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Heat-driven liquid metal cooling device for the thermal management of a computer chip

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Abstract
The tremendous heat generated in a computer chip or very large scale integrated circuit raises many challenging issues to be solved. Recently, liquid metal with a low melting point was established as the most conductive coolant for efficiently cooling the computer chip. Here, by making full use of the double merits of the liquid metal, i.e. superior heat transfer performance and electromagnetically drivable ability, we demonstrate for the first time the liquid-cooling concept for the thermal management of a computer chip using waste heat to power the thermoelectric generator (TEG) and thus the flow of the liquid metal. Such a device consumes no external net energy, which warrants it a self-supporting and completely silent liquid-cooling module. Experiments on devices driven by one or two stage TEGs indicate that a dramatic temperature drop on the simulating chip has been realized without the aid of any fans. The higher the heat load, the larger will be the temperature decrease caused by the cooling device. Further, the two TEGs will generate a larger current if a copper plate is sandwiched between them to enhance heat dissipation there. This new method is expected to be significant in future thermal management of a desk or notebook computer, where both efficient cooling and extremely low energy consumption are of major concern.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Control of chip temperatures and temperature gradients within a certain range is essential for the successful and reliable operation of a microelectronic unit. Therefore, removal of the large amount of heat generated in the electronic components remains as a big challenge facing current computer system designers and thermal management engineers. Serious heat load and high heat flux of the hot chips nowadays have put a high request on cooling beyond what can be offered by the state-of-the-art finned heat sink structures, heat-pipes, forced air cooling, etc. Consequently, alternative ways such as single- or two-phase fluid cooling systems are being implemented gradually. However, in most liquid-cooling systems, the low thermal conductivity of the working fluids (e.g. water) necessitates a large-size heat exchanger for effective heat transfer from the source. The available driving pumps often have poor reliability and mechanical limitations [1] such as are implied by orientation-dependent performance, moving parts and noise. In the case of using electro osmotic pumps, high electrode potentials may often result in a dissociation of water molecules.

Miniaturization on heat exchanger and improvement of excellent thermal properties of coolants calls for the advent of alternative candidates. In the year 2002, Liu and co-workers [2, 3] proposed to use liquid metal or its alloy to cool the computer chip. This was perhaps the first trial in the convective cooling in thermal management of a computer. The recent

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Table 1. Properties of the TEG.

Type	Maximum electric current	Maximum temperature difference	Maximum voltage	Dimension
TEC1-127.08	8 A	68 °C	15.4 V	40 mm × 40 mm × 3.8 mm

Table 2. Properties of liquid metal used in this paper. Data measured at (a) 77 °C, (b) 30 °C and (c) 32 °C.

Material	Thermal conductivity ($\mathrm{W\,m^{-1}\,°C^{-1}}$)	Heat capacity ($\mathrm{J\,kg^{-1}\,°C^{-1}}$)	Density ($\mathrm{kg\,m^{-3}}$)	Surface tension	Viscosity ($10^7\,\mathrm{m^2\,s^{-1}}$)	Pr	Melting point (°C)	Boiling point (°C)
Gallium	28.7[a]	381.5[b]	6095[b]	709[b]	3.1[c]	0.021	29.8	2200

work by Miner and Ghoshal [4] further strongly supports this effort. Liquid metals used as coolant offer a unique solution to cooling high density power sources and spreading 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 a silent, vibration-free, low energy consumption rate, nonmoving and compact magnetofluiddynamic (MFD) pump because of its high electric conductivity [4]. Clearly, with about several dozen times larger thermal conductivity than that of water, a liquid metal such as gallium is expected to have a much better performance in transferring heat away.

The dc conduction pump exploits the Ampere force arising from the application of direct current normal to the magnetic field in the region of the fluid between the two permanent magnets. In the past efforts, the peristalsis pump [5], electrowetting [6, 7] and MFD pump [3, 4] have been adopted to drive the liquid metal gallium. Because the liquid metal coolant is electrically conductive, the driving of the MFD pump generally needs a low voltage however a high electric current [3]. To overcome the flow resistance, a large Lorenz force is needed which depends on an as high as possible electric current. Meanwhile, the electric resistance across the liquid metal is rather small, say of the order of mΩ. Therefore the voltage as applied on the metal is pretty low. In Miner and Ghoshal's work [4], a rather large current up to 15–30 A has been used to drive the MFD pump which makes the device a little far from practical application. In one of our previous works, the electricity used to drive the MFD pump is also over 5 A [3]. Clearly, an optimization of the pump design would make things better. As will be shown in this study, after optimizing the design and through reducing the gap distance between the two magnets and shielding the magnetic field, a much smaller current (∼0.1 A) would be strong enough to drive the MFD pump, which makes the thermoelectric generator (TEG) very promising in providing energy to drive the liquid metal cooling loop. Clearly, the small gap size design and shielding adoption increase the magnetic field intensity and thus the driving force. The simplicity of designing such pumps, particularly in lack of moving parts, warrants long-term reliability. Previously, a thermoelectric-electromagnetic (TEM) pump conceptually similar to the MFD pump plus TEG was used in the SNAP-10A space nuclear reactor in 1965 [8, 9]. More recently, TEMs have also been designed for larger space nuclear reactors. In those works, a tremendously large temperature difference is easily available due to nuclear reaction. It is therefore of no difficulty to make full use of such strong thermoelectric energy. As an alternative, a normally high temperature difference as provided by a computer will also work well for driving the TEG, MFD and thus the flow of liquid metal.

