-metallic liquids, which the former suitable for electro-wetting transport. Electro-wetting has also been used to transport liquid metals or alloys from a pool to hot spots on a chip, as shown in Fig. 7 [98]. These characteristics indicate that the electro-wetting of a liquid metal or its alloys can achieve heat flux removal capabilities far beyond what many other alternative techniques can offer.

It should be noted that mercury is also an option. Mercury has very high surface tension and can be easily and effectively mobilized by electro-wetting. However, mercury is generally not recommended in chip cooling systems because of its toxicity.

7 Theoretical issues in liquid metal cooling

It is important to evaluate the heat transfer performances of liquid metals over existing coolants. The following is Newton's equation

$$Q = Ah(T_f - T_w) \quad (3)$$

where Q , A , h , T_f , T_w are respectively the total power dissipated, area, heat transfer coefficient, temperature of the coolant and temperature of the wall.

There are two ways to evaluate the cooling capability of liquid metal coolants. The first is by comparing the heat

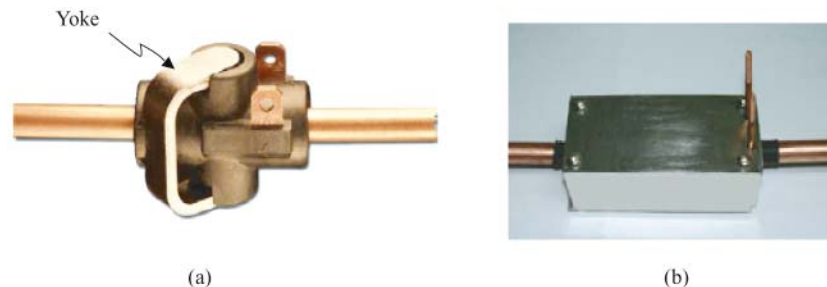


Fig. 5 Prototype of MHD pumps
 (a) MHD pump by NanoCoolers [99]; (b) MHD pump

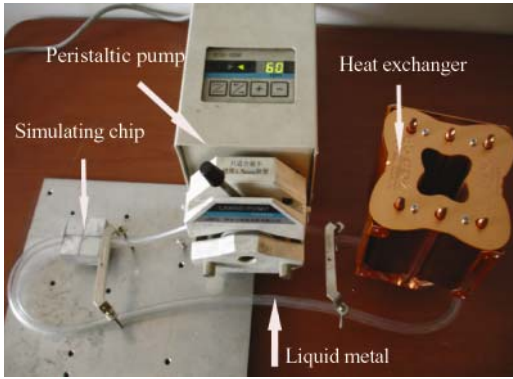


Fig. 6 Liquid metal cooling driven by a peristaltic pump

transfer of each in the same condition and the other is by comparing the temperature of the wall.

7.1 Simple model for flow and heat transfer of liquid metals

Lee [103] developed a 2-D model for the thermohydraulic analysis of the hot pool in liquid metal reactors and gave the numerical simulation.

The governing differential equation for the heat transfer process between the liquid metal fluid flowing in a cylindrical duct and the duct surface yields [104]

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = \frac{1}{r} \frac{\partial}{\partial r} \left(a_r r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial x} \left(a_x \frac{\partial T}{\partial x} \right) \quad (4)$$

where a_r and a_x are the thermal diffusivity of the liquid metal which can be obtained for simplicity by the following correlation

$$a_r = a_x = a = \lambda / (\rho c)$$

For special boundary conditions

$$\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0 \quad (5)$$

$$T|_{r=R} = T_w \quad (6)$$

$$T|_{x=0} = T_0 \quad (7)$$

The following solution can be obtained

$$\frac{T - T_w}{T_0 - T_w} = 2 \sum_{m=1}^{\infty} \exp \left(\frac{Lx'}{R} \frac{Pe}{2} \left(1 - \sqrt{1 + \frac{4\beta_m^2}{Pe^2}} \right) \right) \frac{J_0(\beta_m r')}{J_1(\beta_m) \beta_m} \quad (8)$$

where $r' = r/R$, $x' = x/L$, and R, L are the diameter and length of the duct through which the liquid metal coolant flows, while eigenvalue β_m is the positive roots of the following equation

$$J_0(\beta_m) = 0 \quad (9)$$

where J_0 and J_1 are Bessel functions of order 0 and 1, respectively.

When the temperature distribution is available, the Nu number of the liquid metal considering the axial heat conduction can be obtained. According to the heat transfer relationship

$$-k \left. \frac{\partial T}{\partial r} \right|_R = h(T_m - T_w) \quad (10)$$

where h is the heat transfer coefficient, and T_m is the mean temperature of the cross section and can be depicted as follows for the duct

$$T_m = \frac{2 \int_0^R T r dr}{R^2} \quad (11)$$

Consider the dimensionless number $Nu = \frac{2Rh}{\lambda}$ and the following equation

$$\int_0^R r J_0(\beta_m r') dr = \frac{R^2}{\beta_m} J_1(\beta_m) \quad (12)$$

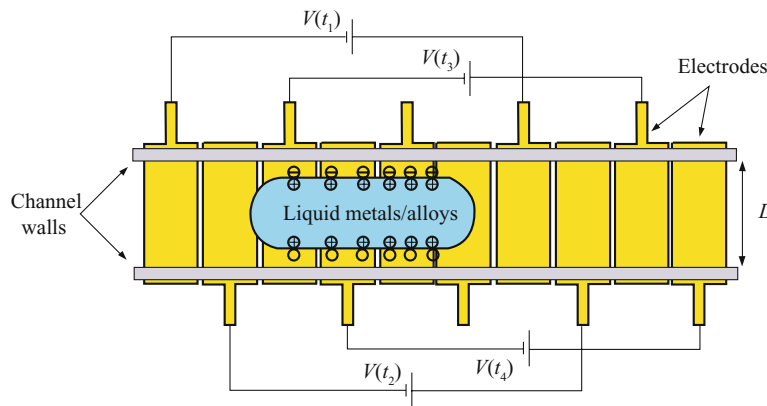


Fig. 7 Continuous electro-wetting

By sequenced activation of voltages on electrodes at times t_1, t_2, t_3 , a liquid metal droplet can be transported to any location in a microchannel [98]

