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A powerful way of cooling computer chip using liquid metal with low melting point as the cooling fluid

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Abstract With the improvement of computational speed, thermal management becomes a serious concern in computer system. CPU chips are squeezing into tighter and tighter spaces with no more room for heat to escape. Total power-dissipation levels now reside about 110 W, and peak power densities are reaching 400–500 W/mm^2 and are still steadily climbing. As a result, higher performance and greater reliability are extremely tough to attain. But since the standard conduction and forced-air convection techniques no longer be able to provide adequate cooling for sophisticated electronic systems, new solutions are being looked into liquid cooling, thermoelectric cooling, heat pipes, and vapor chambers. In this paper, we investigated a novel method to significantly lower the chip temperature using liquid metal with low melting point as the cooling fluid. The liquid gallium was particularly adopted to test the feasibility of this cooling approach, due to its low melting point at 29.7 °C, high thermal conductivity and heat capacity. A series of experiments with different flow rates and heat dissipation rates were performed. The cooling capacity and reliability of the liquid metal were compared with that of the water-cooling and very attractive results were obtained. Finally, a general criterion was introduced to evaluate the cooling performance difference between the liquid metal cooling and the water-cooling. The results indicate that the temperature of the computer chip can be significantly reduced with the increasing flow rate of liquid gallium, which suggests that an even higher power dissipation density can be achieved with a large flow of liquid gallium and large area of heat dissipation. The concept discussed in this paper is expected to provide a powerful cooling strategy for the notebook PC, desktop PC and large computer. It can also be extended to more wide area involved with thermal management on high heat generation rate.

Eine leistungsfähige Kühlungsmethode für Computer Chips durch den Einsatz von flüssigen Metallen mit einem niedrigen Schmelzpunkt

Zusammenfassung Die Steigerungen der Rechengeschwindigkeiten in modernen Computersystemen in Verbindung mit einer stetigen Erhöhung der Leistungsdichte führt dazu, dass eine effektive Abführung der in Form von Wärme freigewordenen Energie zu einer zentralen Aufgabe geworden ist. Inzwischen beträgt die in CPUs dissipierte Energie 110 W bei Wärmestromdichten von 400–500 W/mm^2. Die bisher eingesetzten Kühlungsverfahren sind hierfür nicht geeignet, so dass neue Prozesslösungen erforderlich sind. In dieser Arbeit wird ein neues Verfahren vorgestellt, bei dem flüssiges Metall mit einer niedrigen Schmelztemperatur eingesetzt wird, um die Temperatur leistungsstarker Chips signifikant abzusenken. Als Flüssiges Kühlmittel wird Gallium eingesetzt, das eine Schmelztemperatur von 29,7 °C und hohe Werte der thermischen Leitfähigkeit und der Wärmekapazität aufweist. Messungen wurden mit unterschiedlichen Mengenströmen und Energiedissipationsraten ausgeführt und mit den Ergebnissen für wassergekühlte Systeme verglichen. Das vorgestellte Konzept kann sehr wirkungsvoll für unterschiedlichste, leistungsstarke Rechnersysteme eingesetzt werden.

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List of symbols

A	Cross section area of the tube (m^2)
c_p	Specific heat of liquid ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)
c'_p	Specific heat of water ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)
d	Diameter of the tube in cold plate (m)
h	Apparent heat convection coefficient between the liquid and the heating plate ($\mathrm{W \cdot m^{-2} \cdot K^{-1}}$)
L	Length of the tube (m)
k	Thermal conductivity of the liquid ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)
k'	Thermal conductivity of the water ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)
Nu_d	Nusselt number
Nu'_d	Nusselt number of water
P	Power-dissipation of the computer chip (W)
Pe	Peclet number
Pr	Prandtl number of liquid metal
Pr'	Prandtl number of water
q_w	Heat flux per unit wall area and time ($\mathrm{W \cdot m^{-2}}$)
R	Radius of the tube (m)
Re_d	Reynolds number of liquid metal
T_f	Temperature of the liquid (K)
$\bar{T}_f$	Fluid bulk temperature (K)
$\bar{T}_{f,in}$	Liquid temperature at the inlet of the tube (K)
$\bar{T}_{f,out}$	Liquid temperature at the outlet of the tube (K)
T_w	Tube wall temperature (K)
$\bar{T}_{w,center}$	Wall temperature at the middle of the tube (K)
u_0	Centerline velocity at the inlet of the tube ($\mathrm{m \cdot s^{-1}}$)
$\bar{u}$	Mean velocity ($\mathrm{m \cdot s^{-1}}$)

Greek symbols

ρ	Density of liquid ($\mathrm{kg \cdot m^{-3}}$)
ρ'	Density of water ($\mathrm{kg \cdot m^{-3}}$)
μ	Viscosity of liquid metal ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)
μ'	Viscosity of liquid water ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)
Δ	Wall temperature difference between liquid metal and water at $x = L/2$ (°C)

1 Introduction

Today's rapid IT development requires high PC performance capable of processing more data and more speedily. To meet 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 and failure of CPU. The reliability of the electronic system will suffer if high temperatures are permitted to exist. Therefore, removal of heat has become one of the most challenging issues facing computer system designers today. However, conventional thermal management schemes such as air-cooling with fans, liquid cooling [1], thermoelectric cooling [2–5], heat pipes [6], vapor chambers [7], and vapor compression refrigeration [8] have either reached their practical application limit or are soon to become impractical for recently emerging electronic components. Therefore, exotic approaches were regarded as an alternative to these conventional methods insufficient for cooling further high power processors.