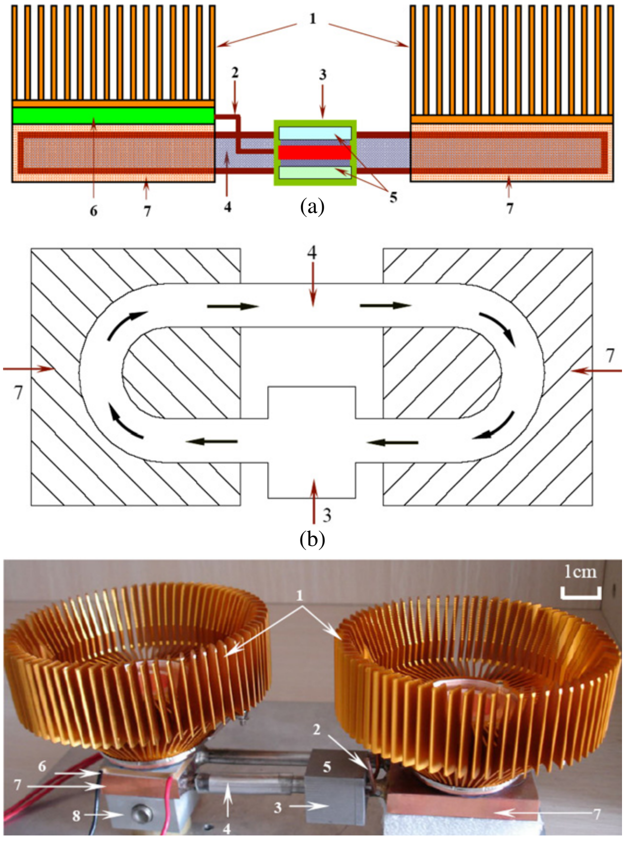
The aim of this paper is to demonstrate the feasibility of the self-driven liquid metal cooling loops directly using waste heat from the hot chip.

2. Experimental set up

According to the Seebeck effect [10], an electric current will be generated within the closed circuit when a temperature difference exists between the hot and cold sides of a TEG. A real TEG contains many thermoelectric elements, each of which is composed of P-type and N-type semiconductor legs. TEGs nowadays have found wide applications in many areas [11]. In fact, they are the reversible application of thermoelectric coolers [12–16]. The MFD pump in this paper is powered by the TEG whose maximum output can be obtained when its internal resistance is nearly equal to the external load resistance [17, 18]. The parameters for the TEGs used for the present test have been listed in table 1. TEGs made of a pair of n-type and p-type semiconductors are commercially available and can be bought from the Tande Energy and Temperature Associates PTY Co. [19].

The liquid metal used to cool the chip surface was gallium and its properties are given in table 2.

In table 1, the TEG has been labelled as having a maximum current of 8 A and a maximum voltage of 15.4 V. Here, we had directly adopted the thermoelectric cooler (TEC) as the TEG. Therefore, strictly speaking, the parameter as listed in table 1 in fact stands for that of a TEC. Such a value represents the electricity requested to drive the working of a TEC. As a thermal electric device, the TEG and the TEC are in fact the same. The only difference between them depends on their working role: either generating electric power when subjected to a temperature difference or causing a temperature reduction when an electric current is applied. The current generated by a TEG will be much smaller than the current required to operate the same device operating as a TEC at maximum temperature difference—dT, regardless of the efficiency of the device. This is because the generated current is driven by the temperature difference (and ZT), while the current required to achieve maximum dT is determined by the temperature itself (and ZT).



(a)

(b)

(c)

Figure 1. Principle and prototype of liquid metal cooling loop driven by a TEG. 1: finned heat exchanger; 2: electrodes of TEG; 3: MFD pump; 4: liquid metal; 5: permanent magnetic plate; 6: TEG; 7: substrate with flow channels; 8: simulating chip. (*a*) Principle, (*b*) top view of closed loop channel for liquid metal flow and (*c*) prototype.

