The Way We Were and Are Going on Cooling High Power Processors in the Industries

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The purpose of this paper is to provide an overview of various practical cooling solutions including the use of heat pipes and vapor chambers for cooling high power processors in a confined space of personal computers (PCs). This paper discusses how to extend the air cooling capability and maximize its performance. Included in this paper are the design, data, photos, and discussion of various fan sink air cooling designs showing how the design changes can push the limit of the air cooling capability. In the main section of this paper, we present various innovative ideas of cooling solution that we are under the process developing for the cooling of next generation of high power processors. Finally, we would suggest what and which way we are going to develop next generation of high power cooling chips.

1. Introduction

After the introduction of Pentium^{TM} processor in 1993, the trend of the processor performance and power consumption have been increased significantly each year. For example, in 1993, the clock speed of processors used in personal computers (PCs) was in the range megahertz, but in the year 2000 and 2005 the clock speed reached approximately 1 GHz with power consumption 20 W and 3 GHz with power consumption 130 W. A heat dissipation has been increased but in contrast the size of die on the processor has been reduced or remained the same as a result of fine silicon circuit technology and thus the heat flux is critically high. The heat flux was about 10 ~ 15 W/cm^2 in the year 2000 and had reached 100 W/cm^2 in 2006.

Thermal management of electronic components is one of the key technologies for successful product launch. There are many cooling technologies available ranging from passive cooling to cryogenics. To name a few: fin heat sink with or without heat pipes with air blowing devices; liquid cooling single or two-phases heat transfer with a mechanical pump; thermoelectric cooler; refrigeration; direct liquid submersion cooling, and so on. Obviously, the choice of the cooling technology is dependent on factors such as heat flux, power dissipation, reliability, mobility, integration, maintenance, and cost. The technology that can deliver the required thermal performance with the least operation and maintenance cost is the winner.

For the current desktop and server processors, the heat dissipation, in general, exceeds 100 W and the heat flux could be more than 100 W/cm^2. Passive cooling is no longer appropriate to deliver the cooling requirement. Other technologies such as liquid cooling, thermoelectric cooling, and refrigeration can deliver the required thermal performance, and have been put into practical use for cooling of computers. However, these cooling options have not yet been widely used because of the integration complexity of the system, limited reliability life data, yet limited availability of high volume manufacturing capability, and especially the higher cost. The cooling technology that is most widely used in cooling for computers is air cooling, because this is a mature technology with the least operation and maintenance costs. The purpose of this paper is to provide insight into how to extend the air cooling capability and maximize its performance. This paper includes designs, data, and discussions of various fan sink air cooling designs showing how the design changed to push the limit of the air cooling capability. For example, heat sink designs to maximize heat transfer surface areas, fin efficiency, and air flow, and the use of heat pipes or vapor chambers to improve effective heat transfer by optimizing fan airflow performance.

The processor's die surface where the heat is generated is usually small, approximately 1 cm^2. Effective cooling should required least temperature gradient between the heat source and radiating components. The best-known devices for effective heat transfer with lowest thermal resistance are the heat pipes and vapor chambers. Basically, the heat pipes and vapor chambers are two phase heat transfer devices, is an evacuated and sealed container which contains a small quantity of working fluid. One end of the container is heated, causing the liquid to vaporize and the vapor to move to the cold end and condense. As

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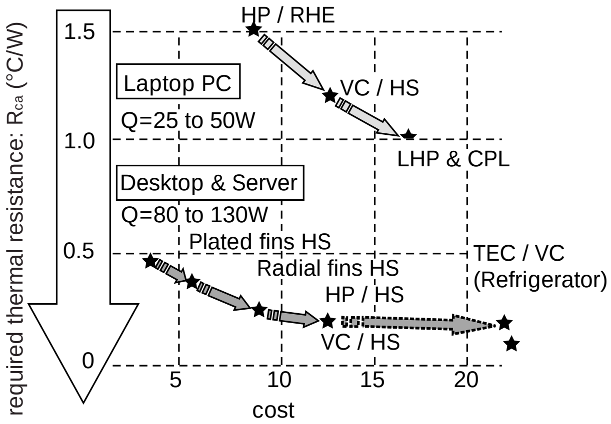

Fig. 1. Thermal solution trend.

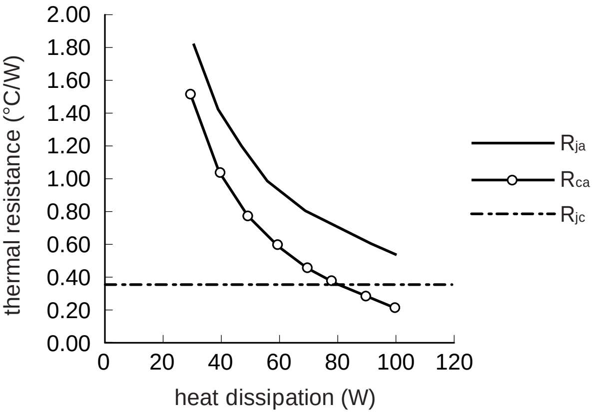

Fig. 2. R_{ja}, R_{jc}, and R_{ca} vs. heat dissipation.

the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from end to end. Thus, it is a device of very high thermal conductance. Its equivalent thermal conductivity can be several hundred times than that of a solid copper device of the same dimensions.

Heat pipes and vapor chambers have emerged as the most significant technology and cost-effective thermal solution owing to their excellent heat transfer capabilities, high efficiency and structure simplicity. A selection of the working fluid is based on the operating temperature of the application. In computer applications, the operating temperatures are normally between 50 and 100 °C. Within this temperature range water is the best working fluid.