The Nu number can be obtained from Eqs. (8)–(12) as follows

$$Nu_x = \frac{\sum_{m=1}^{\infty} \exp\left(-\frac{Lx'}{R} \left(\frac{Pe}{2} - \frac{Pe}{2} \sqrt{1 + \frac{4\beta_m^2}{Pe^2}}\right)\right)}{\sum_{m=1}^{\infty} \exp\left(-\frac{Lx'}{R} \left(\frac{Pe}{2} - \frac{Pe}{2} \sqrt{1 + \frac{4\beta_m^2}{Pe^2}}\right)\right) / \beta_m^2} \quad (13)$$

If the axial heat conduction of liquid metals is ignored, Eqs. (8) and (13) can be simplified as

$$\frac{T - T_w}{T_0 - T_w} = 2 \sum_{m=1}^{\infty} \exp\left(-\frac{Lx' \beta_m^2}{R Pe}\right) \frac{J_0(\beta_m r')}{J_1(\beta_m) \beta_m} \quad (14)$$

$$Nu_x = \frac{\sum_{m=1}^{\infty} \exp\left(-\frac{Lx' \beta_m^2}{R Pe}\right)}{\sum_{m=1}^{\infty} \exp\left(-\frac{Lx' \beta_m^2}{R Pe}\right) / \beta_m^2} \quad (15)$$

From the result of Eq. (14), the local Nusselt number can be obtained. After integrating the local Nusselt number, the overall Nusselt number of the flowing region can be obtained.

7.2 Evaluation on the convective heat transfer coefficient of liquid metals

Evaluation on the heat transfer performance between liquid metals and ordinary liquid coolants such as water can be done through comparing the heat transfer of each in the same condition. For such purpose, a hydrodynamically and fully developed laminar state in a pipe was taken into consideration. Here, a comparison was made only between liquid metals and water. Similar researches can be performed with other alternative coolants.

For liquid metal coolants with constant heat flux, it could be represented with reasonable accuracy by a simple approximate equation [105] for the circular cross section

$$Nu_d = 7 + 0.025Pe^{0.8} \quad (16)$$

where Pe represents the Peclet number and $Pe = RePr$. For channels with different cross sections, Table 3 has gathered and listed several typical correlations of the Nusselt number

for liquid metals. The dimensionless parameters Re , Pr , Nu are Reynolds number, Prandtl number and Nusselt number, respectively. The parameters D_2 , D_1 are the outer and inner diameters of the annular cross section, respectively.

In a thermal management situation, the heat transfer coefficient h obtained in the system is a useful parameter to evaluate alternative coolants. The coefficient h is the rate at which thermal energy is removed from a surface per unit surface area per temperature differential, and it is related to Nu number by the following equation

$$h = \frac{\lambda Nu}{d} \quad (17)$$

where λ is the thermal conductivity and d is the characteristic dimension of the geometry. For the case of heat transfer in a pipe considered here, d is the pipe diameter. The following equation can be obtained from Eq. (17)

$$\frac{h_{lm}}{h_{water}} = \frac{\lambda_{lm}}{\lambda_{water}} \frac{Nu_{lm}}{Nu_{water}} \quad (18)$$

where h_{lm} , λ_{lm} , Nu_{lm} denotes the heat transfer coefficient, thermal conductivity, Nusselt number of the liquid metal, respectively; h_{water} , λ_{water} , Nu_{water} are the counterpart parameters of water, respectively.

As is well-known, a fully developed laminar water flow in a pipe under constant wall heat flux can be shown by analytic solution to exhibit a constant Nu_{water} of 4.36 and a constant Nu_{water} of 3.66 under constant wall temperature [107]. Therefore, the heat transfer coefficient for the laminar flow of a liquid metal and that of water for a given pipe geometry when the heat flux is constant can be expressed as

$$\frac{h_{lm}}{h_{water}} = \frac{\lambda_{lm}}{\lambda_{water}} \frac{7 + 0.025Pe^{0.8}}{4.36} \quad (19)$$

When the wall temperature is constant, the following equation is obtained

$$\frac{h_{lm}}{h_{water}} = \frac{\lambda_{lm}}{\lambda_{water}} \frac{5 + 0.025Pe^{0.8}}{3.66} \quad (20)$$

Consider the fact that

$$\frac{\lambda_{lm}}{\lambda_{water}} \gg 1, \quad \frac{7 + 0.025Pe^{0.8}}{4.36} > 1 \text{ and } \frac{5 + 0.025Pe^{0.8}}{3.66} > 1$$

Table 3 Correlation of Nu for liquid metals under different cross sections

Cross section	Heat transfer correlation	Application prerequisite	Source
Circular	$Nu_d = 7 + 0.025Pe^{0.8}$ (1) or $Nu_d = 6.3 + 0.0167Pe^{0.85}Pr^{0.93}$ (2)	Uniform heat flux	Reference [105]
Reference [19]	$Nu_d = 5 + 0.025Pe^{0.8}$	Uniform wall temperature	Reference [106]
Planar	$Nu_d = 5.8 + 0.02Pe^{0.8}$	Uniform heat flux and other side adiabatic	Reference [106]
Annular	$Nu = 5.25 + 0.0188Pe^{0.8} \left(\frac{D_2}{D_1}\right)^{0.3}$	Uniform heat flux	Reference [106]

Clearly, it is sure that the following equation can be obtained

$$\frac{h_{\text{lm}}}{h_{\text{water}}} \gg 1 \quad (21)$$

That is to say, the convective heat transfer coefficient of the liquid metal used as coolant is far larger than that of water. Therefore, it is expected that liquid metals generally have better performance in heat removal than water.

7.3 Evaluation of using temperature of wall

In the case of constant heat flux q_w per unit wall area and time, the wall temperature difference between liquid metals and water at $x = L/2$ could be expressed as [1]

$$\Delta = \left(\frac{P}{\pi L \lambda' Nu'_d} + \frac{2P}{\rho' c'_p \bar{u} \pi d^2} \right) - \left(\frac{P}{\pi L \lambda Nu_d} + \frac{2P}{\rho c_p \bar{u} \pi d^2} \right) \quad (22)$$

where A , L , and d are respectively the cross section area, length, and diameter of the tube; ρc_p and λ are the volume specific heat and heat conductivity of the liquid, \bar{u} is the mean velocity connected with the centerline velocity u_0 by the relationship $\bar{u} = u_0/2$. P is the power-dissipation of the computer chip. Nu_d is the Nusselt number of the liquid metal. $\rho' c'_p$, λ' , Nu'_d are respectively counterparts of water. To fully exert the powerful cooling capacity of the liquid-metal based system, the surface area of the fan-cooled radiator should be large enough so as to provide the best cooling performance. For the evaluation purpose, a simple criterion should be established. This would be based on that, when $\Delta < 0$, the cooling performance of the liquid metal is better than that of the water and vice versa.