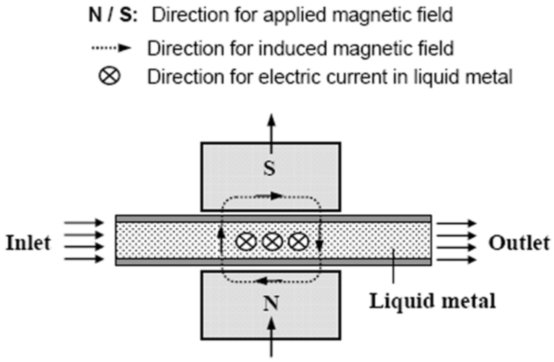


Figure 2. Schematic diagram of the working principle for the MFD pump.

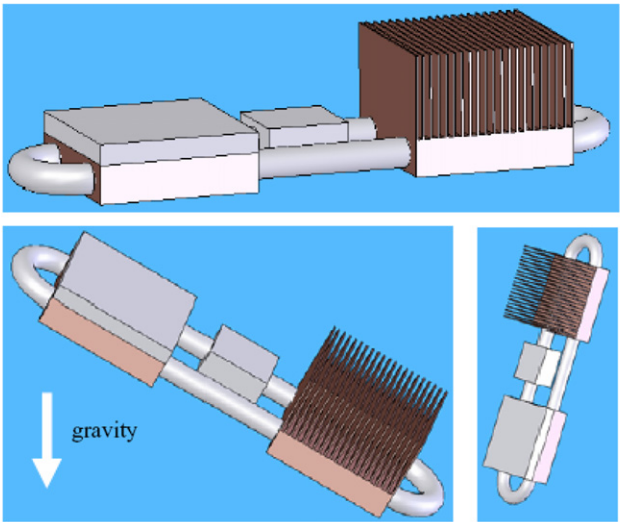


Figure 3. The liquid metal flowing in a closed loop is independent of gravity and orientation.

Figure 1(*a*)–(*c*) illustrate the working principle and prototype of the 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 was then subsequently used to drive the flow of the liquid metal inside the channel of the substrate.

The left cooling finned heat exchanger in our present study was chosen to dissipate the heat from the cold side of TEG as much as possible in order to guarantee a large temperature difference across the TEG and thus improve its power generation. Of course, the other alternative heat sink can also be adopted to realize such goal. For example, the inner wall of electronics devices such as a laptop can be intimately contacted with the cold side of the TEG. A fan can be mounted around the TEG. Even only exploiting the natural convection, the temperature difference across the TEG can also possibly generate useful direct electric current. Therefore, on the cold side of the TEG, the cooling fin is not always a prerequisite condition. Here, what one cares about is to take full use of the advantage of liquid metal cooling.

With the flow of the liquid gallium, the heat generated from the simulating hot chip will be absorbed and transferred away to the far end of the finned heat exchanger. As is well known, the Ampere force applied on a metal object can be expressed as $F = BIL\sin\theta$, where B is the magnetic strength, I the electric current, L the length of liquid metal normal to the flowing direction in the magnetic field and θ the angle between the magnetic field and the current. The electric current interacts with the vertical magnetic field and produces an Ampere force to drive the liquid gallium to flow and cool the hot chip surface. A schematic diagram of the working principle for the MFD pump is shown in figure 2.

Because of the closed loop configuration, the running of the whole of the liquid is independent of gravity and orientation once the flow was successfully initiated. That is to say, for a closed liquid loop, if the pump could drive the liquid horizontally, it would also be able to run the liquid vertically if its initial driving force could overcome the flow barrier. Here, the word ‘orientation’ refers to the setup position of the closed liquid loop, as shown in figure 3. A similar description can also be found in Miner and Ghoshal’s work [4].

The liquid metal will move continuously once the Ampere force is strong enough to overcome the viscous drag throughout the whole circulation path. In the experimental set up, a finned heat exchanger was particularly fixed immediately above the cold side of the TEG, whose purpose is to enhance heat conduction there and thus guarantee a large enough temperature difference across the two sides of the TEG. The simulating hot chip is just below this TEG. In normal working condition, the larger the temperature difference, the higher the electric current yielded and therefore more heat will be taken from the chip surface until a thermal steady state is finally reached. The MFD pump mainly consists of two permanent magnets with a small gap distance of 2.5 mm for the liquid metal to pass through, two electrodes extruding to the TEG and a yoke which was covered to prevent the magnetic field from leaking and seal the liquid metal. Two holes are made as inlet and outlet on the pump for the flow of liquid metal coolant. The entrance to fill the liquid metal is sealed with plastic hose clamps and the other parts are metal and welded to avoid leakage. Clearly, the driving force for the flow of liquid metal depends on the size of the channels. For a conceptual experimental study, the inner diameter of the tube has been chosen as 6 mm in our test. The distance between the two permanent magnets made of BFeNb is 2.5 mm and the dimension of each magnet plate is 20 mm × 20 mm × 6 mm, respectively. Two electrodes with diameter 2.3 mm and insulation layers were used to connect between the TEG and the MFD pump. Further, a yoke with thickness of 5 mm was used to seal all the parts together. Using the present design, the liquid metal running between the two permanent magnets can easily be driven by the Ampere force when the electric current was generated.