Figure 1 shows the current and future expectation of thermal solution for laptop and desktop PCs, and the server units. As shown, the performance required the comparison of, R_{ca} (R_{ca}: Case of CPU to ambient temperature) to the cost of solution. For the laptop PCs, the current solution of using a heat pipe with remote heat exchangers is able to deliver R_{ca} performance of approximately 1.5 °C/W. Further to improve the performance using the vapor chamber solution need to be considered. The estimated cost for laptop PCs solution, including fan, is in the range of $US 5 ~ 15 depending on the performance requirement. For the desktop PCs and servers, the majority still use traditional solutions such as high aspect aluminum extrusion parallel or radial fin heat sinks; aluminum or copper plate fins soldered to aluminum or copper metal base. However, as the performance requirement tightens, the trend is moving towards using heat pipes and vapor chambers to maximize the performance and to extend the air cooling capability to the limit.

2. Formulation

A basic formulation to calculate the thermal resistance required for the cooling solution is as follows:

$$R_{ja} = R_{jc} + R_{ca} = (T_j - T_a - T_{sys})/Q \text{ ....(1)}$$

where,

Q = Heat dissipation (W)

R_{ja} = Thermal resistance from the CPU die to ambient (°C/W)

R_{jc} = Thermal resistance from the CPU die to CPU case surface (°C/W)

R_{ca} = Thermal resistance from CPU case surface to ambient (°C/W)

T_a = Ambient temperature (°C)

T_j = Junction temperature inside die (°C)

T_{sys} = Temperature rise of the ambient inside the system due to other heat generating components (eg. hard disk drive; graphic cards etc..) (°C)

In the case of CPU packaged with an integrated heat spreader, the R_{jc} varies depending on the type of CPU and the manufacturers. In most cases, the R_{jc} is approximately 0.33 °C/W.

The thermal solution provider could only control the R_{ca}. This thermal resistance consisted of the thermal interface material and the cooling solution. Figure 2 shows the required thermal resistance R_{ja}, R_{jc} and R_{ca} versus heat dissipation, assuming that for maximum CPUs the junction temperature is 100 °C, the outside ambient temperature is 35 °C, and system temperature rise of 10 °C.

When the power goes up to 100 W, R_{jc} (0.33 °C/W) cannot be neglected because external thermal margin (R_{ca}) almost reaches the limit of air cooling.

3. Examples of laptop thermal solution $^{1)\ 2)\ 4)}$

3.1 Hybrid system

The hybrid system consisted of heat pipes, die-casting plate, fins, and fans as shown in Fig.3. The three heat pipes were used to spread heat on the aluminum die-casting plate. Aluminum fins attached to the heat pipe and radial fans were used to blow air directly through fins. The R_{ca} of this system was about 1.8 °C/W and capable of dissipating 26W. The system

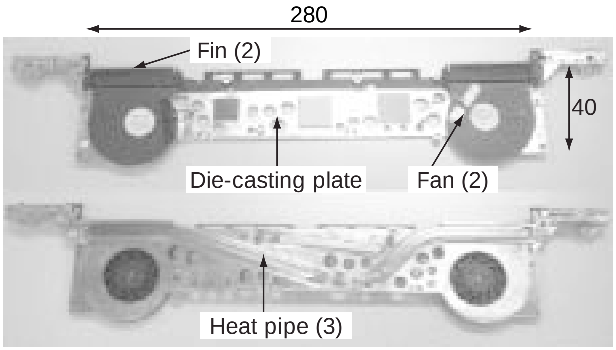

Fig. 3. Hybrid cooling system.

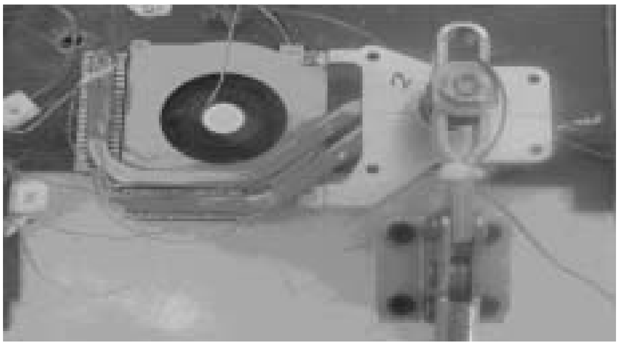

Fig. 4. Remote heat exchanger.

has very comfortable assembly merit as it is a one-piece structure, but some of the heat remains inside PC skin owing to big heat mass of die-casting, which is a disadvantage.

3.2 Remote heat exchanger

Basically, the remote heat exchanger consisted of heat pipe, fin, and fan as shown in Fig.4. The fan size is approximately 45 mm × 45 mm and 10mm thick. The fan airflow was estimated to be 0.15 m^3/min at 0 Pa and 90 Pa at 0 m^3/min when tested in an open environment. The R_{ca} for this design is approximately 1.1 °C/W, with a cooling capacity about 40W.

3.3 Vapor chamber

The principle of operation of a vapor chamber is similar to a heat pipe, which is a two-phase heat transfer device. A heat pipe is made of a round pipe, and after sealing the ends can be bent and flattened to the required shape. The vapor chamber container can be made by stamping, cold forging, or machining processes, so that the shape is fixed and it cannot be bent or flattened. Figure 5 shows the shapes and sizes of various vapor chambers.

An example of a vapor chamber solution is shown in Fig.6. The R_{ca} of this system is about 0.6 °C/W as shown in Table 1. When it is assumed that the boundary condition is T_j =100 °C; T_a = 35 °C; T_{sys} = 10 °C; and R_{jc} = 0.33 °C/W, then this system can dissipate heat of 60W.