Equation (22) can be transformed into the following equation

$$\Delta = \frac{P}{\pi L Nu} \left(\frac{1}{\lambda'} - \frac{1}{\lambda} \right) + \frac{2P}{\pi d^2 \bar{u}} \left(\frac{1}{\rho' c'_p} - \frac{1}{\rho c} \right) \quad (23)$$

From Eq. (23), it is easy to observe that the best coolant should have high thermal conductivity and high heat capacity ρc . Water has a higher ρc than many coolant candidates. As a result, it is a good coolant. Since water has a pretty low thermal conductivity, it is not the best coolant. Considering the application in chip cooling, liquid metal coolants show better performance than water because of their high thermal conductivity and high volume specific heat capacity. However, an optimization on the liquid metal coolant needs further research in the near future.

In the inlet region, the Nusselt number decreases linearly with the increase of $\frac{1}{Re_d Pr d}$ (where Re_d and Pr are the Reynolds number and the Prandtl number of liquid metals, respectively) and approaches the asymptotic value of 4.36 for water. For a liquid metal with a Prandtl number of 0.01 and a

Reynolds number of 1 000, the flow becomes fully developed at $x = d$. The Prandtl number of liquid gallium is about 0.024 at 40°C. However, the water flow will become fully developed at a further distance than $x = d$ because of its large Prandtl number involved. Thus, the heat-transfer coefficient of the liquid metal is smaller than that of water at the inlet region. However, it should be noticed that in a chip cooling system, the liquid is generally circulated in a closed loop. Therefore, the end effect of the inlet region in fact plays no role in the heat transfer performance.

As Eq. (21) shows, the heat-transfer coefficient of the liquid metal is much larger than that of water in the developed region. Thus, the temperature difference in liquid flow ($T_w - \bar{T}_f$) will be much smaller than that in water flow when the heat flux q_w per unit wall area and time is constant. This will help enhance heat transfer during the cooling of a computer chip. If the tube wall temperature T_w is constant, the temperature of the liquid metal is higher than that of water, which will supply more heat from the liquid metal to the environment and thus reduce the surface area of the heat dissipation (see Eq. (3)). On the other hand, the wall temperature T_w will be lower than that in water if liquid temperature \bar{T}_f is constant. It is obvious that a lower wall temperature can thus be expected in computer chip cooling.

8 Experimental phenomena

Up to now, experimental data on chip cooling by liquid metals is still rather limited for this newly emerging technology. To show the basic features of liquid metals over traditional coolants, Liu et al. [21] performed a study on chip cooling using liquid metal gallium and its alloys as coolants. Figure 8 is the schematic of the experimental setup. Compared with water as coolant in the same system, a significant temperature jump can be found for the temperature of the heating plate, which almost immediately drops from its highest 70°C to 46.7°C. However, in the same experimental setup, for the case of using water as cooling fluid, the heating plate temperature only drops from its highest 70°C to 51.9°C. Other data are shown in Table 4. The conclusion can be drawn easily that liquid gallium cooling performance is more powerful than that of water-cooling.

In addition to the adoption of a peristaltic pump, Liu et al. [21] developed a method to circulate liquid metal coolant using the electric magnetic (EM) pump. A prototype of EM-pumped cooling and infrared temperature mapping are shown in Fig. 9 [108]. It can be found that the heat generated by the hot module spread immediately to the far end of the finned heat dissipater after the EM pump was turned on. This reflects the rapid heat transfer performance of liquid gallium. To evaluate the performance of liquid metal cooling in the system level, Yan and Liu [108] conducted a theoretical analysis through the introduction of the compartment model.

Similar to the above schematic, Ghoshal et al. [88] reported their liquid metal cooling system using the EM pump to drive

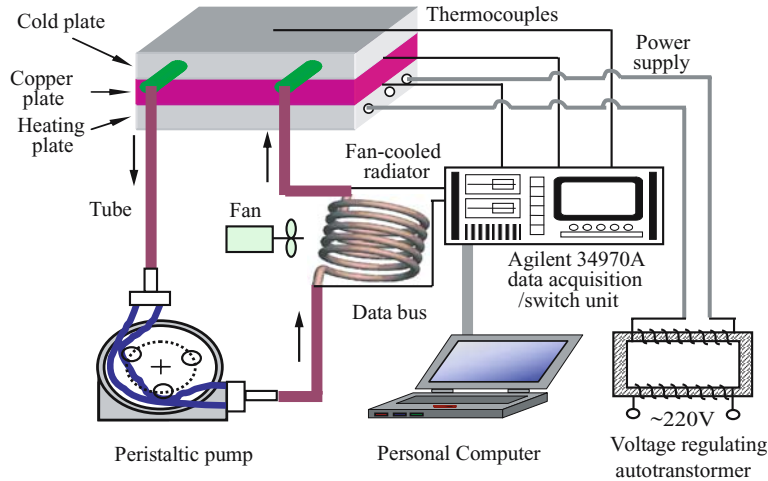


Fig. 8 Schematic diagram of measurement on liquid metal cooling system [21]

Table 4 Results for chip cooling with liquid gallium

Power/W	Mass flow rate/(g·s ⁻¹)	Fluid velocity /(cm·s ⁻¹)	Steady state temperature of copper plate/°C	Surface temperature of cold plate/°C	Radiator inlet temperature/°C	Radiator outlet temperature/°C
18.3	1.36	22.2	42.2	40.2	35.6	33.8
18.3	0.79	12.9	44.0	41.5	36.0	34.4
18.3	0.27	4.4	51.9	45.2	36.1	34.0
38.8	1.36	22.2	52.2	47.5	42.8	37.7
38.8	0.79	12.9	52.5	47.6	43.3	36.7
73.3	1.36	22.2	61.1	54.7	48.6	41.3
73.3	0.79	12.9	67.0	59.5	52.9	43.1