3. Results and discussion

Throughout the whole procedure, the environmental temperature was measured as around 21.6 °C. In the experiment, the temperatures of chip surface, hot and cold sides of TEGs, and cold section of the loop are measured by multiple T-type thermocouples, respectively. To investigate the energy the MFD consumes, several parameters including voltage and electric current of TEG are also monitored. At the beginning of the test, an aluminium block (i.e. 8 in figure 1) serving as the simulating chip was heated. When a thermal steady state was reached, we switched on the electrodes connecting the MFD pumps and the TEG. Then the temperature of the chip surface will dramatically drop as reflected in figure 4. Meanwhile, the temperatures at the hot and cold sides of the thermoelectric device follow the same trend. The liquid metal coolant absorbs the heat and then flows to the cold section of the loop which results in a temperature increase there. Experiments found that the larger the temperature difference between the hot and the cold sides of the TEG, the bigger the current that can be generated and therefore a stronger driving force will be exploited. In the present chip cooling device, no additional energy other than the waste heat was consumed. This is rather important for saving energy in a wide variety of situations especially for those portable electronic devices such as the notebook computer. Here, the waste heat has been successfully implemented as a ‘useful’ power to drive the liquid metal flow which then draws heat away to the far end surface of the heat exchanger. According to the measurement, the MFD pump as developed in this study employs a magnetic flux density of about 1 T, and its typical power consumption rate ranges from 10 to 100 mW.

The major shortcoming of the TEG lies in its low efficiency, less than 8%. In the near future, it is very possible for such performance to be improved. Even for the TEG with a low efficiency, the electric current it yields has already been strong enough to drive the liquid metal loop, whose temperature dropped dramatically from the highest point within a very short time. One must pay attention to the limitation that the TEG could only work well in a certain optimum temperature range. Once the temperature exceeds that limit, the TEG may not be in its good operational state.

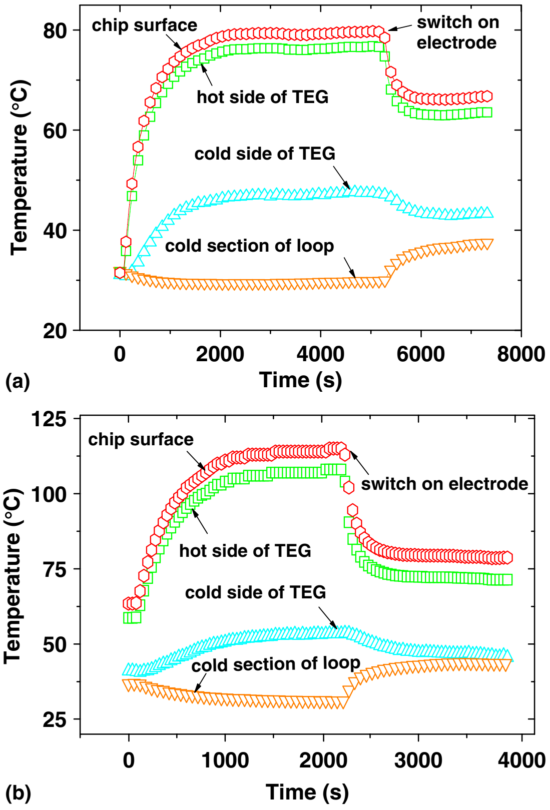


Figure 4. The temperature of chip surface versus the time when the heat load is (*a*) 25 W and (*b*) 32 W, respectively.

The aim of this paper is to demonstrate the feasibility of self-driven liquid metal cooling loops. Presently, the output of the TEG driving cooling still cannot be regarded as good enough with a perfect performance. But the result promises a bright future for such endeavour. This can be seen through an evaluation of the experimental curves as given in figures 4(*a*) and (*b*), respectively. It indicated that, the higher the heat load, the much larger the temperature decrease that will be realized. For example, in figure 4(*a*), only about 15 °C of temperature decrease was obtained for the heat load of 25 W. However, for a little higher heat load of 32 W in figure 4(*b*), a much larger temperature decrease of 37 °C can be obtained. The effect of such improvement is rather evident. This reflects the potential value of using liquid metal cooling for the thermal management of a hot chip. And the TEG driven cooling loop is expected to be important for the safe running of an electric system. When the TEG works properly, the electric current is related to the temperature difference. According to the measurement in figure 5, one can see that the electric current of the TEG appears linear with the temperature difference across its two surfaces.