Compared with air-cooling, water-cooling is a much more efficient way at drawing heat away from the processor and outside of the system. With forced flowing of the convective water, an improvement over air-cooling was found to be more than a factor of 10. However, the use of water as cooling fluid has some limitations. The low thermal conductivity of water may lower its effectiveness as a heat transfer fluid. Also, circulation of water can be driven only by mechanically moving pumps that may be unreliable, occupy large spaces, and contribute to vibration or noise. As is well known, the thermal conductivity for the metal is much higher than that of general liquid. Thus, if certain liquid metal or its alloys with low melting point was used as the cooling fluid, a much higher cooling capacity than water-cooling can be established. Starting from this point, Liu and Zhou [9] proposed for the first time the concept of using the liquid metals with low melting point and their alloys as the cooling fluid to cool the computer chip in the year of 2002.

As a practical cooling fluid, the liquid metal must satisfy the following requests: non-poisonous, non-caustic material, low viscosity, high thermal conductivity and heat capacity. In this side, the liquid gallium can serve as a perfect candidate, which has in fact been widely used in the area of cooling synchrotron [10, 11] and nuclear reactor [12]. However few have used it to cool the high power electronics components, especially for the computer chip. A deep analysis on the thermal properties of gallium strongly suggests that, it also suits very well for the computer chip cooling owing to its low melting point at 29.7 °C and latent heat of 19.16 cal/g [13]. The gallium can generally be kept in the liquid state at a temperature much lower than the room temperature, due to having a large sub-cooling point. Gallium's thermal conductivity is $25.2\,\mathrm{kcal/m \cdot h \cdot {}^\circ C}$, which is far larger than that of the air or water [13]. Besides, this metal is not toxic and relatively cheap. 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 the liquid gallium make it an easy fluid to handle and its high thermal conductivity and heat capacity guarantee it an excellent cooling fluid [10, 14, 15]. Further, the low kinetic viscosity of the liquid gallium improves the capability to remove heat, especially at the liquid-solid interface and enhances its attractiveness as a cooling fluid even more. Gallium's normal (dynamic) viscosity is about 1.5 times that of water, which means that it can be pumped through small channels with relative ease [10, 14, 15]. The surface tension of liquid gallium is much higher than that of water. This feature makes liquid gallium immune to the presence of small cracks or channels in an imperfect seal that would be a serious fluid leak for water as a cooling fluid. Besides, the liquid gallium is not toxic and is relatively cheap. All these compelling properties warrant the future application of gallium to the chip cooling area. Experiments as well as theoretical efforts made in this study are aimed to investigate the above concept.

2 Experimental setup and procedure

2.1 Hardware fabrication

Figure 1 is a prototype of liquid metal cooling modules. To test its cooling performance, a copper plate with size of 40 mm × 40 mm × 2 mm and a heating plate with size of 56 mm × 52 mm × 10 mm were fabricated and constructed together to simulate the Pentium-IV CPU. It is noticed that Gallium reacts with pure copper. As such, the surface of the cooling blocks should be coated, for example, with nickel. In this prototype, the surface of the copper has been oxygenized. There may be some difference between the heating plate used in the liquid metal cooling experiment and the real computer chip. However, the heating plate could easily provide different uniform heat flux by flexibly adjusting the electric voltage applied on the heating wire in it. Therefore more complex and extreme situations can be tested. The heating wire was made of 0.3 mm-dia nickel-chromium with resistance measured as 660 Ω. The heating wire was insulated by the insulating paint. Electronic interference is beyond the scope of the paper and not discussed in this section. Copper plate was placed between the heating and cold plate, and thermally conductive silicone grease was filled between the heating plate, the copper block and the cold plate in order to minimize the thermal resistance occurring in the contact surface. At the same time, these three plates were clamped together tightly to reduce the thermal resistance. Cold plate design must assure efficient thermal transport from copper plate to the liquid metal inside the cold plate. Flat and smooth surfaces for the plates are generally required. The cold plate was fabricated from copper with thin wall design to shorten the thermal path from the target to the liquid metal. The internal diameter of the tube in the cold plate is measured as 2.78 mm.

