

An Examination of CPU Cooling Technologies

Thermal Management Options for Engineers

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Introduction

The Central Processing Unit (CPU) generates a great deal of undesirable heat in modern computing systems. The CPU is responsible for processing most of the data within systems and is often referred to as a computer's central processor or simply processor. As data is processed within a system, heat is generated. Once heat thresholds are exceeded, CPUs are placed at risk of malfunction or permanent damage.

To overcome overheating, systems can be equipped with cooling systems that help to regulate temperature within a unit thus maintaining efficient operation. This paper examines the most common cooling technologies used today as well as a few that are currently in the early stages of research and development.

Any examination of CPU cooling, or any kind of electronics cooling for that matter, must take into account Moore's law which predicts the number of transistors placed on integrated circuits will double every two years. As CPUs continue to decrease in size while exponentially increasing in power each year, adequate cooling methods will increasingly become an integral part of new design planning efforts. Figure 1 shows the evolution of module-level heat flux in high-end computers over several decades. As shown, module heat flux has continued to creep upward with each passing year.

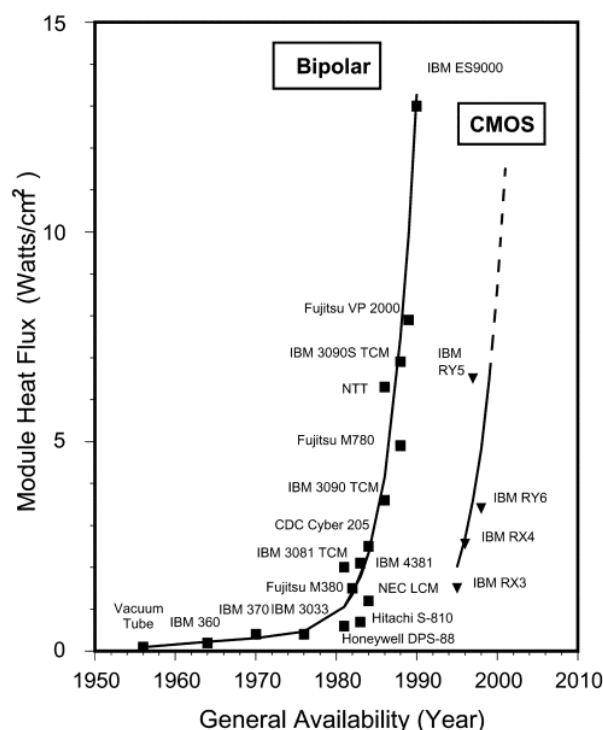


Figure 1: Evolution of module level heat flux in high-end computers [1]

This paper evaluates several CPU cooling methods that are currently available to mitigate overheating, with specific emphasis placed on liquid cooling technologies. The following section begins with the basic cooling technology most commonly used in the past – air-cooling. The paper next examines incremental improvements over air-cooling including the use of heat sinks, heat pipes, and a complete liquid cooling setup. We will also examine several advanced options

that emerge from these basic system types such as the use of heat pipes for existing heat sinks, active liquid heat sinks, liquid immersion, and thermoelectric cooling technologies. Relevant data and comparison derived from a number of published papers are presented to support the provided information.

Air Cooling

Air-cooling, which incorporates the use of fans, is currently the prevalent method of cooling CPUs in computing environments. It has several advantages including reduced cost, relatively low noise, and is free of piping elements, tubes and cables. [2] The main function of fans is to pump air so that heat is effectively carried away from the CPU assembly. Air pressure can vary by incorporating fans in series (placed on top of one another) or parallel configurations (side-by-side). [3] The serial setup increases the discharge pressure while the parallel setup increases the area coverage.

Based on several studies completed in recent years [1][2][4][5][6][7][8][9], air-cooling technology is insufficient to keep up with the growing requirements of CPU cooling in the marketplace. As a result of these deficiencies, a number of new cooling technologies have been developed while other advanced cooling technologies are currently under study.

Heat Sink

One simple CPU cooling solution is accomplished via the use of a basic heat sink. A heat sink is a term for a component assembly that transfers heat generated within a solid material to a fluid medium such as air or a liquid. [4] A heat sink uses its extended surface (also called fins) to extend the surface of the material that is in contact with air or liquid. The main factors that affect the heat sink thermal performance are air velocity, choice of material, and fin design. A sample heat sink is shown in Figure 2.

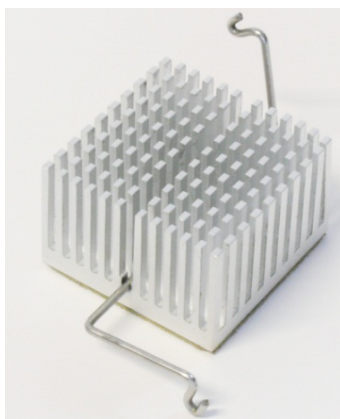


Figure 2: Sample Heat Sink

An experiment [4] was completed that incorporates an aluminum alloy heat sink with 18 fins and a fan designed to produce a $0.026\text{m}^2/\text{s}$ rate of airflow. The maximum temperature of the CPU reached a temperature of 39.83666°C and the heat removed from the configuration is 2-11 Watts (refer to Figure 3).