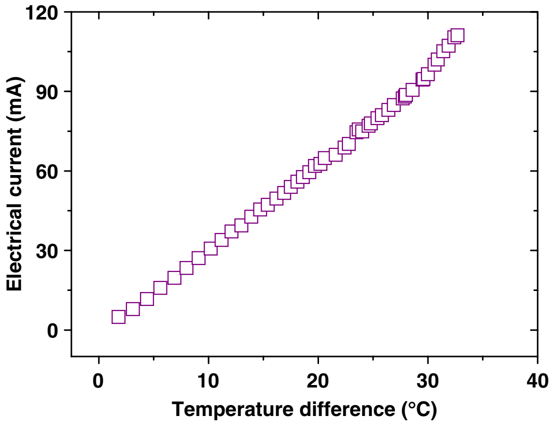


Figure 5. The electric current yielded by the TEG due to temperature difference.

Clearly, a larger temperature difference means much more generated electricity and thus easier driving of the MFD pump. In our working sample, we found that the liquid metal moved slightly even when the temperature difference was just over 10 °C, corresponding to the electric current 35 mA. As is well known, the electric current as well as the driving force becomes larger with the increase in temperature difference across the TEG. At the beginning of switching on the TEG, the temperature difference appears the largest which will generate the strongest driving force. The temperature difference, the electric current and the driving force will keep constant when a steady state is reached.

As figure 5 indicates, once the temperature difference is fixed for a specific TEG, the electric current will keep constant at the same time. If a stronger Ampere force was needed, one must guarantee a larger temperature difference across the TEG and generate a higher electric current. A direct way to realize this object is to enhance heat transfer and reduce the temperature of the cold surface of the TEG as much as possible. However, as an alternative, multiple TEGs can also be used to generate more electricity, for example by using structure as given in figure 6(*a*). To demonstrate this, a liquid gallium cooling device consisting of two stage TEGs (TEG 1 and TEG 2) was tested. The temperatures of chip surface and cold section are experimentally measured. Again at the beginning, a heat load of 25 W was applied to the simulating chip. When the thermal steady state was reached, the electrodes connecting the TEG and the MFD pump were switched on. Then it can be observed that the temperature of the chip surface drops dramatically and the temperature of the cold section is increased (figure 6(*b*)), indicating that the MFD pump has been successfully driven. Before the electrodes were switched on, the temperature of the chip surface adopting two TEGs is higher than that adopting only one TEG because a larger thermal resistance existed for the former case. After connecting the electrode, the chip surface adopting two TEGs has a larger temperature decrease and will finally stay at a lower temperature than that adopting only one TEG. This is because the two parallelly arranged TEGs produced a higher electric current. Therefore, the Ampere force they generate will be much stronger to drive the liquid metal and draw more heat away from the hot chip surface. From figure 6(*b*), one can find that the original steady state temperature of chip surface is 91.5 °C for two TEGs while it is 80.1 °C for one before the MFD pump works, and the steady state temperature of the simulating chip is 62.5 °C for the two TEGs case and 66.8 °C for one when the MFD pump works smoothly. The steady state temperature difference before and after the MFD pump was switched on is 29 °C and 13.3 °C, respectively. Clearly, an additional temperature decrease 4.3 °C (= 66.8 − 62.5 °C) has been realized when two TEGs were used. It should be pointed out here that in the experiments, simply contacting two TEGs together only produces a smaller temperature difference across them and consequently produces a very small electric current. A specific improvement on this was realized by sandwiching a highly conductive copper plate between the two TEGs. Due to heat release of the copper to the surrounding environment, a reasonable larger temperature difference between the end surfaces of the total two TEGs was realized, which will add to generation of a higher electric current than that using only one TEG. Such a strategy can be fully adopted in future optimizing a chip cooling device. Of course, to obtain a better cooling performance, other approaches can still be tried such as using multiple MFD pumps, more TEGs and combining them with different driving methods. Naturally, increase in liquid metal flowing velocity, adoption of low melting point liquid alloy with higher conductivity such as using nanoliquid metal fluid [20] will probably help in realizing a better cooling performance. All these practical considerations raise many interesting scientific and technical issues for solving in the near future.