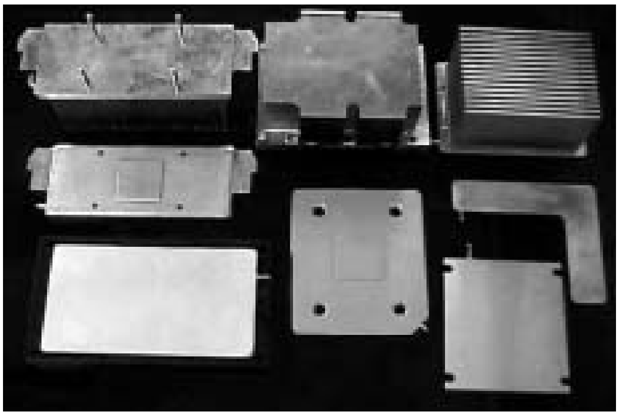

Fig. 5. Various vapor chambers.

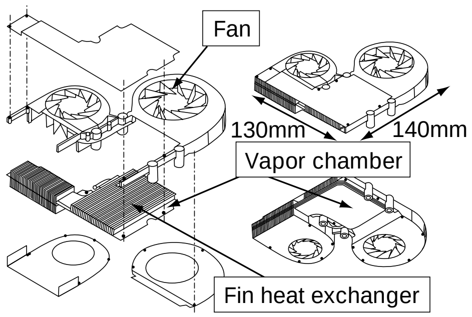

Fig. 6. Vapor chamber solution.

Table 1. Summary of R_{ca} for various thermal solutions.

No.	Solution	R_{ca} (°C/W)	Q (W)
1	Hybrid system	1.8	26
2	Remote heat exchanger	1.1	40
3	Vapor chamber	0.6	60

The performance of vapor chamber is better than a heat pipe because of the two-dimensional heat transfer element. The advantages of vapor chamber solution compared with heat pipe solution are given as follows:

- Heat flow is two-dimensional as compared with one-dimensional flow in a heat pipe. This gives vapor chamber a higher heat transfer and lower thermal resistance.
- Higher heat flux capability of over 50 W/cm^2.
- Vapor chamber has uniform temperature distribution, large body surface area so it is excellent for heat dissipation.
- Vapor chamber can be placed directly in contact with the CPU (via thermal interface material), eliminating conducting and contacting resistance of the “heat block” to which heat pipe is attached.
- Fins can be attached directly to the vapor chamber, having higher surface of contact thus, it can reduce contact resistance and increased fin efficiency.

A summary of the R_{ca} and heat dissipation capability for various thermal solutions is shown in Table 1.

Figure 7 shows the trend of thermal solution in lap-

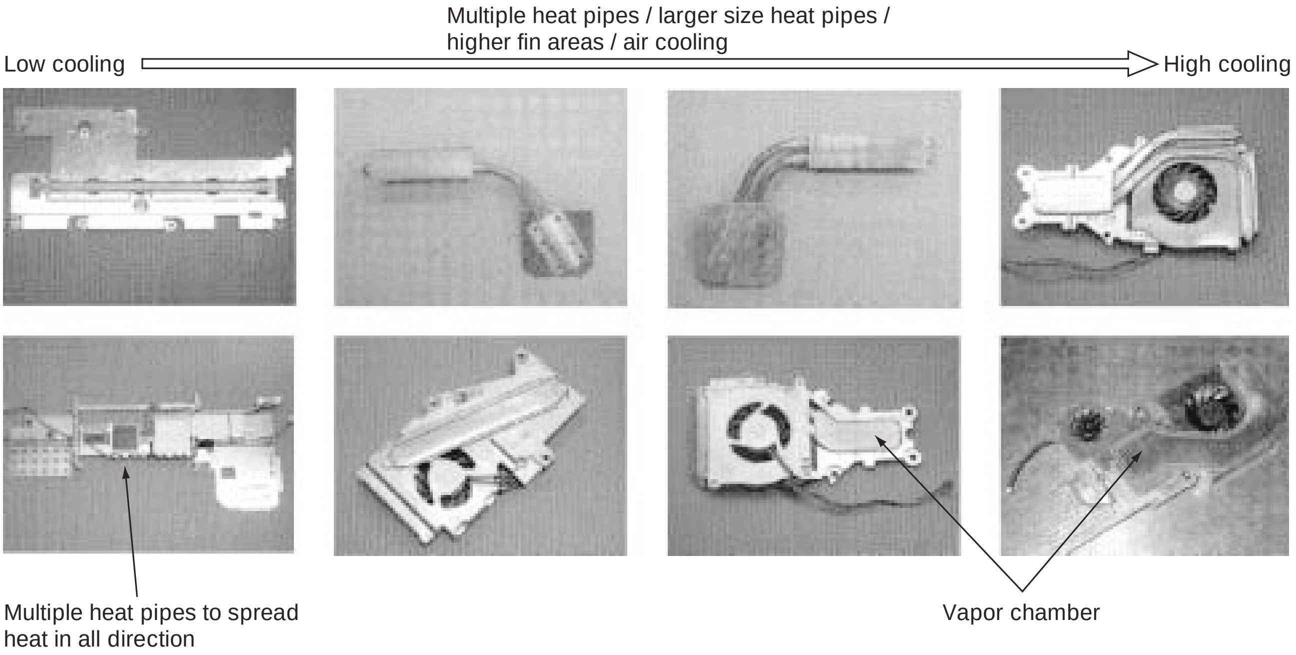

Fig. 7. Trend of thermal solution in laptop PC.