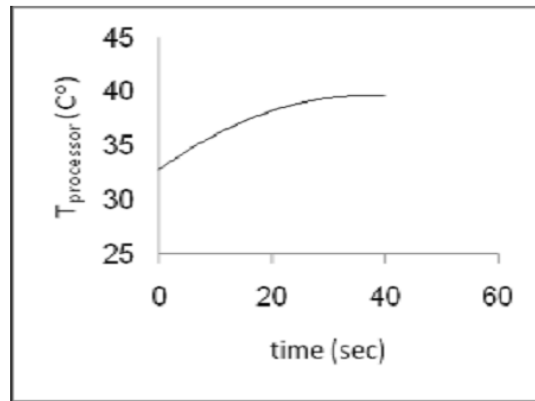


Figure 3: Time with respect to the temperature of processor

Heat Pipe Radiators

Another study [1] was conducted to extend the capability of heat sinks with fins. The research examined a heat sink that uses heat pipes as a replacement for the fins. The primary difference is that the heat pipes for the heat sink are hollow, while the fins are solid material. The assumption is that the heat pipes are geometrically equivalent to the solid pipes but possess a higher heat-transfer coefficient. An illustration of a heat sink that utilizes heat pipes is shown in Figure 4.

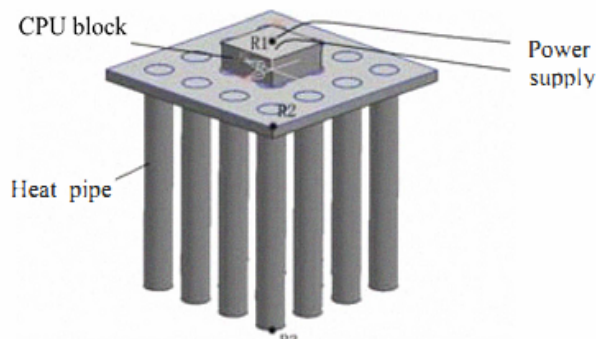


Figure 4: Heat sink that uses heat pipes

The study compared the thermal performance of a heat pipe radiator (i.e. heat sink) and the finned radiator. We can see in Figure 5 that the heat pipe radiator is an improvement over the ordinary finned radiator.

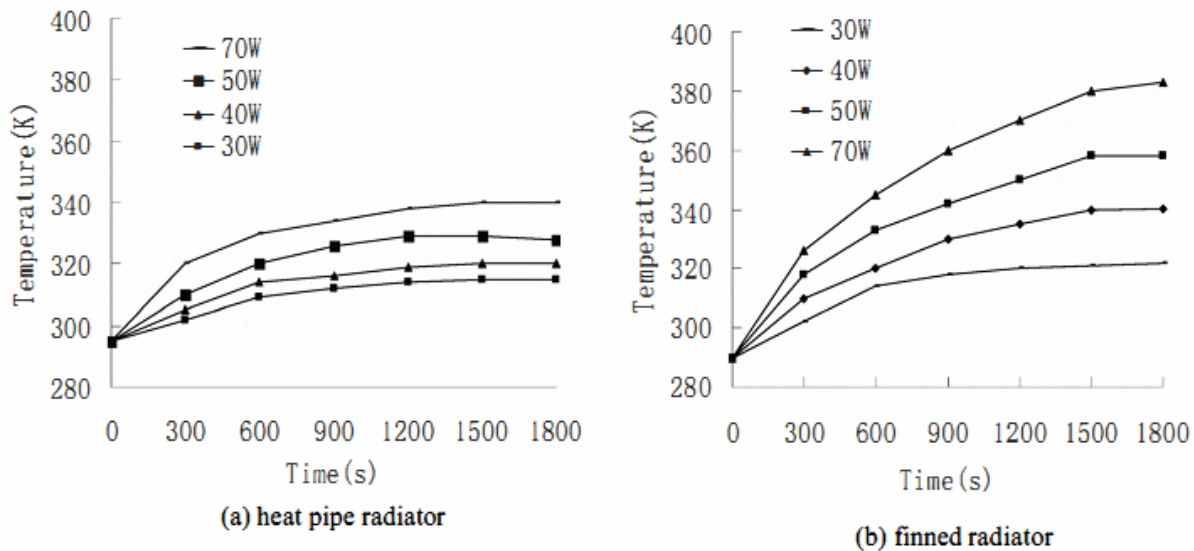


Figure 5: Heat pipe radiator v. finned radiator

Researchers also studied the effects of varying the heat pipe diameter along with the number of heat pipes used. The results are shown in Figures 6 and 7 respectively. We can see that increasing the number and diameter of the pipes increases the thermal performance of the heat pipe radiator.

