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Hybrid liquid metal–water cooling system for heat dissipation of high power density microdevices

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Abstract The recent decades have witnessed a remarkable advancement of very large scale integrated circuits (VLSI) and electronic equipments in micro-electronic industry. Meanwhile, the ever increasing power density of microdevices leads to the tough issue that thermal management becomes rather hard to solve. Conventional water cooling is widely used, but the convective coefficient is not high enough. Liquid metal owns much higher convective coefficient and has been identified as an effective coolant recently, but the high cost greatly precludes its large scale utilization. In this paper, a hybrid liquid metal–water cooling system which combines the advantages of both water and liquid metal cooling was proposed and demonstrated. By utilizing a liquid metal "heat spreader" in front of the water cooling module, this system not only owns more excellent cooling capability than that based on water alone, but also has much lower initial cost compared with absolute liquid metal cooling system. A series of experiments under different operation conditions have been performed to evaluate the cooling performance of this hybrid system. The compared results with absolute water cooling and liquid metal cooling system showed that the cooling capability of the new system is competitive with absolute liquid metal cooling, but the initial cost could be much lower. The theoretical thermal resistance model and economic feasibility also have been analyzed and discussed, which shows that the hybrid liquid metal–water cooling system is quite feasible and useful.

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List of symbols

R	Thermal resistance (°C/W)
T	Temperature (°C)
Q	Heat power (W)
h	Convective heat transfer coefficient (W/m^2 °C)
A	Heat dissipation area (m^2)
η	Fin efficiency
ΔT	Temperature difference (°C)

Subscript

LM	Liquid metal

1 Introduction

The ever increasing power density of electronic component and more compact package technology lead to the necessity for more innovative cooling designs. Meanwhile, the recent developing high-performance cooling technology must be able to couple with the heat flux of 100–1,000 W/cm^2 for the increasing emergence of highly integrated computer chips, high brightness LEDs, and large power solid-state lasers, etc. [1–3].

Conventional cooling methods can be classified into many types, such as fan heat sink, heat pipe, vapor compression, micro channel, and jet impingement, etc. [4–7]. The coolants are also abundant and various, for instance air, water, fluorocarbon, and ethanol, even the nanofluids have been widely studied [8–10]. Nevertheless, up to now, the most effective and practical way for heat dissipation of high power density devices still belongs to water based cooling due to its high heat capacity and the lowest cost. The only disadvantage of water lies in its low thermal conductivity which would greatly reduce its convective heat transfer coefficient. From this point of view, liquid metal with low melting point was proposed to be used as a highly efficient coolant for thermal management of high power density devices [11]. The convective coefficient of liquid metal is much higher than that of water and can be over 1 × 10^5 W/m^2 °C due to its high thermal conductivity [12]. What is more, liquid metal can be driven by an electromagnetic pump with no moving parts. Therefore, higher driving efficiency and absolute silent operation characteristic can be achieved. However, the recent alternative liquid metals are rather expensive, and in conventional system large amount of liquid metal would be wasted in the remote radiator since the radiator has large coolant charge but liquid convection only plays a small role in the total radiator thermal resistance [13, 14]. Therefore, reducing the coolant charge and the cost is of great importance for liquid metal cooling system.

Comprehensively considering the high convective coefficient of liquid metal and the low cost characteristic of water, we proposed a practical hybrid liquid metal–water cooling system. That means utilizing a liquid metal "heat spreader" in front of the water cooling module to fabricate a two stage compound cooling system. In this way, the system not only has high convective heat transfer coefficient in the cold plate, but also the cost could be acceptable. In fact, the concept of "heat spreader" has already been proposed several years ago [15], but "liquid metal heat spreader" with very high convective coefficient has not been reported in any literature as far as the authors know. In the present work, we have experimentally investigated the heat transfer behavior and analyzed the economic feasibility of this hybrid liquid metal–water cooling system. Some important results and experimental data are presented and discussed.