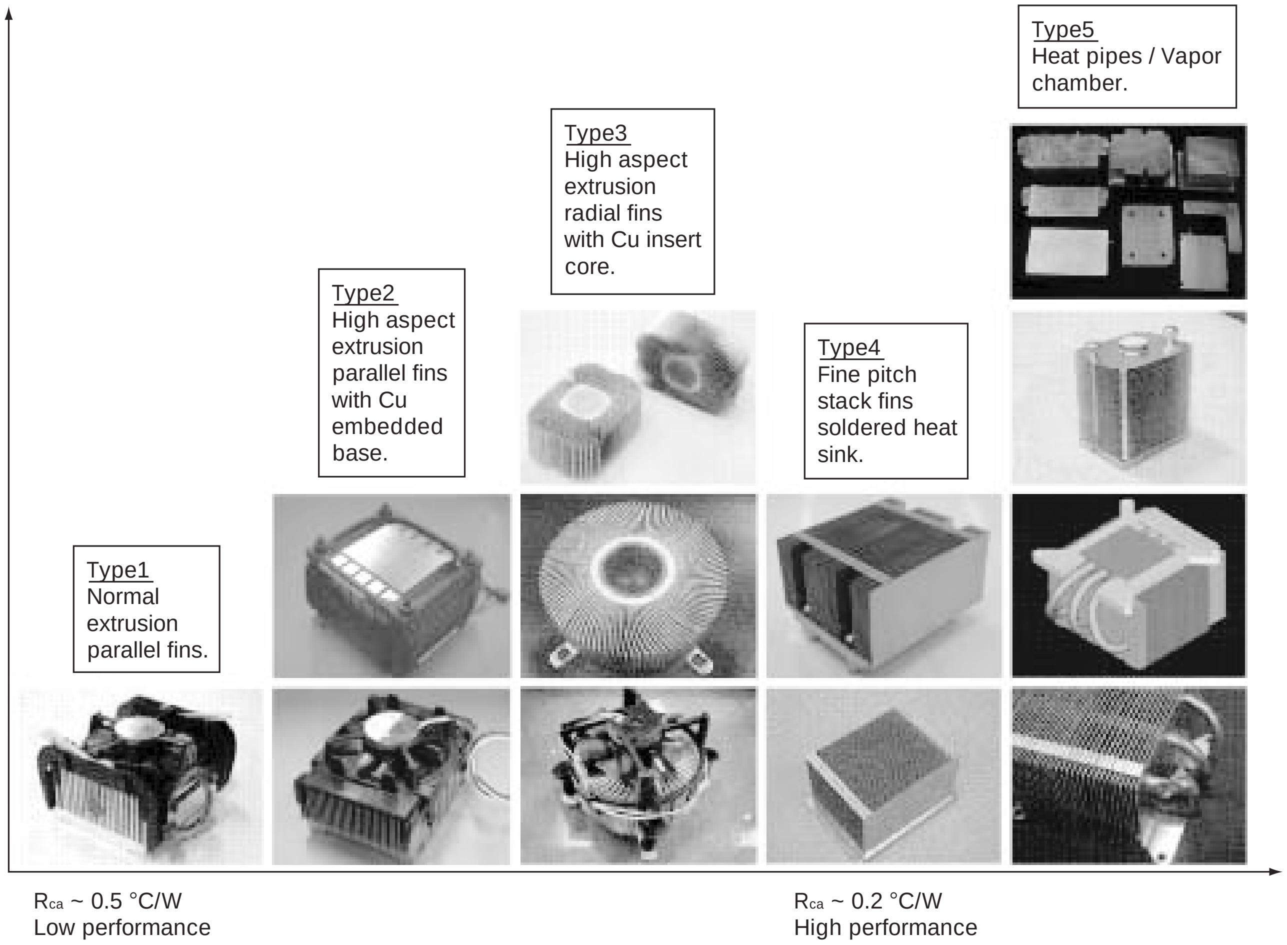

Fig. 8. Summary of cooling design trend for desktop PCs.

top PCs. It is evident that to maximize the performance and to push the limit of the air cooling capability, the design needs multiple heat pipes or vapor chambers with high-density packed fins and multiple fans.

4. Examples of desktop thermal solution2) 3) 4) 5)

Figure 8 shows a summary of design changes to

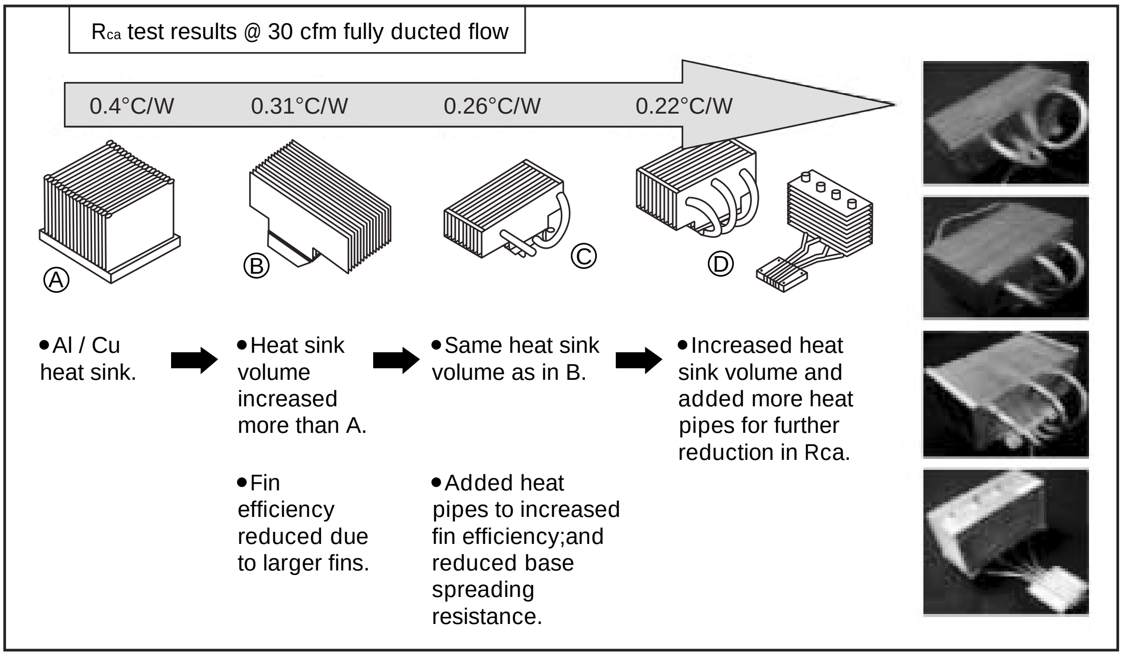

Fig. 9. Heat pipe heat sink solution for cooling desktop PCs.