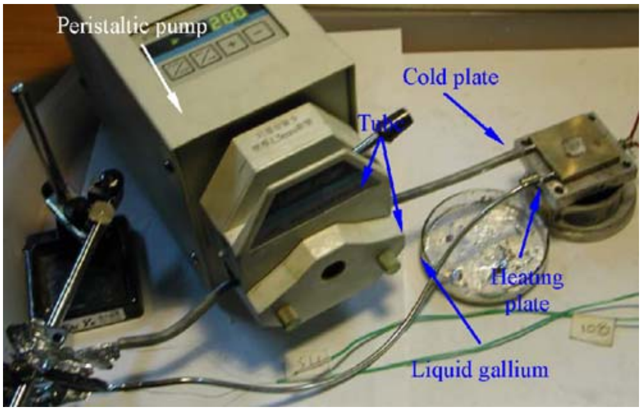


Fig. 1 Prototype of liquid metal based cooling system

A wave like fined-tube heat exchanger was adopted as the fan-cooled radiator in this prototype, which was made by copper tube (the external and internal diameter are 2.90 mm and 1.76 mm, respectively) coiled with small aluminum foils. A commercially available micro fan blows these fins with a constant rotational speed. The surface of the fan-cooled radiator is so small that it could compare the difference between liquid metal cooling and water-cooling in extreme condition. It will help to investigate the feasibility of realizing the tightly packed integrated chip cooling system. The peristaltic pump, fan-cooled radiator, and cold plate are connected together by a flexible plastic tube with external diameter of 6.24 mm and internal diameter of 3 mm. The driving force for the liquid to flow in the tube comes from the peristaltic pump. In this way, a liquid cooling system circulating either liquid metal or water through the cold plate attached to the heating plate was thus constructed. As the 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.

In each experiment, the copper was heated up to 70 °C by the heating plate from the room temperature. Then the cooling fan and the peristaltic pump began to work and the liquid was continuously circulated in the cooling system. The heating plate was turned off until the copper reached a steady state. However, the peristaltic pump kept working to cool the copper plate and prepared for the next experiment.

For brief, only conceptual experiments were performed in this paper to test the concept of using liquid metal for the computer chip cooling. Clearly, it would be much lighter and smaller for the above system to be made if more industrial design was considered. Especially when an electromagnetic induction pump was adopted to replace the present peristaltic pump, more highly compact cooling chip can be made, which would find significant applications in notebook computer, where small space is a prerequisite. Researches about such practical problems will be reported in our later study.

2.2 Measurement system

The schematic diagram of the apparatus developed to facilitate the systematic study is depicted in Fig. 2. The electrical

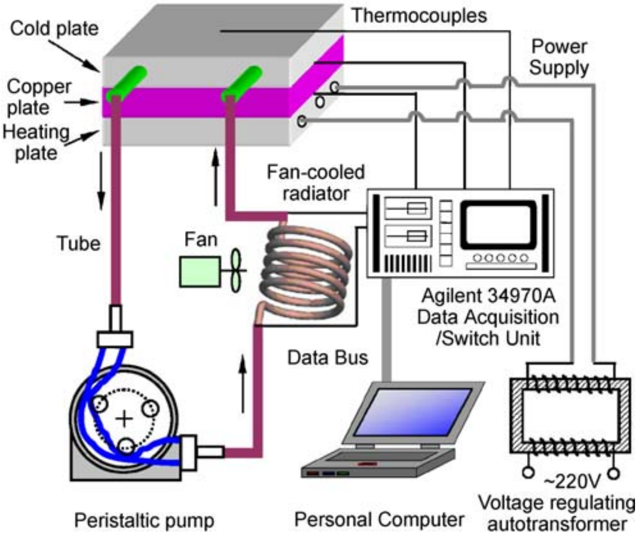


Fig. 2 Schematic diagram of measurement on liquid metal cooling system

current for the heating plate is controlled by a voltage regulating autotransformer, whose working range is 0 ∼ 380 V. The thermocouples are calibrated in the ice water and an accuracy of ±0.1 °C is obtained. The transient temperature are obtained using a 48 channels HP Agilent 34 970 Data Acquisition/Switch Unit and displayed at 2 s intervals by the computer. The HP Agilent 34 970 Data Acquisition/Switch Unit is connected with the personal computer with the data acquisition card (HP E2078, USA). The acquisition software uses HP Bench Link Data Logger, which can immediately display, analyze and save the input measurement data.

The thermocouples were placed at the inlet and outlet of the fan-cooled radiator to monitor the operational aspect. Another three thermocouples were amounted on the centers of the upper surface of heating plate, copper plate, and cold plate to evaluate the cooling performance. Electric voltages of 110 V, 160 V and 220 V were chosen to regulate the heating power, respectively. Liquid gallium or water was driven by an adjustable peristaltic pump, which runs at speed of 20 rpm, 60 rpm and 100 rpm, respectively in this experiment.