2 Experimental set up

2.1 Materials

Up till now, the liquid metals with melting point below room temperature are rare, mainly include mercury, NaK alloy, gallium, and gallium based alloy, etc. Comprehensively considering the melting point, toxicity, safety, cost and other influencing factors, gallium–indium and gallium–indium–tin alloys are the most suitable coolant for liquid metal cooling system. In this work, $GaIn_{20}$ (Ga 80%, In 20%) which has the melting point about 16°C was adopted to be used in the liquid metal module. It has been confected through melting method with pure gallium and indium which are commercially available from Asian Light Economic Trade Co., Ltd. Due to the undercooling effect, the $GaIn_{20}$ could stay in liquid state even under 10°C. The detailed thermal physical properties, including thermal conductivity and heat capacity have been measured in the previous experiments. And the comparison result with water is shown in Table 1 [16]. It can be seen that the thermal conductivity of liquid metal is about 40 times higher than that of water, which is the main reason for liquid metal to be an excellent coolant. Except for the superior thermal physical properties, $GaIn_{20}$ is non-toxic, not easy to leak, with low viscosity, high thermal and chemical stability, so it is very suitable to be an excellent liquid metal coolant in this experiment.

Table 1 Thermal physical properties of liquid metal and water [16]

	Ga	$GaIn_{20}$	Water
Melting point (°C)	29.8	16	0
Density (kg/m^3)	6,093[a]	6,335[c]	998.2[c]
Thermal conductivity (W/(m K))	29.28[b]	26.58[c]	0.599[c]
Heat capacity (J/(kg K))	409.9[b]	403.5[c]	4,183[c]

[a] 33.28°C

[b] 29.8°C

[c] 20°C

2.2 Test platform

The whole experimental platform consists of a first stage liquid metal "heat spreader" and a second stage water circulation system. As can be seen from Fig. 1, firstly, liquid metal flows through the small area high-density heat source and carries the heat away efficiently based on its high convection capability. Then, the heated liquid metal dissipates the heat directly to the water in the middle heat exchanger with large area, where the "heat spreader" function can be achieved. Lastly, all the heat in the water circulation module would flow towards the remote radiator where the heat would be released into the ambient air. Although the heat source has very limited dissipation area, the use of liquid metal could achieve high convection performance since it has very high convection coefficient. As to the heat exchanger, although water convection is involved, the heat exchange area is large enough therefore the convection performance is also excellent. In this way, the total liquid convection thermal resistance of the whole system is very small which guarantees its high cooling performance.

The heat source in the experiment is composed of a heating rod and an aluminum block, with a heat dissipation area of 3 × 3 cm^2 and heating power of 45 W. Therefore, a heat flux of 5 W/cm^2 could be generated on the top surface of the heating block while the other surfaces were thermally isolated. Because the dissipation area of high power heat source is rather limited and disturbance enhanced heat transfer structures are not easy to be implemented in most