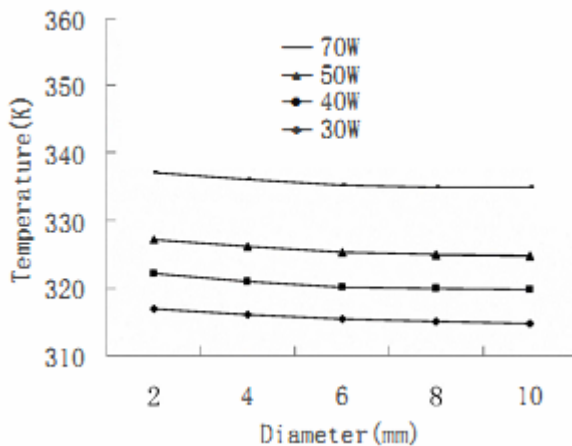


Figure 6: Varying the diameter of heat pipes

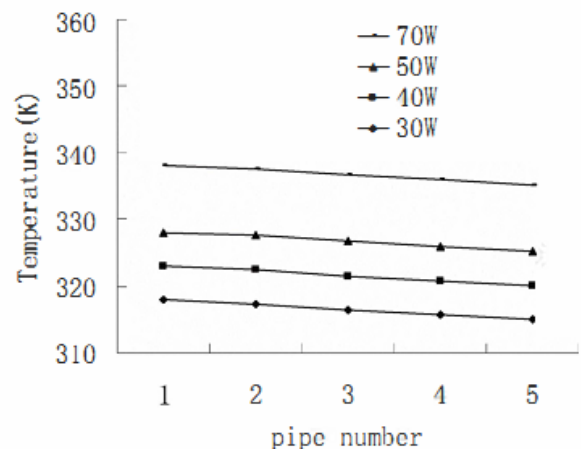


Figure 7: Varying the number of heat pipes

Heat Pipe

A heat pipe is an evacuated and sealed pipe that contains a small amount of working fluid and a wick structure. [6] A heat pipe is an additional structure that is added to a heat sink. Figure 8 shows the model of a heat pipe layout and an actual heat pipe is shown in Figure 9. This is a relatively simple design, as it involves no moving elements or additional tubes for the liquid. It also does not require a power source because it uses the natural convection of liquid for distribution. A heat sink with embedded heat pipes can offer thermal performance improvements of up to 20% when compared to a typical aluminum or copper base heat sink. [6]

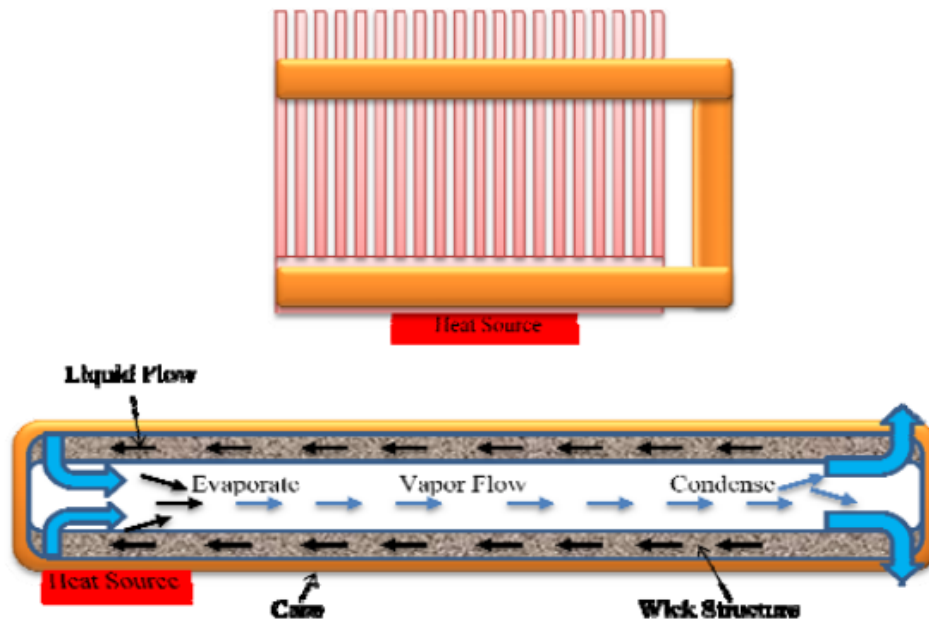


Figure 8: Heat sink design with embedded heat pipe



Figure 9: Sample heat sink with heat pipe [Source: circuitremix.com]

Heat pipes offer three primary advantages. First, the heat pipes help to distribute heat thereby increasing thermal conductivity. Second, they serve as a heat conductive path for transmitting heat from the base to another location so that heat can be managed within small CPU packages. Third, the heat sink effectively increases the conductivity and the efficiency of the traditional heat sink. [6]

The design of heat pipes can be varied to improve their performance as well. Figure 10 shows the performance of heat pipes with varying pipe diameter. The diameter is varied between 3mm, 4mm, and 6mm. The Y-axis, ($Q_{max} \bullet Le_{eff}$) shows the amount of heat that the pipe can carry per

meter length. We can see that performance of the heat pipe is improved as the diameter is increased. The heat pipe also has a higher efficiency rating as temperatures rise.