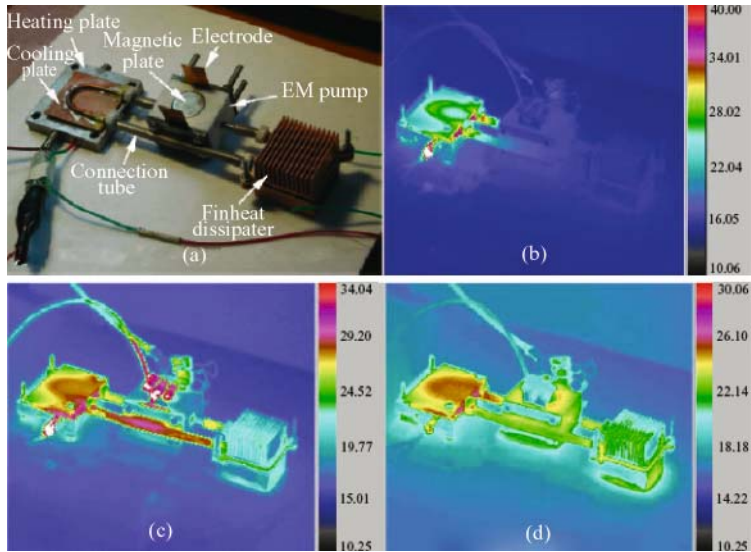


Fig. 9 Prototype of an EM-pumped cooling and infrared temperature mapping [108]
 (a) Prototype of the EM-pumped cooling; (b) before pumping; (c) after pumping; (d) stop pumping

gallium coolant and its alloys. They tested the impingement with a Ga₆₁In₂₅Sn₁₃Zn₁ liquid metal alloy as the working fluid. The excellent performance immediately aroused commercial interest. The only problem is that the electricity used to drive the MHD pump is still pretty high, that is, 15–30 A.

Recently, Ma and Liu [100] advanced the EM pump and realized the operation of the EM pump under a DC current less than 1 A, which promotes the application of the thermoelectric generator (TEG). The DC current generated by the TEG due to temperature difference successfully drives the

MHD pump as shown in Fig. 10. The temperature variation versus time is shown in Fig. 11.

Figure 10(a) and (b) illustrates the working principle and prototype of a TEG driven liquid metal cooling device, respectively. In this structure, a TEG was sandwiched between the substrate heat sink and the finned heat exchanger. The temperature difference across this TEG will generate electricity I which is then subsequently used to drive the flow of the liquid metal inside the channel of the substrate. Therefore, this leads to the realization of a zero-energy-input liquid metal cooling device which consumes no other additional energy. Noticeably, they cool the hot module down without the aid of fans. Figure 11 shows the curves of measured temperature versus time.

9 Applications and practical developments

As a newly emerging technology, the liquid metal used in chip cooling is still in its fermentation stage. One existing commercially available example can be found in its application as a material to reduce the thermal resistance [109]. It is reported that several times higher of efficiency has been achieved than thermally conductive silicone grease. Contact resistance is one of the largest thermal barriers in chip cooling. The liquid metal can reduce the thermal resistance greatly. The liquid metal between the chip and the heat sink can not flow. It just dissipates the heat through conduction.

Up to now, the current liquid metal system has been performed to cool high heat-flux accelerator targets, which employs an annular inductive electromagnetic pump, based on the eutectic alloys of gallium and indium (GaIn) with a melting point of 15.7°C. Experiments show that it is capable of accommodating a heat flux of about 20 MW/m² over an area of 10⁻⁴ m². The jet velocity is less than 4 m/s and the required differential pressure from the pump is less than 10⁵ Pa [110]. Aimed at the computer chip cooling, several proof-of-concept devices with different driving approaches were developed in the lab [20,21,100]. For commercial purpose, a prototype that use an EM pump to drive liquid metal fluids was devised by a corporation named NanoCoolers [88,99]. However, tremendous fundamental efforts should be made in this area.

Overall, liquid metal gallium or its alloys are non-toxic, non-flammable, and relatively environmentally safe. Its applications in graphic card cooling and as thermal grease just began. In the near future, liquid metals may possibly be used on a large scale in electronic devices such as CPUs. The revolutionary use of an electromagnetic pump means low power consumption and almost silent operation without internal moving parts.

At the present stage, the devices using liquid metal as coolants in chip cooling are still not commercially available. But in the near future, this situation may be significantly changed. Using liquid metals as coolants could be a unique way to

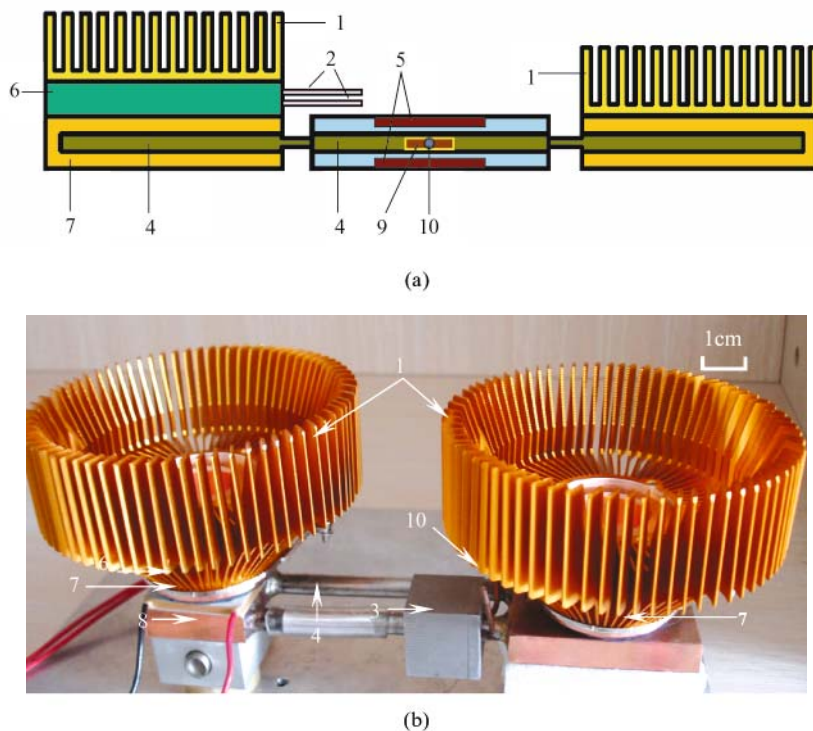


Fig. 10 Principle and prototype of liquid metal cooling loop driven by a thermoelectric generator