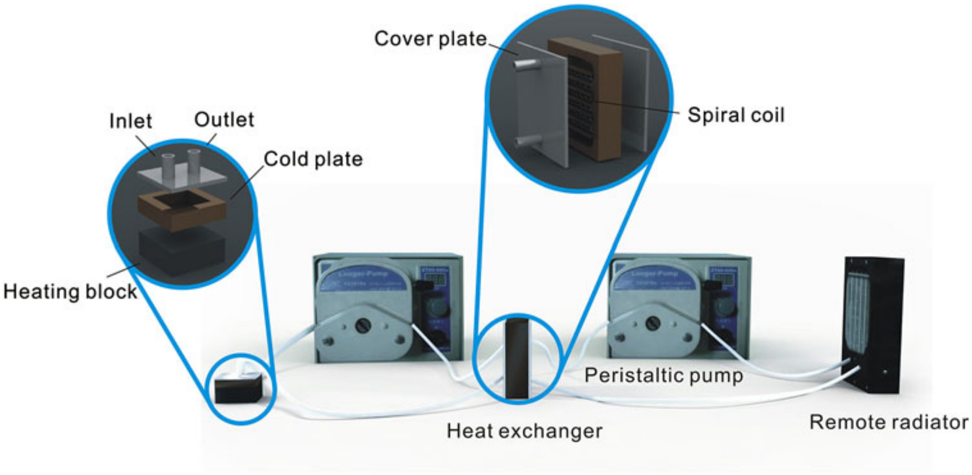

Fig. 1 Schematic of experimental platform

cases, a common injection structure with direct heat dissipation area of 2×2 cm^2 was adopted in the cold plate. The heat exchanger was designed with a "Z" type flow channel and had a heat exchange area of 59.87 cm^2. Meanwhile, spiral coil was implemented to enhance the heat exchange of liquid metal and water since the heat transfer space was adequate. Both the cold plate and heat exchanger adopted T2 copper alloy as the substrate so as to reduce the conductive thermal resistance. And stainless steel cover plate and silicone ring were used to seal each module. In order to achieve higher heat exchange efficiency, the counter current flow of liquid metal and water was employed in the heat exchanger. Though electromagnetic pump is more preferred for practical liquid metal "heat spreader", peristaltic pump ZT60-600a available from Baoding Longer Precision Co., Ltd., China was adopted to drive the liquid metal and water since the result comparison was more convenient to conduct. The remote radiator was purchased from Thermaltake Inc., China, with a fan-fin structure and heat dissipation area of 0.38 m^2. A low power DC fan with the power of 5.76 W was utilized to effectively dissipate the heat to the ambient air.

The heating block, cold plate, and heat exchanger were wrapped with insulated cotton cloth so as to reduce the system heat leak. Meanwhile, a thin layer of thermal grease was applied to reduce the contact thermal resistance between the heating block and the cold plate. Except that, nine thermal couples were used to measure the real time temperature of cold plate substrate, cold plate inlet and outlet, heat exchanger substrate, heat exchanger inlet and outlet, and ambient temperature, respectively. And all the temperature dates were obtained and displayed using Agilent 34970A with the time interval of 2 s. The absolute liquid metal and water cooling system in this paper both refer to the liquid cooling system only comprised of the cold plate and the remote radiator with no heat exchanger.

In order to precisely evaluate the electric power provided to the heating block, the input voltage and current were measured and recorded with a digital multimeter MY-65 from MASTECH Co., Ltd, China. It has been found that the accuracy of the calculated electric power was estimated to be about ±5%. Because the heating block, cold plate, and heat exchanger were wrapped with insulating cotton cloth, the heat loss would be very small and can be calculated based on the insulating layer temperature, nature convective coefficient, and the heat exchange area. It can be estimated that the heat loss would be <3 W, which thus produced little effect on experimental result. Finally, all the temperatures in the experiment were measured with an Agilent 34970A, which had been carefully calibrated and tested. Therefore, the accuracy of temperature is about ±0.5°C, which appears very reasonable for the experimental uncertainty.

3 Experimental results

3.1 Cooling capability comparison with absolute water cooling

When compared with absolute water cooling, hybrid liquid metal–water cooling system owns a first stage liquid metal "heat spreader". Therefore, the cooling performance could be effectively improved. Because the contact thermal resistance between heat source and cold plate mainly depends on the thermal grease properties and has no relation with liquid cooling capability, the temperature of cold plate substrate rather than the heat source was used to evaluate the cooling capability of the liquid cooling system. Figure 2 shows the cold plate substrate temperature of absolute water cooling and hybrid liquid metal–water cooling when a heat load of 45 W is applied, and the volume flow of both liquid metal and water are 5 ml/s.

As can be seen from Fig. 2, hybrid liquid metal–water cooling system could have more excellent cooling

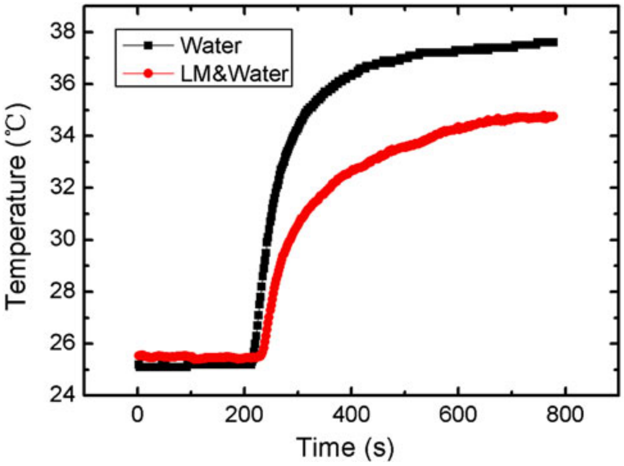

Fig. 2 Cold plate substrate temperature of absolute water cooling and hybrid liquid metal–water cooling. *LM* liquid metal

capability than absolute water cooling system, which is mainly due to the much higher convective heat transfer coefficient when using liquid metal to replace water in the cold plate. Although the hybrid liquid metal–water cooling system has the additional heat exchanger thermal resistance, the decreased convective thermal resistance could be far beyond the additional heat exchanger thermal resistance. Therefore, the total system thermal resistance could be effectively reduced. As to an absolute water cooling system, increasing the coolant flow is the most direct and effective way to improve the cooling performance. Figure 3 shows the cold plate substrate temperature of absolute water cooling system under different volume flow.