3 Results and discussion

3.1 Experimental results

In order to make a comparison between the cooling performances of liquid gallium and water, typical experiments were carried out by arranging different conditions according to the specific voltages applied on the heating plate and different liquid flow rate produced by the peristaltic pump. These conditions were carefully classified as 14 groups as given in Tables 1 and 2. The liquid gallium and water flow velocities are measured as 16.3 cm/s and 22.2 cm/s respectively when the peristaltic pump runs at 100 rpm. Both the Reynolds numbers (1490 for liquid gallium and 944 for water) are smaller than the critical Reynolds number 2300 in tube flow. This indicates that the flows of liquid gallium and water are both in a laminar state, which agreed with the experimental observation. As the above two tables and Fig. 3 show, the cooling performance of the liquid gallium is much better than that of the water, just as anticipated. The tem-

Table 1 Results for chip cooling with liquid gallium

Group No.	1	2	3	4	5	6	7
Voltage (V)	110	110	110	160	160	220	220
Pump rotation speed (rpm)	100	60	20	100	60	100	60
Power (W)	18.3	18.3	18.3	38.8	38.8	73.3	73.3
Mass flow rate (g/s)	6.1	3.8	1.2	6.1	3.8	6.1	3.8
Flow speed (cm/s)	16.3	10.2	3.2	16.3	10.2	16.3	10.2
Copper plate steady state temperature (°C)	41.2	42.2	46.7	51.6	52.7	59.0	63.9
Cold plate surface temperature (°C)	37.5	40.3	42.3	45.4	47.0	52.5	51.5
Radiator inlet temperature (°C)	32.0	33.2	33.3	43.3	42.8	47.6	48.1
Radiator outlet temperature (°C)	29.8	31.4	29.4	41.2	40.5	44.5	45.0

Table 2 Results for chip cooling with water

Group No.	8	9	10	11	12	13	14
Voltage (V)	110	110	110	160	160	220	220
Pump rotation speed (rpm)	100	60	20	100	60	100	60
Power (W)	18.3	18.3	18.3	38.8	38.8	73.3	73.3
Mass flow rate (g/s)	1.36	0.79	0.27	1.36	0.79	1.36	0.79
Flow speed (cm/s)	22.2	12.9	4.4	22.2	12.9	22.2	12.9
Copper plate steady state temperature (°C)	42.2	44.0	51.9	52.2	52.5	61.1	67.0
Cold plate surface temperature (°C)	40.2	41.5	45.2	47.5	47.6	54.7	59.5
Radiator inlet temperature (°C)	35.6	36.0	36.1	42.8	43.3	48.6	52.9
Radiator outlet temperature (°C)	33.8	34.4	34.0	37.7	36.7	41.3	43.1

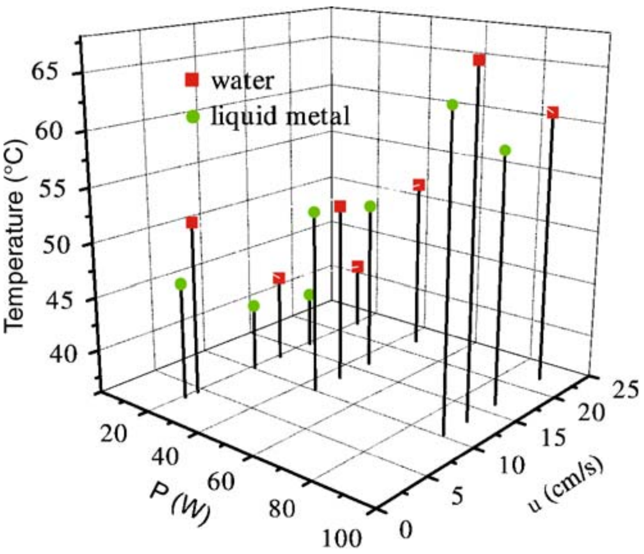
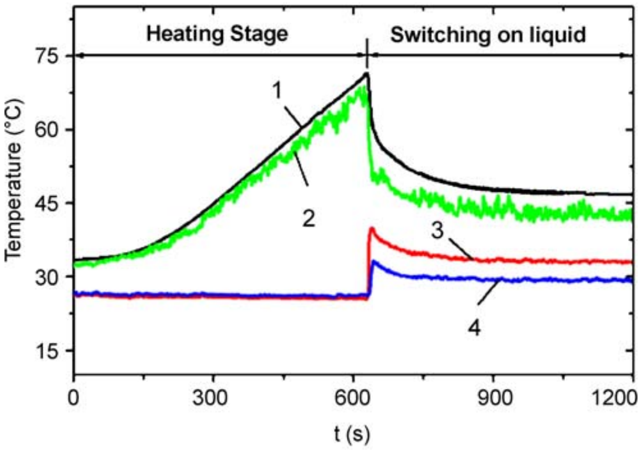
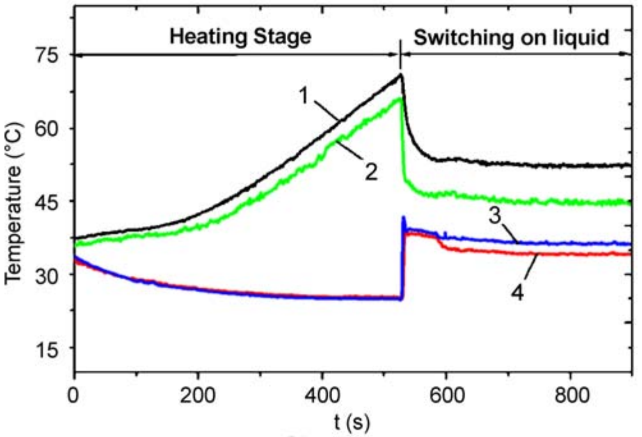