(a) Principle; (b) prototype

1) Finned heat exchanger; 2) electrodes of TEG; 3) MHD pump; 4) liquid metal; 5) permanent magnetic plate; 6) TEG; 7) substrate with flow channels; 8) simulating chip; 9) and 10) electrodes of MHD [100]

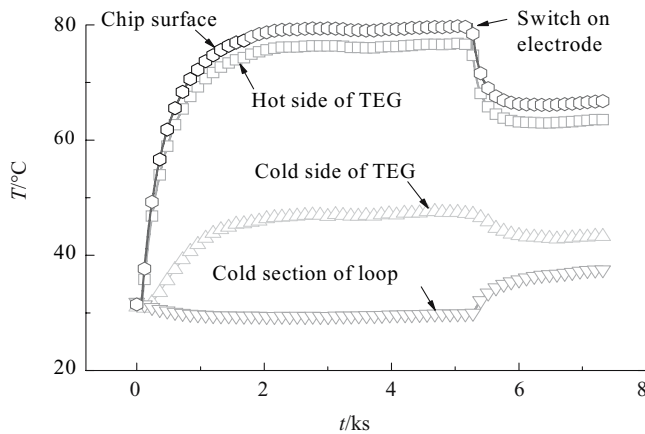


Fig. 11 Temperature of chip surface versus time when the heat load is 25 W [100]

solve the tough issues in the thermal management area. It is expected that the following applications or research topics could be attractive fields.

1) In view of the advantage of the metal coolant, water cooling may partially be replaced by liquid metal cooling.

2) Liquid metals may be used as the working fluid in certain pulse heat pipes under a special situation.

3) The best liquid metal or its alloys with perfect all-round properties should be investigated.

4) Nano liquid metal is an interesting material worth investigating. After all, the liquid metal or its alloys are somewhat expensive, whose prices are much higher than the ordinary metal. Some nano-particles or other high conductive material can be added to the liquid metal to make things better. However, special attention should be paid to new problems that will thus arise.

5) The ways to circulate liquid metals are a major direction to explore. The MHD pump is a good choice to drive liquid coolants but may not be the best.

6) Fundamental flow and heat transfer of liquid metals with low melting points should be comprehensively studied. There are plenty of opportunities within this area.

10 Several challenges

There are several engineering challenges that need to be addressed. The first one is how to deal with the situation where the ambient temperature is lower than the melting point. It is noted that the liquid metal coolant is not suitable when the computer works in a colder temperature environment such as 0°C. How to melt and circulate the coolant quickly before the chip temperature exceeds the permissive temperature is very important. Another issue is that the minimization of the MHD pump and the whole cooling parts may be a little more expensive than conventional liquid cooling. Besides, the integration of the cooling parts is also a main challenge faced with designers. Furthermore, the liquid metal embrittlement needs to be resolved. Appropriate choice of

materials may be of vital importance. It should be noted that the liquid metal coolant may be oxidized, for which therefore necessary efforts should be made to keep the liquid cooling system from leaking. In this respect, the prevention of corrosion and erosion of structural materials is a basic problem. Finally, the shortage of an appropriate measuring technique might be considered as a main reason for the relatively slow progress in the investigations of liquid metals as coolants. Powerful optical methods used in measurements of transparent liquids are obviously not available for the study of liquid metals. Some researchers [111] measured bubbles and liquid velocities in the eutectic alloy GaInSn under the influence of a DC longitudinal magnetic field (parallel to the direction of bubble motion) using ultrasound Doppler velocimetry (UDV). Yeliseyev et al. [112] studied the kinetics of liquid metal penetration into the solid metal and a structural irregularity of the corrosion front progression. However, unfortunately, a number of problems with respect to the capabilities and limitations of UDV application in two-phase flows still remain.

11 Conclusion

Although controlling and reducing the cost is always a permanent objective, the overriding consideration was to provide the necessary cooling performance even if the cost was higher than desired. Today, things are considerably different with intense competition on demanding increased performance at a reduced cost. While the focus remains on providing the necessary cooling, it is no longer acceptable to do so at a higher cost than desired. Liquid metal cooling shows the outstanding advantages over its counterpart methods. Successful applications in the nuclear industry and other high-flux-density occasions indicate that liquid metal based chip cooling is becoming a new frontier in the thermal management of computer systems. With more superior thermophysical properties than that of ordinary fluids, the liquid metal would guarantee a higher heat transfer performance over traditional coolants, which may finally lead to a brand new way of making advanced chip cooling devices. As has been widely used in the nuclear industry, liquid metal coolants would probably be adopted in chip cooling on a large scale in the near future.

Acknowledgements This work was partially supported by the National Natural Science Foundation of China (Grant Nos. 50575219 and 50325622).

References

1. Li T, Lv Y G, Liu J, et al. A powerful way of cooling computer chip using liquid metal with low melting point as the cooling fluid. *Forsch Ingenieurwes*, 2005, 70: 243–251
2. Pautsch G. How is high heat flux cooling technology being driven by supercomputers. *Proceedings of the 9th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, 2004, 2: 702–703