It can be seen from Fig. 3 that increasing the water flow can reduce the cold plate substrate temperature to some extent. But with the increase of the volume flow, the temperature decrease would gradually slow down, especially when the water flow increases from 5 to 10.8 ml/s in Fig. 3. Therefore, absolute water cooling has its limitation, and it is difficult to further decrease the system temperature by simply increasing the volume flow. Meanwhile, with the increase of volume flow, the flow resistance and the required pump power would increase significantly, which would have very bad effect on the system stability. However, if considering from the coolant perspective and applying a liquid metal "heat spreader" in front of the water module, the temperature could decrease by 3°C with the constant volume flow of 5 ml/s, while in the absolute water cooling system the temperature decrease is only 1.4°C when increasing the water flow from 5 to 10.8 ml/s. Therefore, the improved cooling performance by using liquid metal "heat spreader" is rather evident.

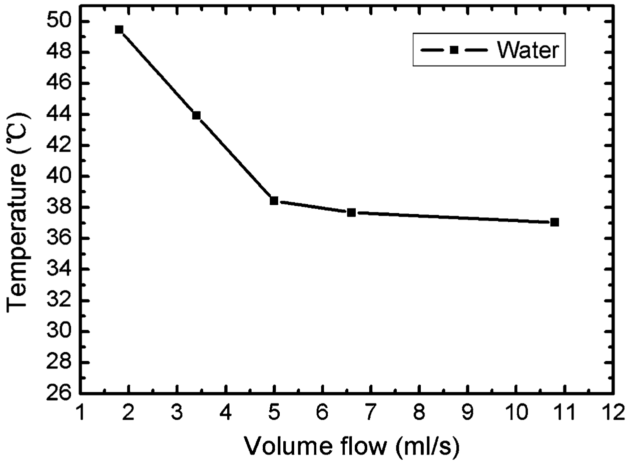

Fig. 3 Cold plate substrate temperature of absolute water cooling system under different volume flow

3.2 Thermal resistance evaluation under different water volume flow

Quantitative description of the thermal resistance of each component is of great importance to evaluate the cooling performance of a liquid cooling system. Absolute water cooling has relatively simple structure, and the thermal resistances from cold plate to the ambient air could be defined as:

$$R_{coldPlate} = (T_{coldPlate} - \bar{T}_f)/Q \qquad (1)$$

$$R_{radiator} = (\bar{T}_f - T_{ambient})/Q \qquad (2)$$

where, $R_{coldPlate}$ and $R_{radiator}$ are thermal resistances of the cold plate and radiator, respectively. $T_{coldPlate}$ is the temperature of cold plate substrate, $\bar{T}_f$ is the mean coolant temperature (here it means the mean temperature of fluid inlet and outlet), $T_{ambient}$ is the ambient temperature, and Q is the dissipated heat power. As to the hybrid liquid metal–water cooling system, because of the additional heat exchanger, the system thermal resistance must include the convective thermal resistances on the two sides of heat exchanger, which can be defined as:

$$R_{heatExchanger\_LM} = (\bar{T}_{LM} - T_{heatExchanger})/Q \qquad (3)$$

$$R_{heatExchanger\_water} = (T_{heatExchanger} - \bar{T}_{water})/Q \qquad (4)$$

where, $R_{heatExchanger\_LM}$ and $R_{heatExchanger\_water}$ are the convective thermal resistances on the liquid metal side and the water side of heat exchanger. $\bar{T}_{LM}$ is the mean liquid metal temperature in the heat exchanger, $T_{heatExchanger}$ is the temperature of heat exchanger substrate, and $\bar{T}_{water}$ is the mean water temperature in the heat exchanger. Figures 4 and 5 show the thermal resistances distribution of absolute water cooling and hybrid liquid metal–water cooling system under different water flow. The heat power is 45 W and the volume flow of liquid metal is 5 ml/s.