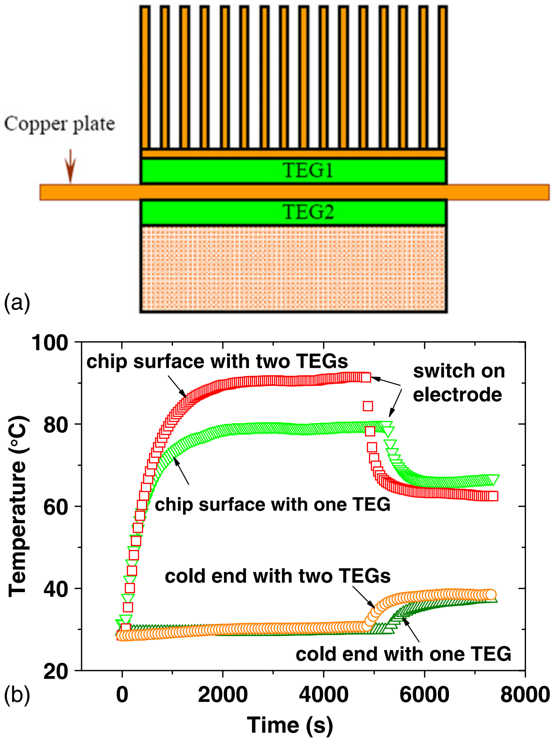


Figure 6. Enhancement of the TEG driven chip cooling device. (*a*) Schematic for the two TEGs used for generating a larger electric current. (*b*) The temperature response of chip surface and cold section using one and two TEG when the input power is 25 W.

In this study, the TE devices are adopted to generate electricity to drive the MFD pump by making full use of the waste heat coming from the chip. Compared with the power consumed by the computer, the currently available energy from the TEG is still not large enough, for example about 10–100 mW in the prototype. However, such energy has already been significant enough to drive the liquid metal loops to work smoothly. In this way, no net energy from the outside is requested. And no electric wires are needed to be connected with the power source, which will simplify the electronic component design. Although the energy supplied by a set of TEGs is not large enough, assembly of many such TEGs will provide rather strong energy which can have significant applications in a computer with distributed hot chips such as multi-core CPU.

For the latest computer design, reducing energy consumption as much as possible has become a major concern. If many MFD pumps are needed, the total energy consumption cannot be regarded as a small value. Adoption of the waste heat is therefore highly desirable. Recently, with the aim developing a computer with a low energy consumption rate, however, a high running speed, cooling on a hot point within an extremely confined space is becoming critically important. The method proposed in the paper is expected to play a useful role in such a situation.

It should be pointed out that the power generated by the TEG will not work when used to drive an ordinary liquid such as water or some other popular coolant. Owning to the unique electromagnetic drivable property of the liquid metal, such waste heat was successfully demonstrated as a useful source for driving the MFD pump. This may open a wide space for further investigation on the application of TEG in a variety of energy consumption ways. Further, one can observe that when the power supply is abruptly shut off, the liquid metal loop still keeps circulating. This is because the temperature difference there still exists and is capable of driving the TE devices, the MFD pump and thus the convective cooling by liquid metal. If the electricity comes directly from the computer power source, such a cooling system will stop working immediately due to unanticipated abrupt power off. In this sense, the TEG driven liquid-cooling system is a self-regulatory one, which can balance the heat generation and dissipation.

Clearly, introduction of TEG may also possibly introduce additional thermal resistance between the simulating chip and the surrounding air. But in the present cooling device, the surface area immediately above the heating module is not the main path to draw heat away due to its limited size. More heat is in fact transferred far away via the flow of the liquid metal and dissipates at the cold section of the loop.

Let us devote a little more effort to analyse the thermal resistance issues. As can be seen from figure 7(*b*), the introduction of TEG would increase the thermal resistance of the path 1. However, it does no harm to the thermal resistance of the path 2. In figure 7, $R_{\text{interface}}$ represents the thermal resistance between the chip surface and bottom of heat sink, including the contact thermal resistance and the thermal resistance of interfacial materials, respectively. $R_{\text{heat sink } i}$ $(i = 1, 2, 3)$ is the thermal resistance of the heat sink by conduction and the thermal resistance between the heat sink and air by convection. R_{TEG} is the thermal resistance due to introduction of TEG and R_{LML} is that due to introduction of liquid metal loops. T_{chip} and T_{f} are the temperatures of chip surface and environment, respectively. The heat sink 2 is mounted at the cold surface of TEG to guarantee the temperature difference and therefore generate the electric current which the MFD pump needs. In fact, the heat sink 2 can be replaced by other approaches. For example, the cold side of the TEG can be contacted to the inner wall of a laptop, which could also serve as a good heat sink. As for the simplest way, the natural convection around the cold side of TEG sometimes will also work well to reduce temperature at this surface.