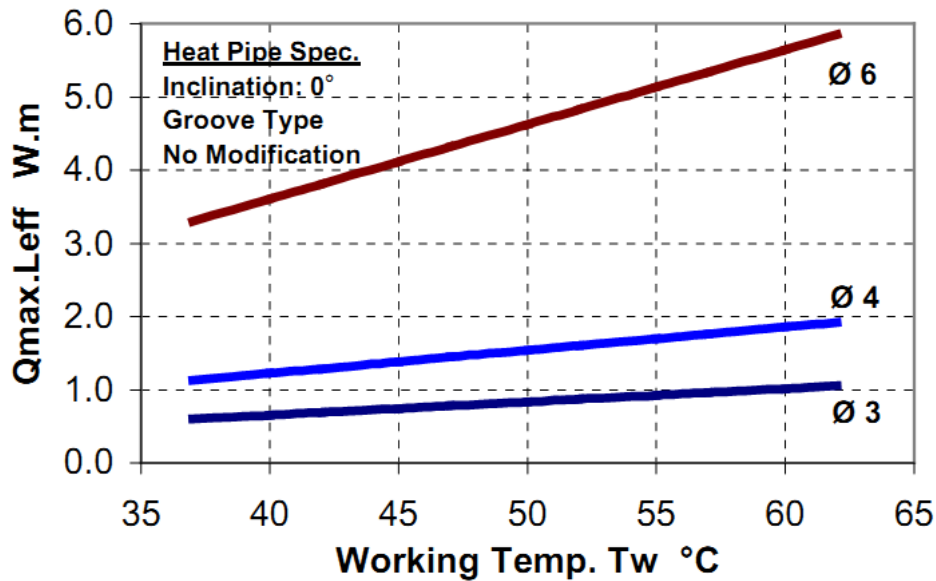


Figure 10: Thermal Performance of Heat Pipes with Varying Diameter [6]

Water Cooling

The next cooling technology to review is the basic liquid cooling system. A liquid-cooled system places a liquid-cooled heat exchanger in the heat source to extract heat and reduce air temperature. [7] Compared to air, water-cooling can provide almost an order of magnitude reduction in thermal resistance due to the higher thermal conductivity of water. Because of higher density and specific heat of water, its ability to absorb heat in terms of the temperature rise across the coolant stream is approximately 3500 times that of air. [7]

A study [8] was conducted to compare a liquid cooling system to a heat sink with heat pipe configuration discussed above. The heat sink used is the IBM power series server x3350 cooler. It contains a straight fin array with bended heat pipe heat spreader. [8] Cooling air was sucked by four hot swap fans and transferred out the left side of the system (Figure 11).

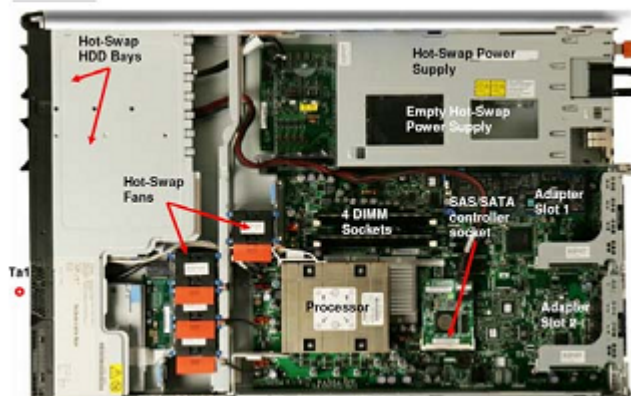


Figure 11: Cooling system for IBM power series server

As for the liquid cooling system, an integrated cold liquid and pump liquid cooling system was used (Figure 12). The fan shown is an integration of a fan and a heat sink.

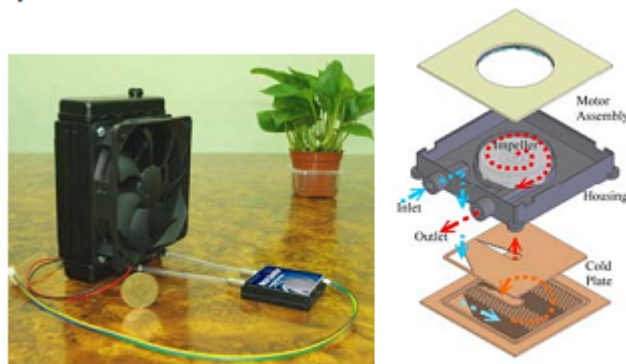


Figure 12: Assembly diagram of the liquid system

Three different types of heat sink-fans were used. The specifications of each fan are shown in Table 1.

Table 1: Detail Dimension of the Fan and the Fin Array Tested

system	Fan size (cm)	Fin arrays size (cm)	V (cm ³)	W (g)	Material
IBM	4x4x4.8x3	13x11x2	286	650	copper
LC-1212	12x12x2.5	15x12x4	720	200	aluminum
LC-0808	8x8x2.5	12x8x3	288	110	aluminum
LC-0416	4x4x2x4	20x4x3	240	100	aluminum

The result of the experiment is shown in Figure 13. We can see that the liquid cooling system performs better than the existing integrated heat sink with heat pipe that the current IBM server is using. We can also see there that the bigger the dimension of the fan, the better the thermal performance. This shows that the LC-1212 cooling system is the best cooling system for this experiment.