3. International Technology Roadmap for Semiconductors (ITRS 2005 Edition). In: <http://www.itrs.net/Links/2005ITRS/Home2005.htm> 2007, last accessed 28/03/2007
4. Strassberg D. Cooling hot microprocessors. EDN (European Edition), 1994, 39: 40–48
5. Lundquist C, Carey V P. Microprocessor-based adaptive thermal control for an air-cooled computer CPU module. In: Proceedings of the 17th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose, USA: IEEE, 2001, 168–173
6. Semeniouk V, Fleurial J P. Novel high performance thermoelectric microcoolers with diamond substrates. In: Proceedings of the 1997 16th International Conference on Thermoelectrics, Dresden, Germany: IEEE, 1997, 683–686
7. Disalvo F J. Thermoelectric cooling and power generation. Science, 1999, 285: 703–706
8. Simons R E, Chu R C. Application of thermoelectric cooling to electronic equipment: A review and analysis. In: Proceedings of the 16th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose, USA: IEEE, 2000, 1–9
9. Xie H, Ali A, Bhatia R. Use of heat pipes in personal computers. In: Proceedings of the Intersociety Conference—Thermomechanical Phenomena in Electronic Systems, Seattle, USA: IEEE, 1998, 442–448
10. Nguyen T, Mochizuki M, Mashiko K, et al. Use of heat pipe/heat sink for thermal management of high performance CPUS. In: Proceedings of the 16th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose, USA: IEEE, 2000, 76–79
11. Rao W, Zhou Y X, Liu J, et al. Vapor-Compression-Refrigerator Enabled Thermal Management of High Performance Computer. Beijing: International Congress of Refrigeration, 2007
12. Amon C, Murthy J, Yao S C. MEMS-enabled thermal management of high-heat-flux devices EDIFICE embedded droplet impingement for integrated cooling of electronics. Exp Therm Fluid Sci, 2001, 25: 231–242
13. Kang W, Xu Z, Pan C. MHD stabilities of liquid metal jet flows with gradient magnetic field. Fusion Eng Des, 2006, 81: 1 019–1 025
14. Tuckerman D B, Pease R F W. High-performance heat sinking for VLSI. IEEE Electron Device Lett, 1981, 2: 126–129
15. Ma H B, Wilson C, Borgmeyer B, et al. Effect of nanofluid on the heat transport capability in an oscillating heat pipe. Appl Phys Lett, 2006, 88: 143–116
16. Choi S U S. Enhancing thermal conductivity of fluids with nanoparticles. In: Springer DA, Wang H P, eds. Developments and Applications of Non-Newtonian Fluids. New York: ASME, 1995, FED-Vol.231/MD-Vol.66, 6–12
17. Buongiorno J. Convective transport in nanofluids. ASME J Heat Trans, 2006, 128: 240–250
18. Liu J, Zhou Y X. A computer chip cooling method which uses low melting point metal and its alloys as the cooling fluid. China Patent, 02131419.5, 2002
19. Miner A, Ghoshal U. Cooling of high-power-density microdevices using liquid metal coolants. Appl Phys Lett, 2004, 85: 506–508
20. Li T, Lv Y G, Liu J, et al. Computer chip cooling method using low melting point liquid metal or its alloy as the cooling fluid. In: Annual Heat and Mass Transfer Conference of the Chinese Society of Engineering Thermophysics, Jilin, China: Association of Engineering Thermophysics, 2004, 1 115–1 118 (in Chinese)
21. Liu J, Zhou Y X, Lv Y G, et al. Liquid metal based miniaturized chip-cooling device driven by electromagnetic pump. ASME Electronic and Photonic Packaging, Electronic and Photonic Packaging, Integration and Packaging of Micro/Nano/Electronic Systems, 2005, 5: 501–510
22. Zrodnikov A V, Efanov A D, Orlov Y I, et al. Heavy liquid metal coolant: Lead–bismuth and lead-technology. Atomic Energy, 2004, 97: 534–537
23. Anonymous authors. Fast breeder reactors. In: <http://www.npp.hu/mukodes/tipusok/gyorsreak-e.htm> 2007, last accessed 28/03/2007
24. Sato K, Furutani A, Saito M, et al. Melting attack of solid plates by a high-temperature liquid jet II—Erosion behavior by a molten metal jet. Nucl Eng Des, 1991, 132: 171–186
25. Yang W S. Blanket design studies for maximizing the discharge burnup of liquid metal cooled ATW systems. Ann Nucl Energy, 2002, 29: 509–523
26. Smither R K, Forster G A, Kot C A, et al. Liquid gallium metal cooling for optical elements with high heat loads. Nucl Instrum Meth A, 1988, 266: 517–524
27. Blackburn B W, Yanch J C. Liquid gallium cooling for a high power beryllium target for use in accelerator boron neutron capture therapy (ABNCT). In: Proceedings of Eighth Workshop on Targetry and Target Chemistry, St. Louis, Missouri, USA, 1999, 7–9
28. Blackburn B W. High-power target development for accelerator based neutron capture theory. Dissertation for the Doctoral Degree. MIT, Boston, MA, 2002
29. Smither R K. Liquid metal cooling of synchrotron optics. SPIE High Heat Flux Engineering, 1992, 1739: 116–134
30. Tak N I, Song T Y, Kim C H. Thermal hydraulic investigations on lead-bismuth cooled fuel assemblies with ducts. Prog Nucl Energy, 2004, 44: 67–74
31. Farabolini W, Ciampichetti A, Dabbene F, et al. Tritium control modeling for a helium cooled lithium-lead blanket of a fusion power reactor. Fusion Eng Des, 2006, 81: 753–762
32. Zhang Y N, Wang L, Wang W M, et al. Structural transition of sheared-liquid metal in quenching state. Phys Lett A, 2006, 355: 142–147
33. Cornell D A. Structure study of liquid gallium and mercury by nuclear magnetic resonance. Phys Rev, 1967, 153: 208–216
34. Schommers W. Pair potentials in disordered many-particle systems: A study for liquid gallium. Phys Rev A, 1983, 28: 3 599–3 605
35. Narten A H. Liquid gallium: Comparison of X-ray and neutron-diffraction data. J Chem Phys, 1972, 56: 1 185–1 189
36. Koster J N. Directional solidification and melting of eutectic GaIn. Cryst Res Technol, 1999, 34: 1 129–1 140
37. Burton R G, Burton R A. Gallium alloy as lubricant for high-current-density brushes. IEEE Trans Compon Hybr Manufact Technol, 1988, 11: 112–115
38. Kuczkowski T J, Buckley D H. Friction and wear of low melting binary and ternary gallium alloy films in argon and in vacuum. NASA Tech Note, Washington, D. C., NASA TN D-2721, 1965, 1–14
39. Kolokol A S, Shimkevich A L. Topological structure of liquid metals. Atomic Energy, 2005, 98: 187–190
40. Swalin R A. On the theory of self-diffusion in liquid metals. Acta Metallurgica, 1959, 7(N11): 736–740
41. Keck P H, Broder J. The solubility of silicon and germanium in gallium and indium. Phys Rev, 1953, 90(4): 521–522
42. Cao A, Yueh P, Lin L. Bi-directional micro relays with liquid metal wetted contacts. In: Proceedings of 18th IEEE International Conference on Micro Electro Mechanical Systems, Miami Beach, FL, USA: IEEE, 2005, 371–374
43. Burton R A, Burton R G. Properties and performance of gallium alloys in sliding contacts. In: Proceedings of the 34th Meeting of the IEEE Holm Conference on Electrical Contacts, San Francisco, CA, USA: IEEE, 1988, 187–192
44. Sawada T, Netchaev A, Ninokata H, et al. Gallium-cooled liquid metallic-fueled fast reactor. Prog Nucl Energy, 2000, 37: 313–319
45. Badyal Y S, Bafile U, Miyazaki K, et al. Cage diffusion in liquid mercury. Phys Rev E, 2003, 68: 061208
46. Nisoli M, Stagira S, Silvestri S D. Ultrafast electronic dynamics in solid and liquid gallium nanoparticles. Phys Rev Lett, 1997, 78: 3 575–3 578