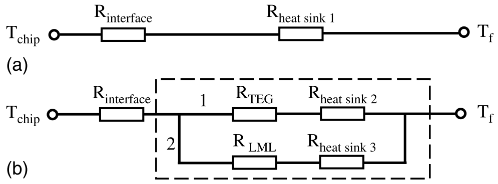


Figure 7. Comparison between thermal resistance of common heat transfer methods (*a*) and that of the hot chip with liquid metal loops driven by TEG (*b*).

The whole thermal resistance between the chip and the atmosphere can be described as

$$R = R_{\text{interface}} + R^{*}, \tag{1}$$

where R^{*} represents the effective thermal resistance as depicted by the dashed line in figure 7(*b*) and

$$R^{*} = \frac{(R_{\text{TEG}} + R_{\text{heat sink 2}})(R_{\text{LML}} + R_{\text{heat sink 3}})}{R_{\text{TEG}} + R_{\text{heat sink 2}} + R_{\text{LML}} + R_{\text{heat sink 3}}}. \tag{2}$$

One would wonder whether the introduction of TEG will make the heat transfer worse. To resolve this question, we can compare R^{*} with $R_{\text{heat sink 1}}$ as follows:

$$R^{*} - R_{\text{heat sink 1}} = \frac{(R_{\text{TEG}} + R_{\text{heat sink 2}})(R_{\text{LML}} + R_{\text{heat sink 3}})}{R_{\text{TEG}} + R_{\text{heat sink 2}} + R_{\text{LML}} + R_{\text{heat sink 3}}} - R_{\text{heat sink 1}}. \tag{3}$$

For simplicity, one can assume

$$R_{\text{heat sink 1}} = R_{\text{heat sink 2}} = R_{\text{heat sink 3}} = R_0. \tag{4}$$

Considering R_{LML} is much smaller than R_0, one can ignore R_{LML} in the following:

$$R^{*} - R_{\text{heat sink 1}} = \frac{(R_{\text{TEG}} + R_0)R_0}{R_{\text{TEG}} + 2R_0} - R_0 = -\frac{R_0^2}{R_{\text{TEG}} + 2R_0} < 0. \tag{5}$$

Then one gets

$$R^{*} < R_{\text{heat sink 1}}. \tag{6}$$

Therefore, the introduction of TEG will not make the heat transfer worsen compared with the commonly used heat dissipation method. In contrast, it will help in reducing the whole thermal resistance between the chip surface and the environment. In fact, in a real application of the liquid metal cooling, most of the heat is transferred through the path 2. This is different from the air cooling method, as commonly used in current computer industry.

For some CPUs such as in a laptop, there is no longer enough space for adding a heat sink in the normal direction of the chip surface. However, it is no problem to mount a TEG plate. For such a situation, heat will have to be transported to the far end and then released there. In this sense, a little more thermal resistance increased by the TEG will cause no evident barrier to the heat transfer. For future design, the large enough substrate surface of a laptop can serve as the heat transfer area. In this way, introduction of TEG will guarantee the working of such a carefully designed liquid metal cooling system, embedded in the block space of a laptop. Overall, the TEG realizes a self-drivable cooling device which would be a plausible merit in future thermal management system. Such self-supporting cooling method is especially useful for computers requesting extremely low total energy consumption.

In this paper, we have also tried to estimate the mean velocity of the liquid metal for a heat transfer analysis. This does appear to be an important however tough issue. For this purpose, we estimated the mean velocity with a peristaltic pump. We additionally chose another rubber tube of the same inner diameter as that used in the above test. To estimate the mean velocity, we made and compared the two cooling loops, in which one is driven by MFD pump, another by peristaltic pump. Regulating the running speed of the peristaltic pump, when the same temperatures on the simulating chip surface are obtained, one can regard that the two cooling loop systems have realized the same mean velocity for the liquid metal flow running inside. The mean velocity of liquid metal driven by peristaltic pump is easy to obtain. In this way, we can approximately estimate the mean velocity of the liquid metal driven by MFD pump.

In some research such as Miner and Ghoshal's work, they have shown that the heat transfer coefficient of liquid metal impingement is about $20 \times 10^4\,\mathrm{W\,m^{-2}\,K^{-1}}$. The heat transfer coefficient of the liquid metal is a function of dimensionless Re and Pr, and can be expressed as the Sleicher–Rouse equation [21] for a uniform heat flux, i.e. $Nu_\mathrm{d} = 6.3 + 0.0167\,Re_\mathrm{d}^{0.85}Pr^{0.93}$ when the cross section is circular. In our test, the mean velocity of liquid metal is obtained as about $10.2\,\mathrm{cm\,s^{-1}}$ when the electric current is 0.1 A. We can thus obtain the Re number as 1974 using the expression $Re = ud/\upsilon$. Given the Prandtl number of gallium as 0.021, one can estimate the mean Nusselt number approximately as 6.6. The convective heat transfer coefficient can thus be predicted as $3.16 \times 10^4\,\mathrm{W\,m^{-2}\,K^{-1}}$. It should be pointed out that, strictly speaking, the Sleicher–Rouse equation corresponds to turbulent flow. For a pipe flow, the critical Re number of the transition is around 2100. Considering that there is currently a strong lack of experimental data on liquid metal and the Re number as estimated in the present study is 1974, which is close to the critical Re number, we choose to the use Sleicher–Rouse equation for an approximate evaluation of the Nu number.