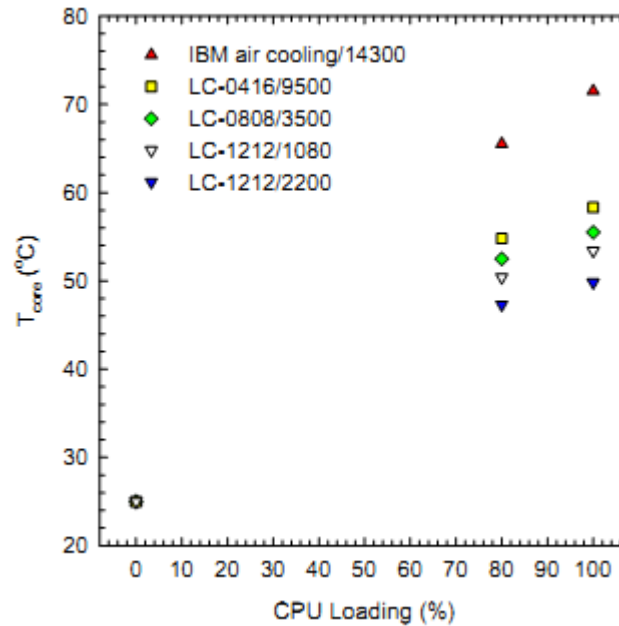


Figure 13: Cooling performance test results

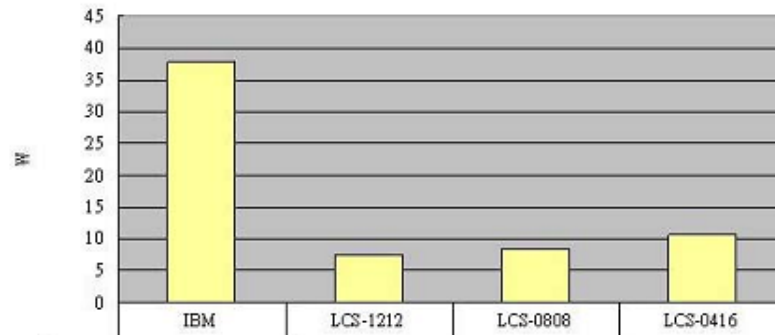
Aside from thermal performance, the noise level and the power consumption of the four cooling systems were also studied. The results are shown in Table 2 and Table 3. These results show that the liquid cooling system provides much higher cooling performance and lower power consumption coupled with lower system noise. The low noise level and low power consumption is due to the significant reduction of the speed of the fan. A large amount of air is not necessary in a liquid cooling system, which consequently lowers noise and power consumption. [8]

Table 2: Cooling performance and noise level test results

Cooling system/ fan speed	power supply fan	system noise (dB)	backgrou nd noise	$T_{core} - T_a$ (°C)
IBM air cooling/ 14,300 rpm	on	59.5	29 dB	46.5
LC-0808/3,500 rpm	off	50.0	29 dB	30.5
LC-1212/2,200 rpm	on	52.5*	31 dB	24.8
LC-1212/2,200 rpm	off	49.5	29 dB	24.8
LC-1212/1,080 rpm	on	50.5*	32 dB	28.4
LC-1212/1,080 rpm	off	36.5	31 dB	28.4

Table 3: Power consumption for each cooling system

system	System description	Power consumption
IBM	fan x 3	$12.6\text{W} \times 3 = 37.8\text{W}$
LCS-1212	Pump + 12 cm fan	$4.2\text{W} + 3.36\text{W} = 7.56\text{W}$
LCS-0808	Pump + 12 cm fan	$4.2\text{W} + 4.2\text{W} = 8.4\text{W}$
LCS-0416	Pump + 4 cm fan x 4	$4.2\text{W} + 1.6\text{W} \times 4 = 10.6\text{W}$



Active Liquid Heat Sink

A new design [9] was created in an effort to simplify the system and remove the external liquid pump of the typical liquid cooling system described above. It is composed of a liquid heat sink, liquid pump, a fan, and a radiator. This new system was called the Active-Liquid-Heat-Sink (ALHS). The main concept of this system is that the liquid heat sink actively pumps the cooling liquid in and out by itself, without the help from outside pumping system. [9] Figure 14 displays the layout of the liquid cooling system and the layout of ALHS. The new design integrates the liquid heat sink and the pump, which eliminates the housing needed for the liquid pump. This reduced the overall dimension of the cooling system. The driving torque of the fan motor is transmitted to the impeller through a magnetic coupling, which means that no extra motor is required to move the cooling liquid.