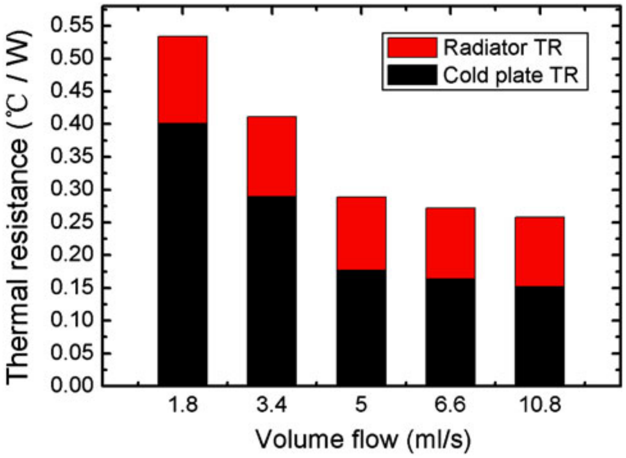

Fig. 4 Thermal resistances distribution of absolute water cooling system. *TR* thermal resistance

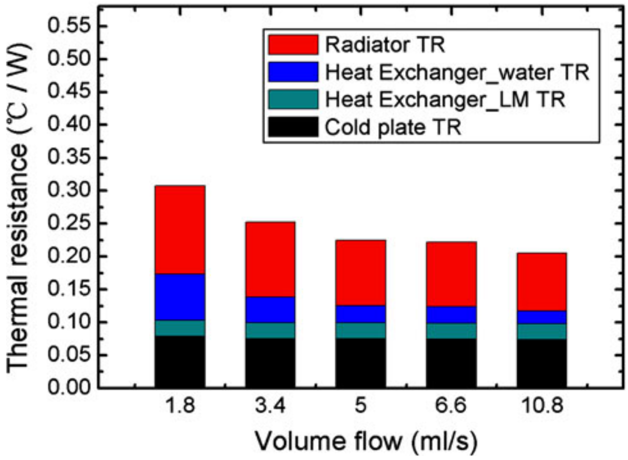

Fig. 5 Thermal resistances distribution of hybrid liquid metal–water cooling system. *TR* thermal resistance

As can be seen from Figs. 4 and 5, convective thermal resistance in the cold plate is the bottleneck of the absolute water cooling system, which is mainly due to the very low thermal conductivity of water. However, as to the hybrid liquid metal–water cooling system, the convective thermal resistance in the cold plate is much lower, even when the water flow is 10.8 ml/s and liquid metal flow keeps 5 ml/s. Meanwhile, it can be found that the thermal resistances on both sides of the heat exchanger only play a small role in the total system thermal resistance. That is mainly because of the large heat transfer area of heat exchanger and the enhanced heat transfer of spiral coil disturbance. Therefore, by applying the liquid metal "heat spreader" in front of the water cooling module, the cooling performance of the whole system could be effectively improved. The decreased thermal resistance in the cold plate far exceeds the additional heat exchanger thermal resistance, so the total thermal resistance can be reduced.

Separately analyzing the thermal resistance of remote radiator, it can be found that though the liquid convective coefficient in the tube would improve with the increase of water flow, the radiator thermal resistance only has very little reduction (the fluid in the radiator of both Figs. 4, 5 are water. The radiator thermal resistance in Fig. 5 is smaller, that is mainly because of the longer heat transfer distance and the greater heat leak of hybrid liquid metal–water cooling). Therefore, it can be concluded that the water convective thermal resistance only plays a small role in the remote radiator thermal resistance, and the total thermal resistance mainly depends on the convective thermal resistance of ambient air. In that case, though using liquid metal in the remote radiator could greatly improve the liquid convection, the overall thermal resistance of radiator would only change a little. Meanwhile, because of the poor convective heat transfer capability of the air side, the heat dissipated to the ambient air per unit length would be very small. Therefore, the liquid metal flow channel is long and the coolant charge is high, which eventually leads to the high cost of absolute liquid metal cooling system. All in all, using liquid metal in the remote radiator has little effect on improving system cooling capability, but results in high cost of the system. And the hybrid liquid metal–water cooling could not only have close cooling capability compared with absolute liquid metal cooling but also has much lower system cost.