47. Mudawar I. Assessment of high-heat-flux thermal management schemes. *IEEE Trans Compon Pack Technol*, 2001, 24: 122–141
48. Gurrum S P, Suman S K, Joshi Y K, et al. Thermal issues in next-generation integrated circuits. *IEEE Trans Device Mater Reliab*, 2004, 4: 709–714
49. Bhattacharya A, Mahajan R L. Finned metal foam heat sinks for electronics cooling in forced convection. *J Electron Packing*, 2002, 124: 155–163
50. Smither R K, Lee W, Macrander A, et al. Recent experiments with liquid gallium cooling of crystal diffraction optics. *Rev Sci Instrum*, 1992, 63: 1 746–1 754
51. Bae K, Guo Z, Sprecher A F, et al. Effects of r-ratio and wave form on the fatigue of 63Sn-37Pb solder used in electronic packaging. *Fifth IEEE CHMT Int Electron Manuf Technol Symp Proc 1988 Des to Manuf Transfer Cycle*, 1988, 5: 143–148
52. Kalashnikov E V. Thermodynamically stable states in eutectic systems. *Tech Phys*, 1997, 42: 330–335
53. Plevachuk Y, Sklyarchuk V, Yakymovych A, et al. Electronic properties and viscosity of liquid Pb–Sn alloys. *J Alloy Comp*, 2005, 394: 63–68
54. Paradis P F, Ishikawa T, Fujii R, et al. Physical properties of liquid and undercooled tungsten by levitation techniques. *Appl Phys Lett*, 2005, 86: 041901
55. Iida T, Guthrie R I L. *The Physical Properties of Liquid Metals*. Oxford: Clarendon Press, 1993
56. Shimoji M. *Liquid Metals*. New York: Academic Press, 1977
57. Kaneko Y, Thoendel M, Olakanmi O, et al. The transition metal gallium disrupts pseudomonas aeruginosa iron metabolism and has antimicrobial and antibiofilm activity. *J Clin Invest*, Published online on March 15, 2007
58. Tripathi V, Loh Y L. Thermal conductivity of a granular metal. *Phys Rev Lett*, 2006, 96: 046805
59. Wang Q, Li Y X. Theoretical study of electrical transport properties of liquid metals and alloy. *Mater Rev*, 2001, 15(8): 7–9 (in Chinese)
60. Wang Q, Li L X. Measurement of electrical resistivity and thermopower of liquid metals. *Mater Rev*, 2001, 15(11): 10–12 (in Chinese)
61. Mathiak G, Plescher E, Willnecker R. Liquid metal diffusion experiments in microgravity-vibrational effects. *Meas Sci Technol*, 2005, 16 (2): 336–344
62. Bohdanský J. Temperature dependence of surface tension for liquid metals. *J Chem Phys*, 1968, 49: 2 982–2 986
63. Lee J, Shimoda W, Tanaka T. Temperature dependence of surface tension of liquid Sn–Ag, In–Ag and In–Cu alloys. *Meas Sci Technol*, 2005, 16: 438–442
64. Hardy S C. The surface tension of liquid gallium. *J Cryst Growth*, 1985, 7: 602–606
65. Wilde G. The static and dynamic specific heat of undercooled metallic liquids. *J Non-Cryst Solids*, 2002, 307–310: 853–862
66. Liu Z, Bando Y, Mitome M, et al. Unusual freezing and melting of gallium encapsulated in carbon nanotubes. *Phys Rev Lett*, 2004, 93: 095504
67. Bosio L, Windsor C G. Observation of a metastability limit in liquid gallium. *Phys Rev Lett*, 1975, 35: 1 652–1 655
68. Cicco A D. Phase transitions in confined gallium droplets. *Phys Rev Lett*, 1998, 81: 2 942–2 945
69. Wang L, Liu J. Discontinuous structural phase transition of liquid metal and alloys. *Phys Lett A*, 2004, 328: 241–245
70. Zhang Y N, Wang L, Wang W M, et al. Structural transition of sheared-liquid metal in quenching state. *Phys Lett A*, 2006, 355: 142–147
71. Prabhu K N, Ravishankar B N. Effect of modification metal treatment on casting/chill interfacial heat transfer and electrical conductivity of Al–13% Si alloy. *Materials Science and Engineering A*, 2003, 360: 293–298
72. Shim J H, Lee S C, Lee B J, et al. Molecular dynamics simulation of the crystallization of a liquid gold nanoparticle. *J Cryst Growth* 2003, 250: 558–564
73. Li H, Bian X, Wang G. Molecular dynamics computation of the liquid structure of Fe₅₀Al₅₀ alloy. *Mat Sci Eng A-Struct*, 2001, 298: 245–250
74. Chen X S, Zhao J J, Sun Q. Surface thermal stability of nickel clusters. *Phys Status Solidi B*, 1996, 193(2): 355–361
75. Ercolessi F, Andreoni W, Tosatti E. Melting of small gold particles: Mechanism and size effects. *Phys Rev Lett*, 1991, 66: 911–914
76. Jellinek J, Beck T L, Berry R S. Solid–liquid phase changes in simulated isoenergetic Ar13. *J Chem Phys*, 1986, 84: 2 783–2 794
77. Labastie P, Whetten R L. Statistical thermodynamics of the cluster solid-liquid transition. *Phys Rev Lett*, 1990, 65(13): 1 567–1 570
78. Hattori T, Kinoshita T, Taga N, et al. Pressure and temperature dependence of the structure of liquid InSb. *Phys Rev B*, 2005, 72: 064205
79. Zhou X W, Chen J Y. Overview on viscosity of liquid metals. *Journal of Shenyang Normal University (Natural Science Edition)*, 2003, 21(4): 255–259 (in Chinese)
80. Prokhorenko S V. Structure and viscosity of gallium, indium, and tin in the vicinity of the crystallization temperature. *Materials Science*, 2005, 41: 271–274
81. Kang S K, Buchwalter S, Tsang C. Characterization of electroplated bismuth–tin alloys for electrically conducting materials. *J Electron Mater*, 2000, 29: 1 278–1 283
82. Kang S K, Buchwalter S, LaBianca N C, et al. Development of conductive adhesive materials for via fill applications. *IEEE Trans Compon Pack Technol*, 2001, 24: 431–435
83. Palmer M, Erdman N S, McCall D A. Forming high temperature solder joints through liquid phase sintering of solder. *J Electron Mater*, 1999, 28: 1 189–1 195
84. Murakoshi Y, Shimizu T, Takagi H, et al. Si based multi-layered pint circuit board for MEMS packaging fabricated by Si deep etching, bonding and metal power injection. *SPIE Proc*, 2001, 4 408: 502–509
85. Kathuria Y P. 3D microstructuring by selective laser sintering/microcladding of metallic powder. *SPIE Proc*, 1999, 3822: 103–109
86. Shen J, Xie Z, Zhou B, et al. Characteristics and microstructure of a hypereutectic Al–Si alloy powder by ultrasonic gas atomization process. *J Mater Sci Technol*, 2001, 17: 79–80
87. Zhang S G, Yang B C, Yang B, et al. A novel ultrasonic atomization process for producing spherical powder. *Acta Metall Sinica*, 2002, 38: 888–892
88. Ghoshal U, Grimm D, Ibrani S, et al. High-performance liquid metal cooling loops. In: *Proceedings of the 21th IEEE Semiconductor Thermal Measurement and Management Symposium*, San Jose, USA: IEEE, 2005, 16–19
89. Liu G Y, Tan H D. Gallium and gallium compounds. In: *Cyclopaedia of Chemical Engineering: Metallurgy and Metallic Materials*. Beijing: Chemical Industry Press, 1994, 329–335 (in Chinese)
90. Schormann M, Klimek K S, Hatop H, et al. Sodium-potassium alloy for the reduction of monoalkyl aluminum (III) compounds. *J Solid State Chem*, 2001, 162: 225–236
91. Baldwin D F, Deshmukh R D, Hau C S. Gallium alloy interconnects for flip-chip assembly applications. *IEEE Trans Compon Pack Technol*, 2000, 23: 360–366
92. Willis K L, Abell A B, Lange D A. Image-based characterization of cement pore structure using wood’s metal intrusion. *Cement and Concrete Research*, 1998, 28: 1,695–1,705
93. Ma K Q, Liu J. Nano liquid-metal fluid as ultimate coolant. *Physics Letters A*, 2007, 361: 252–256
94. Maxwell J C. *A Treatise on Electricity and Magnetism*, Cambridge: Oxford Univ Press, 1904