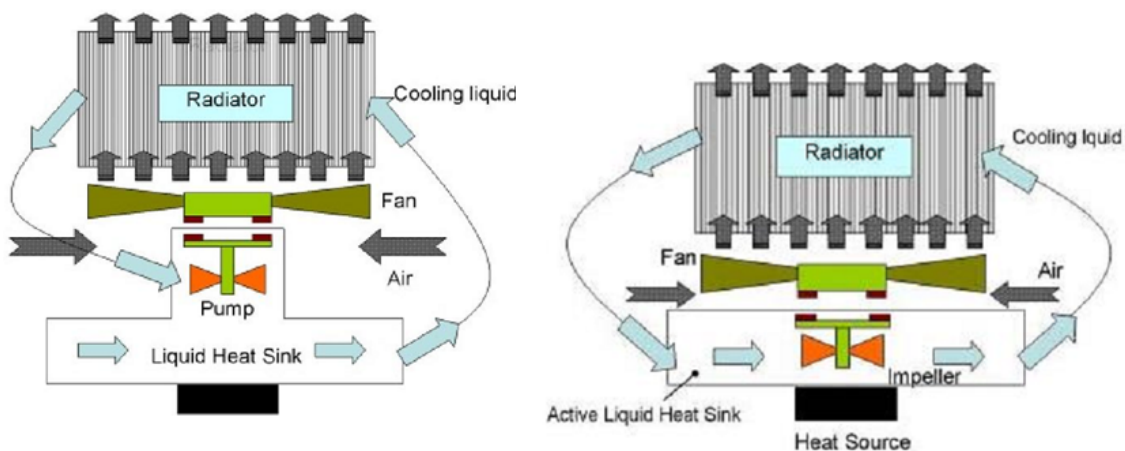


Figure 14: Layout of the liquid cooling system (left) and the ALHS (right)

Figure 15 displays the actual images of the water block cooling system (left) and the ALHS (right). We can see that the ALHS is more compact and is actually comparable to the size of a typical heat sink system.

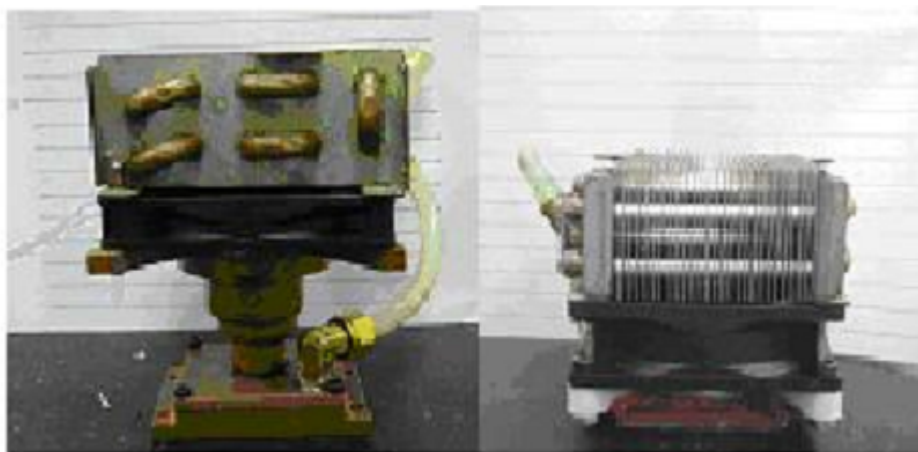


Figure 15: Regular water block v. ALHS

The study also compared the ALHS with three other systems: liquid-cooled system, heat pipe system, and an air-cooled system. We can see in the results shown in Figure 16 that ALHS has the best thermal performance compared to the three cooling systems testing.

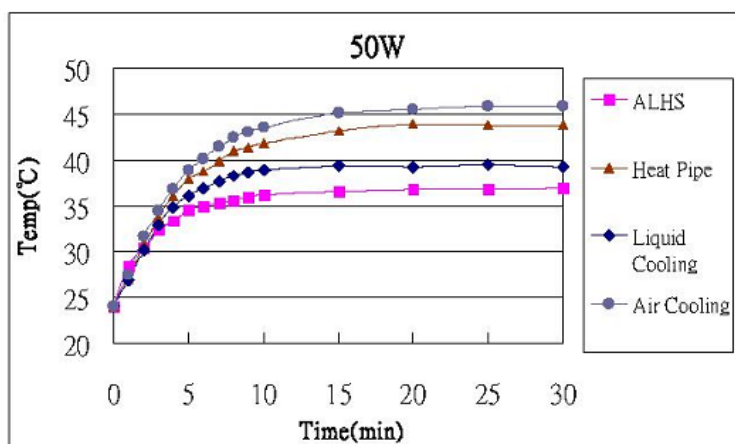


Figure 16: Temperature v. Time

Immersion Cooling

Immersion cooling is another advanced system of cooling CPUs where the coolant is in direct contact with the CPU itself. With this method, most of the contributors to internal thermal resistance are eliminated. Direct liquid immersion cooling offers a high heat transfer coefficient that reduces the temperature rise of the CPU surface above the liquid coolant temperature. [1] One recent technique of immersion cooling is achieved through spray cooling where very fine droplets of liquids are sprayed directly onto the CPU. Cooling of the surface is then achieved through a combination of thermal conduction through the liquid contact with the surface and evaporation at the liquid-vapor interface. [1]

Intermittent spray cooling technique was investigated in a study by [11]. One reason for using intermittent spray cooling is because most systems have varying heat flux and the CPU needs to be cooled in a particular range only. Thus, the spray mechanism is only activated when the temperature of the CPU reaches a certain limit, and is in turn turned off when the temperature decreases to the lower threshold.