3.3 "Heat spreader" performance evaluation under different liquid metal volume flow

The "heat spreader" realizes the function of expanding the high heat flux from the restricted heat source to a much larger heat dissipation surface. When the "heat spreader" structural configuration is determined, the cooling performance would mainly depend on the volume flow of liquid metal. Figure 6 shows the temperature of cold plate substrate and the liquid metal inlet and outlet under different volume flow in a liquid metal "heat spreader".

As can be seen from Fig. 6, when the liquid metal volume flow is low, the cold plate and the fluid outlet would get very high temperature rise, which means the cooling performance of the liquid metal "heat spreader" has been deteriorated. Two main reasons can explain this phenomenon: the first, lower velocity would reduce the convective heat transfer coefficient of liquid metal; and the second, liquid metal owns high thermal conductivity, but the heat capacity is low, so it is easy to get a temperature rise which results in the high temperature of cold plate. As to the first reason, according to the classical heat transfer theory, the Nusselt number for laminar flow in a circular tube with constant heat flux boundary is 4.36. Further considering the injection structure and the entrance region effect, the calculated convective heat transfer coefficient of

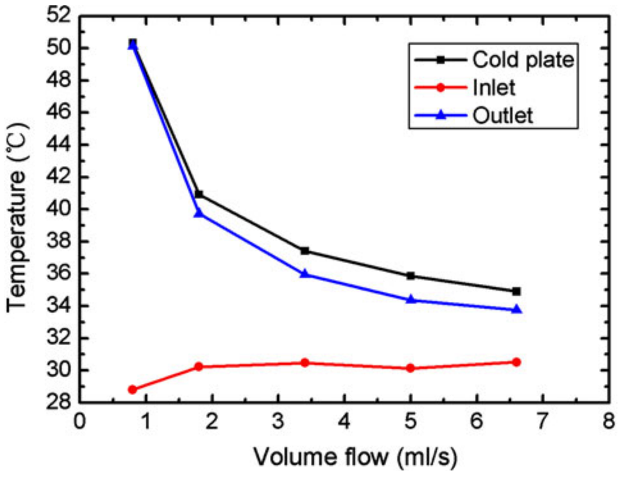

Fig. 6 Temperature of cold plate substrate and the liquid metal inlet and outlet under different volume flow

liquid metal in the cold plate is also very high even under very low volume flow. Therefore, the first reason has little effect on this phenomenon. As to the second reason, because liquid metal has high thermal conductivity and low heat capacity, it is easy to get a temperature rise and the liquid would almost reach the wall temperature after flowing a short distance. Therefore, in the posterior section of the flow channel, though the convective coefficient is high, the heat transferred is not high since the temperature difference between the wall and the liquid is small. Therefore, as to the practical liquid metal "heat spreader" design, appropriate volume flow is of great importance to achieve the high cooling performance of the whole system.

4 Discussion

4.1 Thermal resistance model analysis

As to a hybrid liquid metal–water cooling system, the heat would first be dissipated to the liquid metal, then transferred from the liquid metal to the water, and finally released to the ambient air. Thus, the convective heat transfer plays the most important role in these heat transfer processes. According to the classical convection heat transfer theory:

$$Q = hA\Delta T \tag{5}$$

Some typical convective heat transfer coefficients in the cold plate and remote radiator when the volume flow of both liquid metal and water are 5 ml/s can be calculated and given as follows: in the cold plate, the liquid metal convective coefficient is about 17,600 W/m^2 °C while the water is about 7,090 W/m^2 °C; In the remote radiator, the air side convective heat transfer coefficient of fins is about 25 W/m^2 °C. If converting the fin area into the tube wall area and considering the fin efficiency, the equivalent converted convective coefficient of air (defined in Eq. 14) is about 278 W/m^2 °C, which is much lower than the liquid convective coefficient.