95. Eastman J A, Choi S U S, Li S, et al. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. *Applied Physics Letters*, 2001, 78: 718–720
96. Lu S, Lin H. Effective conductivity of composites containing aligned spheroidal inclusions of finite conductivity. *J Appl Phys*, 1996, 79: 6 761–6 769
97. Eastman J A, Phillpot S R, Choi S U S, et al. Thermal transport in nanofluids. *Annu Rev Mater Res*, 2004, 34: 219–246
98. Mohseni. Effective cooling of integrated circuits using liquid alloy electrowetting. In: *Proceedings of the 21th IEEE Semiconductor Thermal Measurement and Management Symposium*, San Jose, USA: IEEE, 2005, 20–25
99. NanoCoolers puts liquid metal in your PC. In: <http://www.techpowerup.com/?3105> 2007, last accessed 28/3/2007
100. Ma K Q, Liu J. Heat driven liquid metal cooling device for the thermal management of computer chip. *J Phys D: Appl Phys*, 2007, 40: 4 722–4 729
101. Cooney C G, Chen C Y, Emerling M R, et al. Electrowetting droplet microfluidics on a single planar surface. *Microfluidics and Nanofluidics*, 2006, 2: 435–446
102. Lee J, Kim C J. Surface-tension-driven microactuation based on continuous electrowetting. *J Microelectromech Syst*, 2000, 9: 171–180
103. Lee Y B, Chang W P, Kwon Y M, et al. Development of a two-dimensional model for the thermohydraulic analysis of the hot pool in liquid metal reactors. *Ann Nucl Energy*, 2002, 29: 21–40
104. Xuan Y, Roetzel W. Conceptions for heat transfer correlation of nanofluids. *Int J Heat Mass Transfer*, 2000, 43: 3 701–3 707
105. Lyon R N. Liquid metal heat-transfer coefficients. *Chem Eng Prog*, 1951, 47: 75–79
106. Yu J Y, Jia B S. *Thermal Hydrodynamics for Reactors*. Beijing: Tsinghua University Press, 2003 (in Chinese)
107. Yang S M, Tao W Q. *Heat Transfer*. Beijing: Higher Education Press, 1998 (in Chinese)
108. Yan J F, Liu J. Evaluation on the performance of liquid metal cooling chip based on compartment model. In: *Proceedings of China Association of Engineering Thermophysics Symposium on Heat and Mass Transfer*, Beijing, China: Association of: Engineering Thermophysics, 2005, 1,588–1,592 (in Chinese)
109. Furman B K, Gelorme J D, Labianca N C. Thermal interface for facilitating thermal contact between integrated circuit chip surface and heat sink surface, comprises liquid metal layer and barrier layers. US patent, US2006131738-A1, 2006
110. Silverman I, Yarin A L, Reznik S N, et al. High heat-flux accelerator targets: Cooling with liquid metal jet impingement. *Int J Heat Mass Transfer*, 2006, 49: 2 782–2 792
111. Zhang C, Eckert S, Gerbeth G. Experimental study of single bubble motion in a liquid metal column exposed to a DC magnetic field. *Int J Multiphas Flow*, 2005, 31: 824–842
112. Yeliseyev O I, Chernov V M, Tsaran TV. Kinetic features of the component interaction in the V[O]–Li[Ca] system. *J Nucl Mater*, 2002, 307–311: 1 400–1 404