Fig. 3 Equilibrium temperature of computer chip using liquid metal cooling and water cooling with different flow rates and heat dissipation rate



(a) liquid gallium



(b) water

Fig. 4 Temperature transients of cooling system with flowing liquid, 1. bottom surface of cold plate, 2. top surface of cold plate, 3. radiator inlet, 4. radiator outlet

perature of the computer chip decreased with the increasing flow of the liquid gallium. The temperature difference resulted by the liquid metal cooling and water-cooling decreased with increased liquid flow. This is because that the surface area of the fan-cooled radiator is so small that it could not efficiently dissipate to the largest extent the heat to the ambient air. In other words, if using liquid gallium as the cooling fluid, only a much smaller radiator is necessary, compared with that of using water. This is rather beneficial for developing a highly compact chip-cooling device.

Figure 4 further provided the transient temperature distribution in the cooling process by liquid gallium and water-cooling in Groups No. 3 and 10 in detail, respectively. The experimental process is as follows. When the temperature of heating plate (simulating the CPU) was increased gradually to a steady state at 70 °C after about 300 s, the liquid gallium or water was initiated to circulate inside the tube. And a significant enhancement on the convective cooling on the CPU heater was observed. Clearly, 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 when the flow of liquid gallium was initiated. However, for the case of using water as the cooling fluid, the heating plate temperature only drops from its highest 70° to 51.9 °C. This leads to the conclusion that, the liquid gallium cooling performance is more powerful than that of the water-cooling, although the water flow rate in the above case is in fact much faster than that of the liquid gallium. A detailed comparative analysis between the data in Tables 1 and 2 also gives out the same conclusion.

3.2 Theoretical analysis

In order to better understand the virtue of the liquid metal cooling system, steady state heat transfer analysis between laminar flow and the walls of the duct with circular cross section in the cold plate was discussed in this section. The forced convection, i.e., absence of body force, and a constant-property fluid was assumed. Under this condition, the flow field is independent of heat transfer. Therefore the velocity field in the developed region can be described by a parabolic velocity profile, i.e.

$$u = u_0\left(1-\frac{r^2}{R^2}\right) = 2\bar{u}\left(1-\frac{r^2}{R^2}\right) , \tag{1}$$

where, u_0 is the centerline velocity at the inlet of the tube, $\bar{u}$ is the mean velocity connected with the centerline velocity u_0 by the relation $\bar{u} = u_0/2$, R denotes the radius of the tube.

The temperature gradients in the axial direction are usually much smaller than that in radial direction. Correspondingly, the axial conduction was neglected here for simplicity. Inclusion of axial conduction to conduct a more strict analysis needs further research in the near future. In addition, it was assumed that the velocities are small enough to make the temperature increase by internal friction negligible. The energy balance then reads

$$\frac{1}{r}k\frac{\partial}{\partial r}\left(r\frac{\partial T_f}{\partial r}\right)=\rho c_p u\frac{\partial T_f}{\partial x} \tag{2}$$

where, ρ, k and c_p are respectively the density, thermal conductivity and specific heat of the liquid. The boundary conditions could be defined as

$$\begin{aligned} T_f\big|_{x=0} &= T_0=\text{const.}\\ \left.\frac{\partial T_f}{\partial r}\right|_{r=0} &= 0\\ \left.k\frac{\partial T_f}{\partial r}\right|_{r=R} &= q_w=\text{const.} \end{aligned} \tag{3}$$

in which q_w is the heat flux per unit wall area and time.

An energy balance of the fluid flowing through the tube immediately results in the statement that for constant fluid properties the fluid bulk temperature increases linearly in the flow direction. For thermally developed flow, this must also hold for the temperature at any distance r from the tube axis. Therefore, a constant heat rate results in

$$\frac{\partial T_f}{\partial x}=C\,. \tag{4}$$

Then, the temperature in the tube can easily be obtained as:

$$\theta=T_f-T_w=\frac{2\rho c_p\bar{u}R^2}{k}\frac{\partial T_f}{\partial x}\left[\frac{1}{4}\left(\frac{r}{R}\right)^2-\frac{1}{16}\left(\frac{r}{R}\right)^4-\frac{3}{16}\right] \tag{5}$$