Considering the thermal resistance definition of Eqs. 1–4, each thermal resistance in the hybrid liquid metal–water cooling system can be calculated as:

$$\begin{aligned} R_{system\_LM\,and\,water} = {} & R_{coldPlate\_LM} + R_{heatExchanger\_LM} \\ & + R_{heatExchanger\_water} + R_{radiator\_water} \end{aligned} \tag{6}$$

$$R_{coldPlate\_LM} = 1/(h_{LM\_coldPlate}A_{coldPlate}) \tag{7}$$

$$R_{heatExchanger\_LM} = 1/(h_{LM\_heatExchanger}A_{LM\_heatExchanger}) \tag{8}$$

$$R_{heatExchanger\_water} = 1/(h_{water\_heatExchanger}A_{water\_heatExchanger}) \tag{9}$$

$$\begin{aligned} R_{radiator\_water} = {} & 1/(h_{water\_radiator}A_{water\_radiator}) \\ & + 1/(h_{air\_radiator}A_{air\_radiator}). \end{aligned} \tag{10}$$

As to the absolute water cooling system, one has:

$$R_{system\_water} = R_{coldPlate\_water} + R_{radiator\_water} \tag{11}$$

$$R_{coldPlate\_water} = 1/(h_{water\_coldPlate}A_{coldPlate}) \tag{12}$$

In Eqs. 6–12, R, h, A are thermal resistance, convective heat transfer coefficient, and heat dissipation area, respectively. The footnote means the specific component and the convective fluid. The remote radiator thermal resistances $R_{radiator\_water}$ of these two systems are the same due to the same flow condition and convective fluid. Known from Eqs. 6–12, the liquid metal convective coefficient is much higher than that of water ($h_{LM} \gg h_{water}$), and the heat transfer area of heat exchanger is much larger than that of the cold plate ($A_{heatExchanger} \gg A_{coldPlate}$). Therefore, the total thermal resistance of cold plate and the heat exchanger in a liquid metal "heat spreader" would still be smaller than the thermal resistance of cold plate with water as coolant, which leads to a better cooling performance of hybrid liquid metal–water cooling system. When comparing hybrid liquid metal–water cooling with absolute liquid metal cooling system, the thermal resistances in the remote radiator are almost the same, since the liquid convection only plays a small role in the remote radiator heat dissipation. The main difference lies in the additional heat exchanger thermal resistance, which is also very small because of the large heat exchange area and the spiral coil disturbance. Therefore, the hybrid liquid metal–water cooling could only have very slightly decreased cooling performance compared with absolute liquid metal cooling system.

In fact, the heat flux in this experiment is not very high, which can only show the feasibility of liquid metal "heat spreader". The greatest advantage of liquid metal lies in its ultrahigh convective heat transfer coefficient. Therefore, the most suitable application field of liquid metal "heat spreader" is the extremely high heat flux dissipation area, such as the 1,000 W heating power within 1 cm^2. In that case, the convective thermal resistance in the cold plate would play the most important role in the system thermal resistance in a water cooling system. If the liquid metal "heat spreader" is applied, the convective thermal resistance of the cold plate would be greatly reduced. So the system cooling capability could be effectively improved. Meanwhile, the system cost is also acceptable for the small coolant charge. Based on the above analyses, a more suitable liquid metal "heat spreader" with injection structure in the cold plate and the mini/micro structure in the heat exchanger can be proposed. On the one hand, the liquid metal injection structure is easy to be implemented in small heat dissipation area, and the convective coefficient is very high (typically above 10^5 W/m^2 °C) which would lead to a high cooling performance. On the other hand, the mini/micro channel also has very high convective coefficient, and the thermal resistance on the liquid metal and water sides can be easily matched. Furthermore, the coolant charge of mini/micro channel is very small, so the cost of liquid metal "heat spreader" can be further reduced. However, the flow resistance would be higher and the driving capability of the electromagnetic pump should be improved. This part of work will be carried out in the near future.

4.2 Coolant charge and system cost analysis

Compared with conventional absolute liquid metal cooling system, the coolant charge of hybrid liquid metal–water cooling can be greatly reduced. In an absolute liquid metal cooling system, the remote radiator would dissipate the heat from the liquid metal to the tube wall, and then to the ambient air. Thus, the following equations would be satisfied.