The result of this particular study is shown in Figure 17. The study found that for a high heat flux event, the spray cooling is turned on for a longer period. This is because it takes a longer time to cool the CPU. Researchers also observed that temperature fluctuations are minimized when the surface temperature is at a sufficient super heat, due to the cushioning effect provided by the evaporation of liquid on the surface when the spray cooling is off. [11]

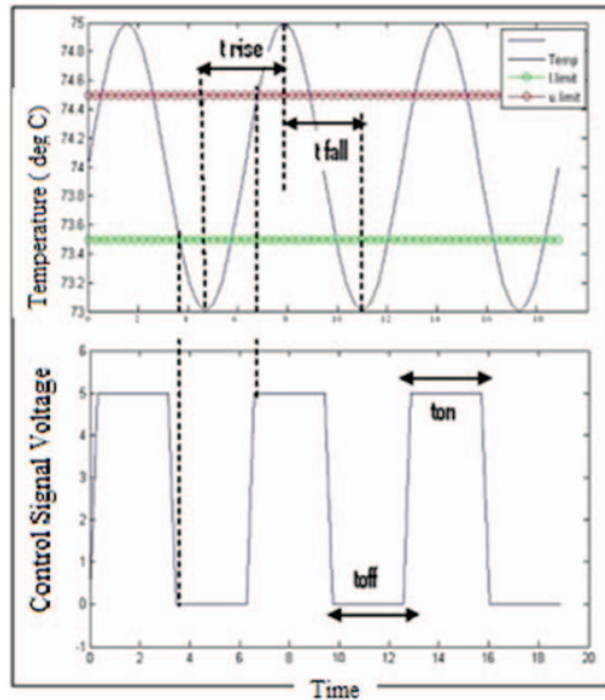


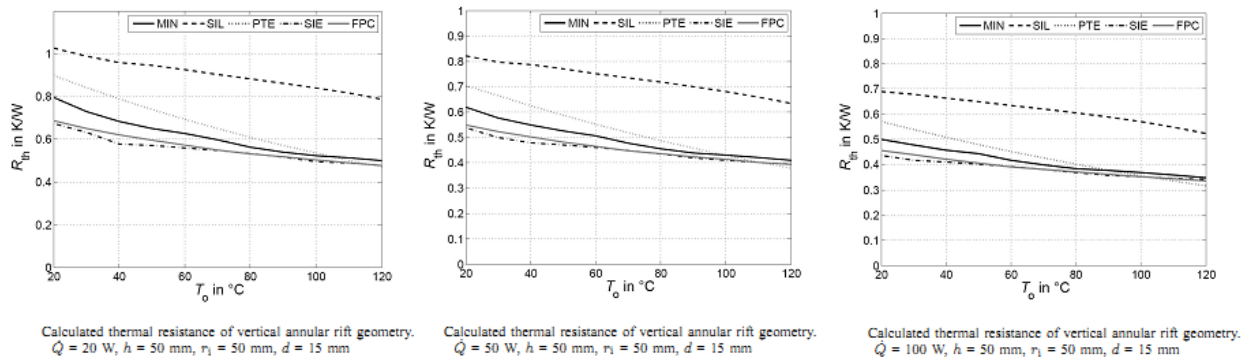
Figure 17: Typical temperature transient and valve state

De-ionized water was used as cooling for the intermittent spray cooling. Research [10] was also done to compare the heat transfer of different dielectric coolants used for immersion cooling. The thermal model used for the comparison of heat transfer is the annular rift geometry model (see [10] for details). The coolants that were studied include mineral oil (MIL), silicon oil (SIL), pentaeryt tetraester (PTE), silicate ester (SIE), and perflourcarbons (FPC). Their thermal properties are shown in Table 4.

Table 4: Thermal Properties of Dielectric Coolants

Fluid Type	ρ kg/m ³	β 1/10 ⁴ K	C_{th} kJ/kgK	k_{th} W/mK	ν mm ² /s
Mineral Oil typ. 20°C 100°C	880 830	8.0 ¹ 8.2 ¹	1.85 2.20	0.130 0.125	25 2.5
Silicone Oil typ. 20°C 100°C	960 930	10.4 10.7	1.5 1.9	0.11 0.09	55 15
Pentaeryt Tetraester Midel® 7131 20°C 100°C	970 913 ¹	7.5 7.5 ¹	1.88 2.26 ¹	0.144 0.135 ¹	70 5.25
Silicate Ester Coolanol® 35R 20°C 100°C	900 840	9 ¹ 9 ¹	2.0 3.2	0.13 0.12	13.5 2.2
Perfluorocarbons Fluorinert® FC40 20°C 100°C	1860 1670	12 ¹ 13 ¹	1.0 1.2	0.07 0.07	2.6 0.54