The temperature profile is the same at any position x. The heat-transfer coefficient is conventionally defined for duct flow with the equation

$$q_w=h\left(T_w-\bar{T}_f\right) \tag{6}$$

in which T_w is the tube wall temperature, h is the apparent heat convection coefficient between the liquid and the heating plate and $\bar{T}_f$ is the fluid bulk temperature defined by the equation

$$\bar{T}_f=\frac{\int\rho c_p u T_f\,\mathrm{d}A}{\int\rho c_p u\,\mathrm{d}A} \tag{7}$$

with the integrations extended over the cross section of the duct under consideration. The bulk temperature, therefore, is the temperature averaged when the fluid flows through this across section. For a constant property fluid flowing through a tube with circular cross section, Eq. 7 reduces to

$$\bar{T}_f=\frac{\int_0^R uT_f r\,\mathrm{d}r}{\int_0^R ur\,\mathrm{d}r} \tag{8}$$

and the Nusselt number is

$$\mathrm{Nu}_d=hd/k\,, \tag{9}$$

where, d represents the diameter of the tube in cold plate. The heat-transfer coefficient is determined by the radial temperature gradient at the tube wall. For the Nusselt number based on the local difference between wall temperature and fluid bulk temperature, a short calculation gives [16]

$$\mathrm{Nu}_d=4.36\,. \tag{10}$$

Many studies show that the minimum value of Nusselt number for turbulent flow, as Prandtl number becomes very small, to be between 4.36 and 8 [17]. It also could be represented with reasonable accuracy by a simple approximate equation [17]:

$$\mathrm{Nu}_d=7+0.025\mathrm{Pe}^{0.8}\,, \tag{11}$$

where, Pe represents the Peclet number.

In the inlet region, the Nusselt number decreases linearly with the increase of $\frac{1}{\mathrm{Re}_d\mathrm{Pr}}\frac{x}{d}$ (where, Re_d and Pr are Reynolds number and Prandtl number of liquid metal, respectively) and approaches the asymptotic value 4.36. For a liquid metal with a Prandtl number as 0.01 and a Reynolds number as 1000, the flow becomes fully developed at $x=d$. The Prandtl number of the liquid gallium is about 0.024 at 40 °C. However, the water flow will become fully developed at the distance far away from the $x=d$ because of the large Prandtl number involved. Thus, the heat-transfer coefficient of the liquid metal is smaller than that of the water at the inlet region. However, it should be noticed that in the liquid cooling system, the liquid is circulated in a closed cycle. The end effect of the inlet region could thus be neglected.

As Eqs. 9 and 10 show, the heat-transfer coefficient of the liquid metal is much larger than that of the water in the developed region. Thus, the temperature difference in liquid flow $(T_w-\bar{T}_f)$ will be much smaller than that in the water flow when the heat flux q_w per unit wall area and time is constant. It will help to enhance the heat transfer for cooling a computer chip. If the tube wall temperature T_w is constant, the temperature of the liquid metal is higher than that of the water, which will enhance the heat transfer from the liquid metal to the environment and help to reduce the surface area of the heat dissipation. On the other hand, the wall temperature T_w will be smaller than that in water if the liquid temperature $\bar{T}_f$ is constant. It is obvious that a lower wall temperature can thus be expected in computer chip cooling.

In order to determine the effect of the flow velocity on the cooling performance, the energy balance reads as

$$P=\rho c_p \bar{u} A\left(\bar{T}_{f,out}-\bar{T}_{f,in}\right) \tag{12}$$

and

$$P=\pi d q_w L\,, \tag{13}$$

where, ρ and c_p are respectively the density and specific heat of the liquid; A and L are the cross section area and length of the tube; $\bar{T}_{f,out}$ and $\bar{T}_{f,in}$ is the liquid temperature at the outlet and inlet of the tube; P is power-dissipation of the computer chip. For the same cooling power P, the temperature difference between the outlet and inlet of the tube in liquid metal is about two times that in water with the same flow velocity because the ρc_p of the water is about two times of that of liquid gallium. It is the advantage of using water to cooling the computer chip in this case. 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 for providing the best cooling performance. For the evaluation purpose, a simple criterion should be established to characterize these two methods.

If the liquid temperature $\bar{T}_{f,in}$ at the inlet of the tube has been known, the wall temperature at the middle of the tube could be obtained from Eqs. 6, 12 and 13 as

$$\bar{T}_{w,center}=\frac{P}{\pi L k \mathrm{Nu}_d}+\frac{2P}{\rho c_p \bar{u} \pi d^2}+\bar{T}_{f,in} \tag{14}$$

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

$$\Delta=\left(\frac{P}{\pi L k' Nu'_d}+\frac{2P}{\rho' c'_p \bar{u} \pi d^2}\right)-\left(\frac{P}{\pi L k \mathrm{Nu}_d}+\frac{2P}{\rho c_p \bar{u} \pi d^2}\right) \tag{15}$$

where, k', ρ' and c'_p are respectively the thermal conductivity, density and specific heat of water; Nu'_d is the Nusselt number of water. When $\Delta > 0$, the performance of the liquid metal cooling method is better than that of the water and vice versa (shown in Fig. 5).