Here, the convective heat transfer coefficient is less than that obtained from Miner and Ghoshal's work [1, 4]. The discrepancy between these two researches comes from many aspects such as different flow condition, device size and configuration and the driving style and capability. A major factor is because a liquid jet impingement was adopted in their work while only a normal convective flow was tested in the present paper. Clearly, the liquid jet impingement generally produces an extremely high heat transfer coefficient due to the liquid having a much higher flow rate. A detailed evaluation of various aspects of using liquid metal for enhanced heat transfer requests additional work in the near future. Such experiments should be performed based on designing a standard heat transfer situation.

As is known to all, the second law of thermodynamics states that the Carnot efficiency is the maximum one can get when heat is converted into electric energy. There is no exception to the law. If taking the temperature values on the hot side and cold side of the TEG, respectively, one can write out the theoretical maximum efficiency as

$$\eta = 1 - \frac{273.15 + T_\text{cold side}}{273.15 + T_\text{hot side}}. \tag{7}$$

In figure 4(*a*), when the steady state is reached, the temperature at cold side of the TEG, $T_\text{cold side}$, can be read out as 43 °C and that of the hot side, $T_\text{hot side}$, 62.5 °C. Therefore, the theoretical maximum efficiency, namely, the Carnot efficiency can be calculated as 5.8%. Hence the TEG power will always be a minor fraction of the power consumed by the chip. This is a fact. In our study, according to the measurement, the MFD pump as developed in this study employs a magnetic flux density of about 1 T, and its typical power consumption rate ranges from 10 to 100 mW. In figure 3(*a*), for the power input being 25 W, even if 10% of the whole heat is dissipated through TEG, namely, 2.5 W, the real efficiency is 0.4–4%, smaller than theoretical maximum efficiency, which agrees well with the second law of thermodynamics.

Comparing the driving methods using the power of the normal electric supply, the advantage of the new strategy lies in that: (1) the heat-driven liquid metal loop is self-powered, self-supported and self-regulated; (2) after the power is shut off, the surface of the hot chip can still keep dissipating heat to the far end and therefore avoid potential damage. The application of TEG as a 'green energy' [22] in fact suggests another valuable choice to power electronics devices in the near future. We just found that some researchers, such as Yazawa *et al* [23], have successfully demonstrated driving an air cooling fan using electricity generated from the heat of the microprocessor. But no effort was made until now to drive the liquid cooling using energy from the waste heat of the computer chip. In addition, TEGs are also widely used in space applications and satellites [24]. In that case, saving energy appears extremely necessary. The present efforts as made in the paper are worthwhile for such applications in the near future.

Finally, one important issue in using liquid metal is the problem of liquid embrittlement, which may cause the failure of the cooling system. Therefore, it is of vital importance to select the appropriate tube material. Some ductile materials such as $\mathrm{Al_{solid}}$–$\mathrm{Ga_{liquid}}$ system can become brittle [25]. Considering this point, copper channels have been adopted in the present research. By such a design, no liquid metal embrittlement was found for the copper over a long time (over one year's) observation.

4. Conclusions

In summary, a heat-driven liquid metal cooling device without moving solid components was demonstrated for the first time in chip cooling. The whole liquid flow loop was driven by a MFD pump powered by a one-stage thermoelectric device directly using waste heat from the hot chip. No other additional energy was consumed and the device is completely self-powered. Experiments show that the temperature of the chip surface could drop dramatically from 91.5 to 62.5 °C without the aid of a fan when the heat load of the simulating hot chip is 25 W. Therefore, the chip cooling device is in a silent state during its running. For generating a stronger driving current to power the MFD pump, two parallelly positioned thermoelectric devices sandwiching a highly conductive plate can be adopted and its practical design was successfully tested. Although the current output of a TEG driving cooling device still cannot be regarded as strong enough, the results show the very promising future of the new method. With future progress in TEG technology, MFD pumps, better liquid metal coolant such as nanoliquid metal [20] and more efficient driving strategies, this self-supporting chip cooling method will find significant applications in a wide variety of engineering fields especially those related to the microelectronics industry.

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