maximize the air cooling capability. For equal comparison all the designs are within the boundary of a cooling volume of approximately 90 mm × 90 mm × 65 mm height. The acoustic level at the maximum specification in general is 45 dBA at 1m from the source. Description of the design is give below.

- Type 1: Normal extrusion heat sink with fins of count approximately 7 fins per inch, 1.2 mm fin thickness, pitch 3.5 mm and 30 mm tall. The R_{ca} range is 0.4 to 0.5 °C/W.

- Type 2: High aspect extrusion heat sink. In this design extrusion had been pushed to the limit capability. Fins count approximately 10 fins per inch, 1 mm fin thickness, pitch 2.3 mm and 30 mm tall. The aluminum base had a copper block soldered to minimize the heat spreading resistance. The R_{ca} range is 0.3 to 0.4 °C/W.

- Type 3: The design changes from parallel fin extrusion to radial type extrusion. The heat sink core has an integrated Cu core to improve heat conduction from base to fins. In general radial fins could capture the air from the fan better than a parallel plate fin, thus providing higher fin-air heat transfer coefficient and more efficient cooling. The R_{ca} is approx. 0.3 to 0.35 °C/W.

- Type 4: High density stack fins were soldered to metal base. The fin thickness can be as thin as 0.2 mm, and fin gap less than 1mm. The R_{ca} is approximately 0.25 to 0.3 °C/W.

- Type 5: For further reduction in R_{ca} less than 0.25 °C/W for the same specification constraints, there would be a need to consider the use of the bases of heat pipes or vapor chambers to maximize the heat transfer from source to fins for improvement in cooling.

Figure 9 shows an example of how heat pipes were used to improve the thermal performance. Heat pipes were used to transfer heat effectively from the heat source to fins, improve the fin efficiency and reduce spreading resistance at the base.

5. Examples of server thermal solution

Thermal solution technology in servers is similar to the desktop. However, the thermal specification and boundary conditions are different. For examples in servers, the heat dissipation is higher, the form factors are different and the acoustic limit is higher at 55 dBA compared with the 45 dBA limit in desktops. Figure 10 shows an example of a fan sink for cooling of a server. This is called an active solution because the fan is integrated with the heat sink. For passive solution, no fan is integrated with the heat sink, but it uses the system fan to blow air through the heat sink. The design shown in Fig. 10 is Cu fins soldered to a Cu base. This design could be further improved by replacing the Cu base with a vapor chamber base as shown in Fig. 5. The vapor chamber has not been used in this particular design because current design Cu fins and Cu base met the required thermal specification, and the cost is higher for the vapor chamber solution.

Figures 11 and 12 show some other examples of server cooling where height is available, so it is ideal to use a “tower” like design. The design can be either multiple heat pipe style or a single large heat pipe style. For the multiple heat pipe style, the one disadvantage is that there is loss of cooling space at the region where heat pipes bend because of no fins are

Fig. 10. Fan sink for cooling sever.

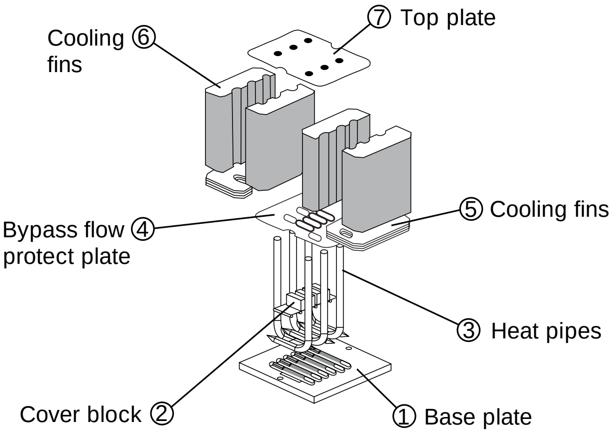

Fig. 11. Multiple heat pipes tower.

attached, whereas for the single large heat pipe style, the fins can be attached to heat pipes all along the pipe. Therefore for the same fin configuration, the multiple heat pipes required taller height. On the contrary, the multiple heat pipe style could have lower air pressure drop than the single large pipe. Thermal performance is similar for both designs assuming that the fin configuration and ducted airflow remain the same.

In the case of low height form factor, the vapor chamber solution is better suited than heat pipes. Figure 13 shows the design of fins soldered directly to the vapor chamber base. Depending on the sizes of heat source and heat sink base for the metal base, there could be a large temperature gradient along the base. For the vapor chamber that utilizes two-phase latent heat transfer, the base is nearly isothermal.

6. Future cooling technologies

6.1 Improving heat spreading from the processor die

Fig. 12. Single large heat pipe tower.

Fig. 13. Vapor chamber base.

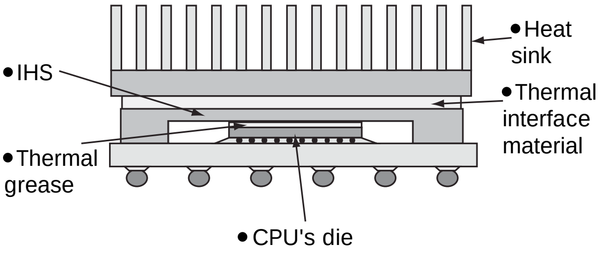

Fig. 14. Thermal solution integration.