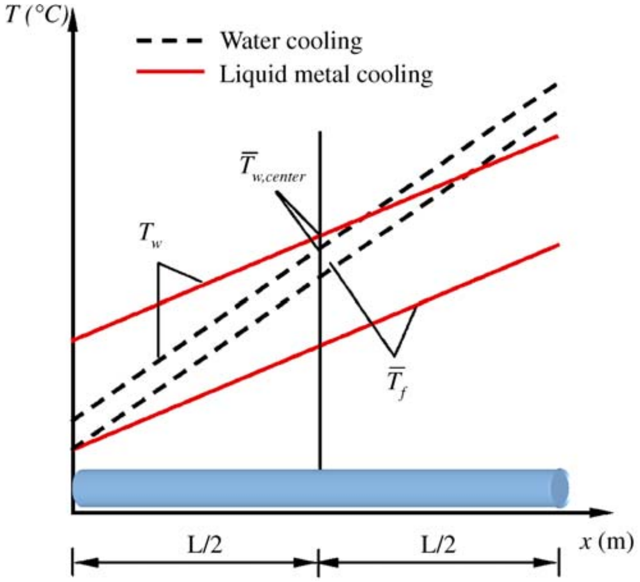


Fig. 5 Schematic temperature distribution of fluid in the tube imbedded in cold plate

Table 3 Characteristics of gallium and water

Kind	Density (kg/m^3)	Specific heat (J/kg · °C)	Thermal conductivity (W/m · °C)	Viscosity (kg/m · s)	Prandtl number
Gallium	6093	344	29.4	1.89E-3	0.024
Water	1000	4200	0.552	5.5E-4	4.34

In the following studies, the typical values for liquid gallium and water properties are applied as given in Table 3 [13, 18, 19]. The length of the tube L is 0.16 m and the liquid temperature at the outlet of the tube $\bar{T}_{f,in}$ is assumed as 25 °C. As shown in Sect. 1, all these attractive properties warrant the future application of liquid gallium in chip cooling area. It is noted that the liquid gallium may not be suitable for the computer to work in a cold temperature such as 0° although it can generally be kept in the liquid state at a temperature much lower than the room temperature, due to having a large sub-cooling point. Instead of the gallium as tested in this study, other liquid metal with low melting point can also be adopted as the cooling medium. For example, alloy of gallium and other metals such as bismuth, stannum and indium etc. generally has a lower melting point. A gallium alloy with 8% of stannum has a melting point at 20 °C, while alloy of gallium with 25% indium will melt at 16 °C. Additional combination of useful metals can produce more candidate liquid metal, with a wide variety of melting points. For example [18], alloy of 62.5% Ga, 21.5% In, 16% Sn has a melting point at 10.7 °C, while alloy of 69.8% Ga, 17.6% In, 12.6% Sn melts at 10.8 °C. These alloys can also possibly be used as the cooling fluid in the present device.

Figure 6 gives the temperature of the computer chip under different flow rates and tube diameters when the heating power is 18.3 W. The results agree with the experimental results perfectly (Fig. 6, Tables 1 and 2). The temperature of the computer chip decreased with increased flow of liquid gallium and tube diameter. This suggested that an even higher power density could be accommodated with higher flow rate of liquid gallium. It is noted that the flow of the liquid gallium and tube diameter can be optimized by the theoretical analysis simply. Further, the temperature difference of the computer chip between liquid metal cooling and

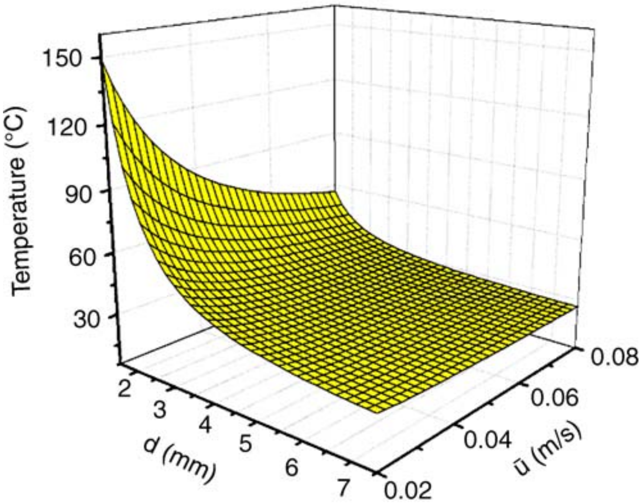


Fig. 6 Temperature of the computer chip subject to cooling by liquid metal with different flow rates and tube diameters ($P = 18.3$ W)

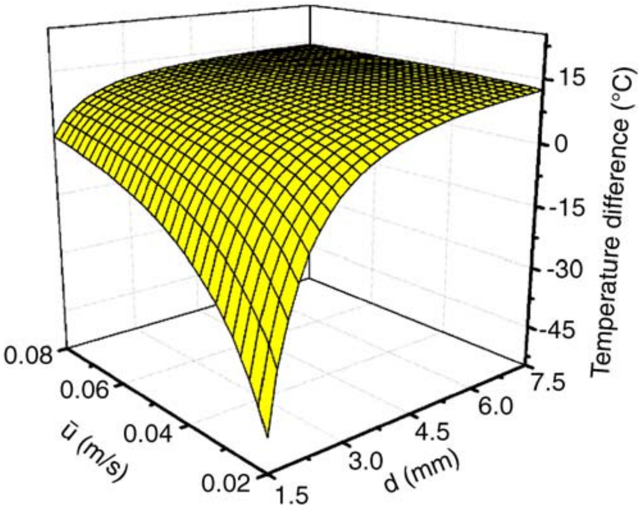


Fig. 7 Temperature difference of the computer chip between the cooling by liquid metal and water with different flow rates and tube diameters ($P = 18.3$ W)