$$Q/(h_{LM}A_{tube\_LM\ and\ air}) + Q/(h_{air}A_{tube\_LM\ and\ air}) = \Delta T_{LM\_air} \quad (13)$$

$$h_{air} = \frac{h_{air\_tube}A_{tube\_LM\ and\ air} + h_{air\_fin}A_{fin}\eta}{A_{tube\_LM\ and\ air}} \quad (14)$$

where, Q is the transferred heat power, h_{LM} is the convective coefficient of the liquid metal side, h_{air} is the equivalent converted convective coefficient of air side when converting the fin area into the tube wall area and considering the fin efficiency, h_{air_tube} is the tube wall convective coefficient of air side, h_{air_fin} is the convective coefficient of air cooled fins, $A_{tube\_LM\ and\ air}$ is the tube wall heat transfer area, A_{fin} is the fin heat transfer area, η is the fin efficiency, and ΔT_{LM_air} is the designed temperature difference of liquid metal and air in the remote radiator. Calculated from Eq. 13, the heat transfer area of liquid metal tube wall in the remote radiator can be expressed as:

$$A_{tube\_LM\ and\ air} = \frac{Q}{\Delta T_{LM\_air}}(1/h_{LM} + 1/h_{air}) \quad (15)$$

As to the hybrid liquid metal–water cooling system, the heat of liquid metal would be transferred to the water rather than air, so the following equation could be obtained:

$$Q/(h_{LM}A_{tube\_LM\ and\ water}) + Q/(h_{water}A_{tube\_LM\ and\ water}) = \Delta T_{LM\_water} \quad (16)$$

where, h_{water} is the convective coefficient of the water side, $A_{tube\_LM\ and\ water}$ is the heat transfer area of one side in the heat exchanger (in this experiment, the heat exchanger was designed with the same heat transfer area of liquid metal and water sides), ΔT_{LM_water} is the designed temperature difference of liquid metal and water in the heat exchanger. Similarly, the heat transfer area of liquid metal side in the heat exchanger can be calculated as:

$$A_{tube\_LM\ and\ water} = \frac{Q}{\Delta T_{LM\_water}}(1/h_{LM} + 1/h_{water}) \quad (17)$$

Comparing Eq. 15 with Eq. 17, because the convective coefficient of air is much lower than water, the heat transfer area of liquid metal to the air would be much larger. Therefore, under a certain structure configuration, the heat transfer space is larger and the coolant charge is much higher. In fact, as to the liquid metal to air heat transfer process in absolute liquid metal cooling, the heat would be very easy to be transferred from liquid metal to the tube wall, but very difficult from the tube wall to ambient air. Therefore, the dissipated heat per unit flow length is small, and the liquid metal charge mainly depends on the tube length rather than the section area. Even the mini/micro channel structure is adopted in the remote radiator in the absolute liquid metal cooling system, because the thermal resistance of the air side would be further increased and the thermal resistances on the liquid and air sides are more difficult to match, the flow length of liquid metal would be longer, which also leads to the large amount of liquid metal charge. Therefore, the mini/micro channel structure is more applicable in the heat exchanger of the hybrid liquid metal–water cooling system. Because the convective coefficient of liquid metal and water sides could match well more easily, and the thermal resistance of heat exchanger could be reduced a lot which guaranties more close cooling performance with absolute liquid metal cooling. Except that, the liquid metal charge could be further reduced which leads to a lower cost of the liquid metal "heat spreader".

In this experiment, compared with the absolute liquid metal cooing system, the liquid metal charge of hybrid liquid metal–water cooling system could be reduced from 44.79 to 11.75 ml (without regarding to the liquid metal in the collection pipes). Assuming the price of liquid metal is $400/kg, the coolant cost could be reduced from $113 to $30 compared with absolute liquid metal cooing system. Further considering the water pump and the heat exchanger would bring additional cost of $30, then the whole system cost is still only about one half of the absolute liquid metal cooling. Therefore, the low cost advantage of hybrid liquid metal–water cooling is rather evident.

5 Conclusions

Cooling capability and system cost are two most critical factors to determine whether a heat dissipation system could be large-scale utilized in industry. In this paper, a hybrid liquid metal–water cooling system which owns the advantages of both water and liquid metal cooling has been proposed. The experimental results showed that this hybrid system could have very close cooling performance compared with absolute liquid metal cooling. Therefore, it is very suitable and practical to deal with high heat flux requirements of micro devices. But appropriate volume flow design of liquid metal is very critical to achieve preferable high cooling performance. As to the cost issue, this hybrid liquid metal–water cooling could have only a half of the cost of absolute liquid metal cooling system. That is mainly because the liquid metal can dissipate heat to the water directly, so the heat transfer area and coolant charge could be greatly reduced. Finally, the mini/micro channels structure was suggested for the heat exchanger, so the system could have better cooling performance and lower coolant charge and cost.

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