Figure 14 shows a schematic presentation of the thermal solution integration with the CPU. In the current technology, the Integrated Heat Spreader (IHS) is made of solid Cu plate which interfaced with CPU's die via thermal grease. IHS is a radiator which can receive heat at its some part and spread in its inside rapidly and transfer to the various cooling components. The average thermal spreading resistance between the die and the IHS (R_{jc} in Fig. 2) is a significant ratio to overall thermal resistance.

There are some possibilities to improve the thermal spreading resistance between CPU's die and the IHS as described in the following sections.

- Instead of solid Cu metal IHS, use a two-phase Micro-channel Vapor Chamber (MVC) as shown in Fig. 15. Basically, the MVC is an evacuated and a sealed container that contains a small quantity of working fluid. Inside the container has micro-fin structures that increases the boiling heat transfer area. When one side of the container is heated, it causes the liquid to vaporize and the vapor to move to the cold side and condense. As the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from end to end. Therefore, the MVC-IHS has low spreading thermal resistance, isothermal temperature distribution, and no local hot spot compared with solid Cu IHS where heat spread solely by thermal conduction.

- Instead of using thermal grease between CPU's die and IHS, the use of brazing or soldering to minimize the contact resistance should be considered. There would be technical challenges such as thermal expansion coefficient mismatch between mating surfaces; reliability issues such as corrosion, chemical reaction and so on. One could plating the surfaces with materials of similar thermal expansion coefficient with the CPU's die, and gold plating.

Figure 16 shows an estimate calculation of thermal spreading resistance and comparison between solid Cu-IHS and MVC-IHS for various IHS sizes. The use of MVC-IHS is an advantage when the IHS size is about 10 times of the die size based on the assumption that the die size is 10 mm × 10 mm.

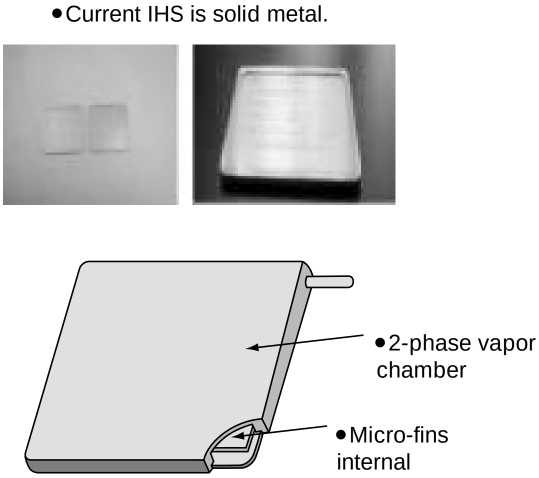

Fig. 15. Micro-channel vapor chamber.

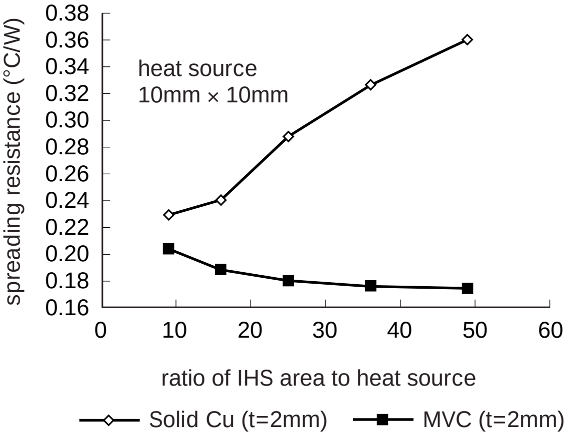

Fig. 16. Thermal spreading resistance and comparison between Cu-IHS and MVC-IHS.

6.2 Improvement heat transfer device – heat pipe

As have been mentioned earlier, the processor's die surface, where the heat is generated, is usually small, approximately 1 cm^2, so for effective cooling least temperature gradient between the heat source and radiating components should be required. The best-known devices for effective heat transfer with lowest thermal resistance are the heat pipes and vapor chambers. As the power and heat flux of the processor continues rising, it is most vital to improve the heat pipe maximum heat transfer (Q_{max}) and reduce heat pipe thermal resistance (R_{hp}). There are some possibilities for the heat pipe improvement as described in the following sections.

- New sintered powder wick heat pipe: The size of powder particles and porosity are the main factors in optimizing maximum capillary forces while there is a need to maintain high permeability. Besides wick thickness and uniformity are key factors for better and stable heat pipe performance.
- New working fluid to improve fluid-wick wet-ability and boiling heat transfer: Preliminary study showed that dilute aqueous solutions of high-carbon alcohols that presented a particular surface tension behavior that have strong liquid flow in the nucleation sites during the boiling process. Experimental studies showed that in pool boiling heat transfer, a significantly smaller bubble size is formed in comparison with water. This indicated that the heat transfer performance would be improved. Figure 17 depicts preliminary results that showed heat pipe performance could be improved.