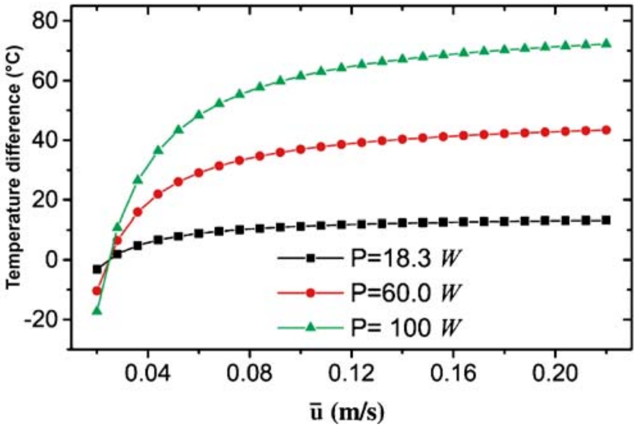


Fig. 8 Effect of flow rates on the computer chip temperature in different heat dissipation rates ($d = 2.78$ mm)

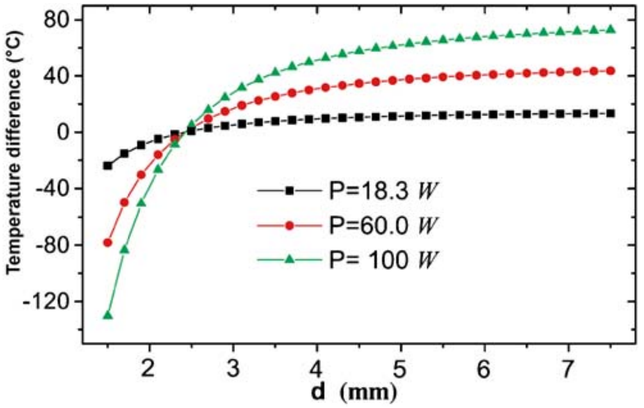


Fig. 9 Effect of tube diameters on the computer chip temperature in different heat dissipation rates ($\bar{u} = 0.032$ m/s)

water cooling in different flow rates and tube diameters is shown in Fig. 7. The computer chip temperature difference will reach about 14 °C in an optimal situation when the heating power is only 18.3 W. This difference will increase with increased heating power according to equation Eq. 15 (also shown in Figs. 8 and 9). All these results demonstrated that the liquid metal could provide a much powerful cooling capacity, especially in the situation of facing extremely high power densities. The liquid metal cooling system will be an alternative to those conventional methods and situations seriously requesting avoidance of high power generation. At the same time, equation Eq. 15 could be used as a simple criterion to characterize the cooling performance between the liquid metal cooling and water-cooling. In the theoretical model, the computer chip temperature difference is a little higher than that in our experiments. It was assumed that the liquid temperature $\bar{T}_{f,in}$ at the inlet of the tube is equal in different conditions. However, the surface area of the fan-cooled radiator is so small that the liquid metal temperature $\bar{T}_{f,in}$ at the inlet of the tube is higher than that of the water in the same condition, which may reduce the temperature difference of the computer chip between liquid metal cooling and water cooling.

4 Conclusion

In this study, we established the method of extending use of liquid metal as the cooling fluid for thermal management of computer chip. A prototype was fabricated to test the concept in which the liquid gallium was particularly used and driven by a peristaltic pump. The system successfully reduces the temperature of the simulating chip from 70 °C to 46.7 °C. A series of experiments under different flow rates and heat dissipation rates were performed to validate the method. The results demonstrated that the liquid metal has more powerful cooling capacity than that of the water-cooling, especially at a low flow rate or high heat generation situation. If designing the present cooling system by various configuration sizes, the method proposed in this paper is expected to be useful in cooling the notebook PC, desktop PC and super computer. It can also be extended to more wide area involved with high heat generation rate.

The other benefit of liquid metal cooling still lies in the reduction of noise within the computer. Most currently existing heat sink and fan combinations tend to generate rather loud noise from the fans that need to circulate air over the CPU and through the system. Many high performance CPUs requires in excess of 7000 rpm that generate noise of 60 decibels. If the electromagnetic induction pump is used to drive the liquid metal, there is no moving part except the liquid in the system and a more reliable cooling device can possibly be realized. At the same time, the liquid metal do not necessarily need to run at a very high speed which also help reduces the noise.

Naturally, broader use of this new cooling technology depends on several factors. The first of all is the size, cost, weight and capacity of method. The cooling system could be much smaller than that tested in this study if the electromagnetic induction pump is introduced. Secondly, practical aspects need to be considered. For example, the gallium is not suitable for the computer chip cooling in an extremely low temperature. Other metals and their alloys should be considered. Some of these results will be reported in our coming work. Efforts made in this paper warrant future applications of incorporating the flowing liquid metal to thermally managing the computer chip, either in large or small scale.

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