Figure 18 displays the resulting thermal resistance of the different coolants in varying conditions. The results suggest that all coolants will show improved behavior with increasing temperature. This is because of the decreasing viscosities at higher temperatures that lead to higher Rayleigh and Nusselt numbers. The PTE has a higher thermal performance compared to other liquid as the temperature increases. On the other hand, the SIL and FPC achieved the lowest thermal resistance with lower temperatures. [10]

**Figure 18:** Results of the thermal modeling for different conditions

Thermoelectric Cooling

Another advance cooling system currently under study is the thermoelectric cooling system. Thermoelectric heat pumps perform the same as other cooling systems where the thermal energy is extracted from a region and then rejected to a heat sink. [4] All other systems use moving parts and require a working liquid whereas thermoelectric elements are all solid state.

Passing a current through the heat pump generates a temperature differential across thermocouples. This transfers the heat from one side to another. The system is illustrated in Figure 19.

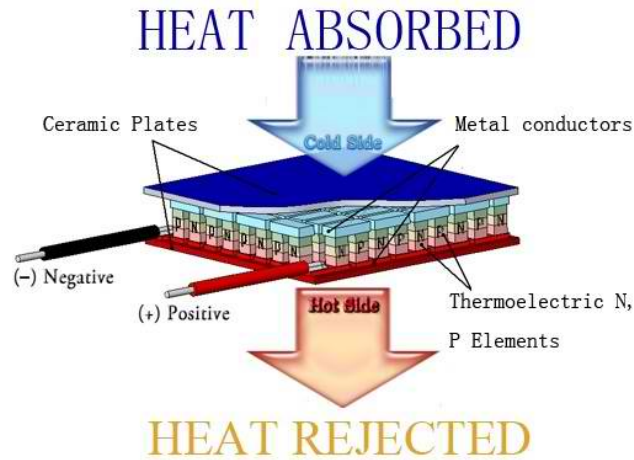


Figure 19: Thermoelectric Cooling System

Researchers compared thermoelectric cooling to three other cooling systems: water-cooling, heat pipe, and heat sink. The results are shown in Figure 20. We can see from the results that the thermoelectric cooling system maintains the temperature of the CPU in an almost constant state.

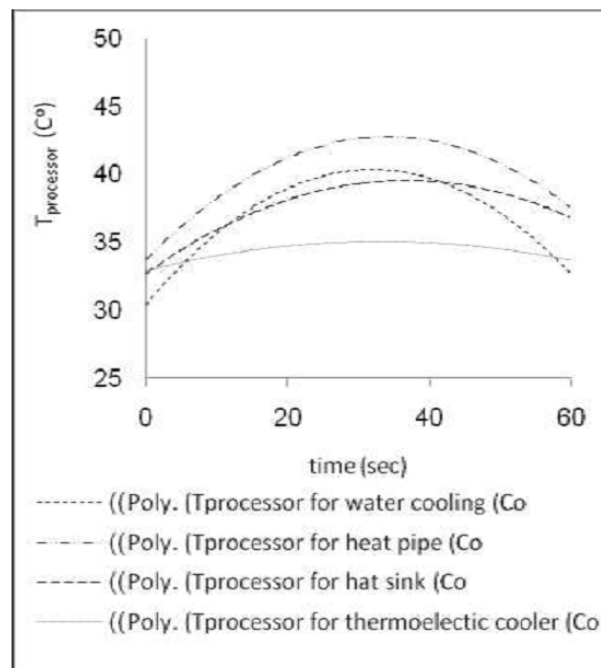


Figure 20: Comparison between processor temperature and time for all systems

Summary

This paper has reviewed different cooling systems beginning with the basic fan-based air-cooling systems commonly used today. Incremental system upgrades were next introduced from one cooling system to another. These include a common cooling method that utilizes a heat pipe cooling system composed of a radiator, heat pipe and a fan, as well as liquid-cooled systems that add a liquid exchanger to the heat pipe cooling design. A system was also presented that involves replacing the typical solid fins of the radiator with a hollow material (head pipes) to increase thermal conductivity. Additionally, the ALHS cooling system was introduced which was created to reduce the size of a typical liquid cooling system. The paper also discussed how CPU immersion could be utilized to remove most internal thermal resistance. The intermittent spray cooling technique was explored which is a type of immersion cooling sometimes used in an effort to maintain the temperature of CPUs within a specified operating range. An alternative technique (thermoelectric cooling system) designed to maintain the CPU in a steady state was explored as well. This method is unique relative to other cooling systems because it uses solid-state materials.

With each system upgrade, CPU cooling and overall thermal management is improved. It is important to note that each upgrade brings new complexity to designs that directly relates to the cost of the selected cooling system. With the current rate of increasing heat flux existing within the semiconductor industry today (and in the future) however, engineers can no longer afford to ignore the benefits that new CPU cooling techniques offer. In the end, the selection of a specific cooling system depends on the application of the CPU. As CPUs continue to advance in terms of computing power in the years ahead, usage of advanced cooling systems such as those outlined within this paper will become increasingly commonplace.

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