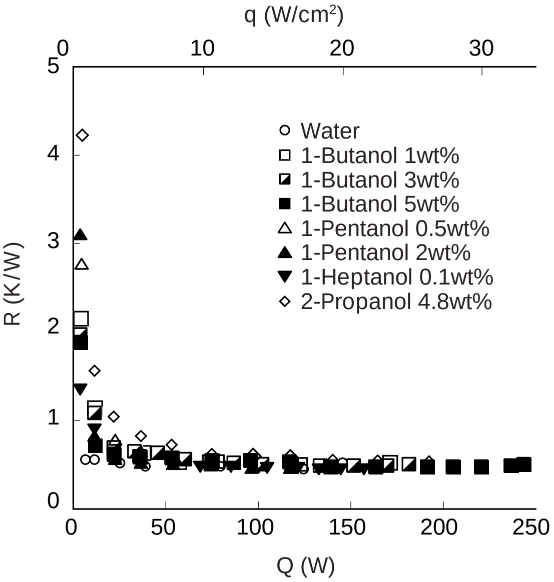

Fig. 17. Heat pipe performance comparison of different fluids for dia. 8mm heat pipe.

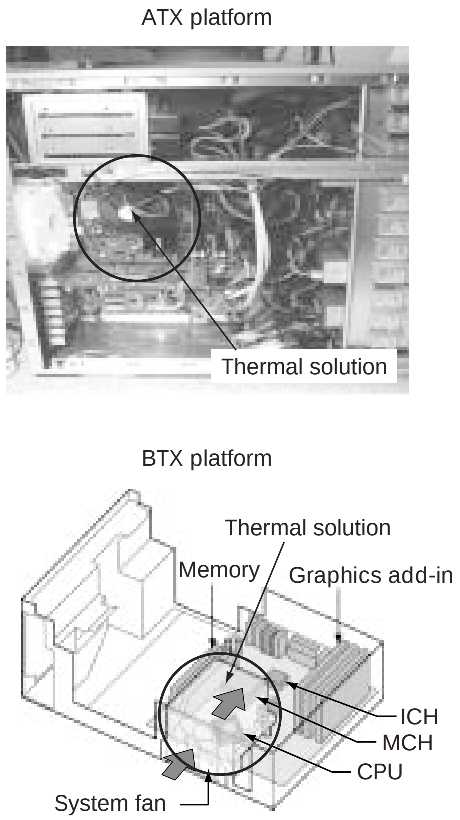

Fig. 18. ATX and BTX platform for desktop PCs.

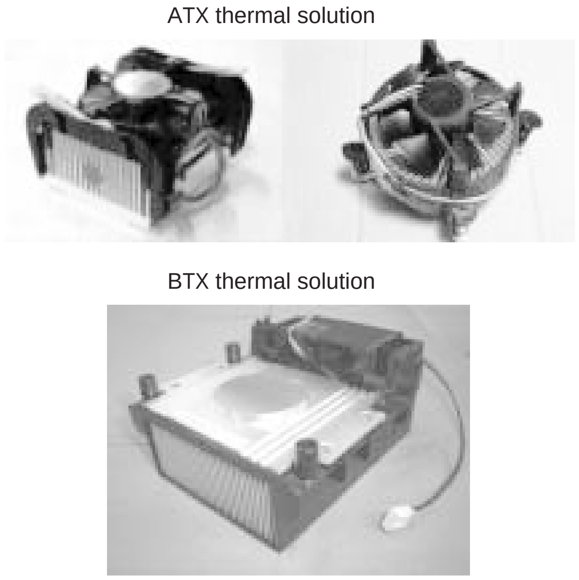

Fig. 19. ATX and BTX typical thermal solution.

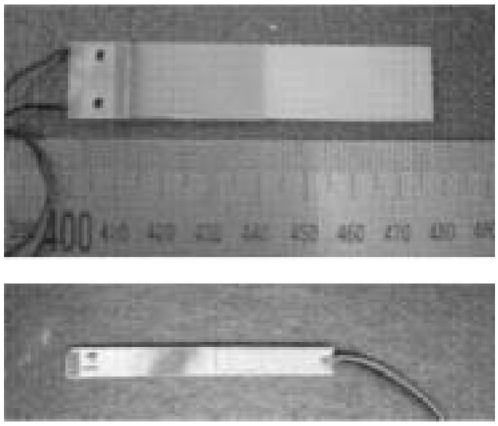

Fig. 20. Single blade Piezo fan.

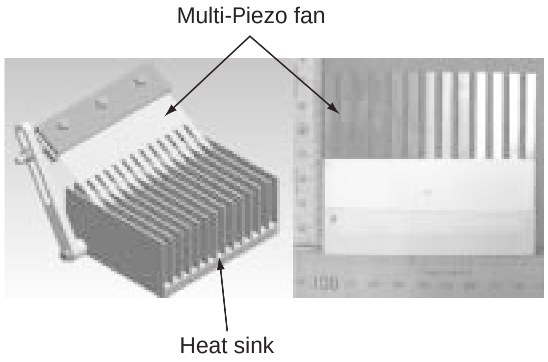

Fig. 21. Multi blade Piezo fan.

6.3 New cooling platform

Figure 18 shows schematic presentation of the Advanced Technology Extended (ATX) and Balanced Technology Extended (BTX) platforms for desktop PCs, where the former is the current platform. Figure 19 shows typical thermal solution for ATX and BTX. The main advantages of the BTX over the ATX are described below.

- In the ATX, the fan impinge cooling air down the heat sink, and the air is forced to turn perpendicular and exit the heat sink. This caused the airflow to lose its static pressure head, and as a results the airflow moves slowly and does not effectively cool other components in the motherboard. Whereas in the BTX, the airflow is blowing parallel through the heat sink, and the air exit has high velocity available for better cooling of other components in the system.
- BTX has fresh cooler inlet air from external ambient, whereas the ATX uses the warmer circulated air in the system. The cooler inlet air will provide better cooling.
- With better cooling the BTX can operate fan at lower speed and therefore lower acoustic.
- BTX has higher airflow in and out of the system, therefore the internal temperature of the system becomes lower.
- With better air cooling the heat sinks require higher thermal resistance, and therefore heat sinks are generally easier and cheaper to manufacture.

6.4 Piezo fan[6)]

The basic principle of the Piezo fan is that when electrical power is applied to the piezoceramic material, it causes it to expand on one side and contract on the other. If the Piezo ceramic material is attached to, say a metal or plastic sheet will cause the sheet to swing. The swinging of the sheet will create airflow

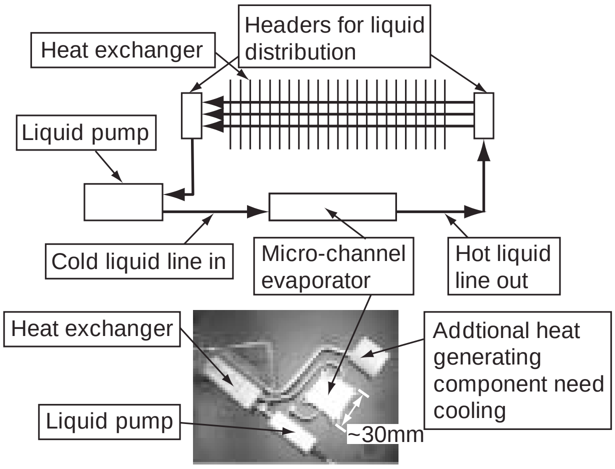

Fig. 22. Schematic micro-channel two-phase pump loop.

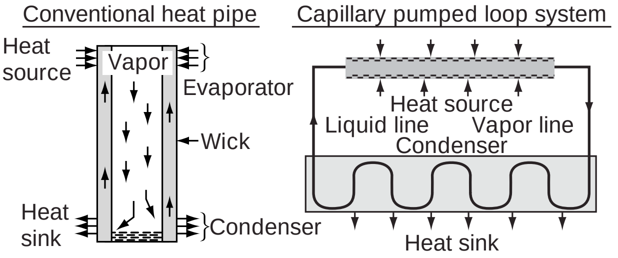

Fig. 23. Schematic of conventional heat pipe and CPL.

for the purpose of cooling. A concept to develop a highly efficient and compact Piezo fans is under progress. The main advantages of the Piezo fan are expected to be lower cost and lower acoustic compared with other air moving devices such as axial fan or blower. Figures 20 and 21 show prototypes of single and multi blades Piezo fan.

6.5 Micro-channel two-phase pump loop

Figure 22 shows a schematic of the micro-channel two-phase pump loop. Detail information of the system will not be given here, except the concept. Typical results indicated that this system could achieve the evaporator thermal impedance less than 0.1 °C-cm^2/W at saturated water flow rate less than 50 ml/min. The system is capable heat flux greater than 50 W/cm^2.

6.6 Capillary pump loop (CPL)[7)]

The principle of CPL is similar to that of heat pipe. It is basically a heat transfer device that uses capillary forces developed in the wick structure and latent heat of evaporation of the working fluid to carry high heat loads over considerable distances. Figure 23 shows the schematic presentation of the conventional heat pipe and CPL. The main difference is that in heat pipe the vapor and liquid flow are counterflow, whereas in CPL the vapor and liquid flow are separated. Owing to this reason the CPL could carry heat over longer distance than a heat pipe. The CPL can have 2 to 3 times heat transfer capacity than heat pipe of the same size.

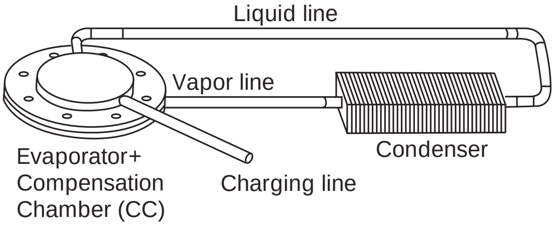

Fig. 24. Concept of CPL prototype developed.

Table 2. Characteristic dimensions of the CPL.

Parameter	Dimension
Evaporator shape	Flat disk shaped
Evaporator diameter OD/Active zone dia.	30/28 mm
Evaporator thickness	10 mm
Body material	Copper
Wick material	Nickel
Wick effective pore radius	3~5 μm
Vapor line diameter (ID/OD)	2/3 mm
Vapor line length	60 mm
Liquid line diameter (ID/OD)	2/3 mm
Liquid line length	200 mm
Condenser material	Copper fins
Condenser length	50 mm
Fin width/height	20/10 mm
Fin pitch	1 mm
Working fluid	Water

Figure 24 shows the concept of the CPL prototype under development. The basic geometry of the system is shown in Table 2. Typical results indicated that this system could transfer ~ 70W, and the evaporator thermal resistance is 0.1 to 0.15 °C/W.

7. Conclusion

- The computer processor's die surface where heat generation is usually small and heat dissipation is large requires a large space for cooling. The most effective way to transfer heat from the heat source to dissipation area is to use heat pipes or vapor chambers. The use of heat pipes in the metal base or vapor chambers as base helps to reduce thermal spreading at the base. Therefore, the cooling capacity can be increased.
- As the processor power increases and thus the required lower thermal resistance (R_{ca}), the tendency of the cooling solution technology to maximize and extend air cooling has moved towards more use of heat pipes and vapor chambers. Processor heat dissipation will continue to increase owing to the demand for higher and faster processors, and therefore to provide adequate cooling, it is essential to continue research

and develop superior heat pipes and vapor chambers having high heat flux capability and minimal possible thermal resistance between heating and cooling ends.

- The thermal resistance from the CPU's die to the IHS comprised a significant ratio of overall thermal resistance. Therefore, there is a need to consider replacing the metal Cu IHS with some other high heat transfer device such as MVC. In additional direct brazing or soldering the IHS to the CPU's die need to be considered.
- Managing better airflow in the system for efficient component and system cooling, could reduce the acoustic owing to the possible running of the fan at lower speed.

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