Abstract
The inevitable rise in CPU heat generation has sparked intense interest in active cooling devices. A dramatic increase in the number of commercial CPU coolers, including water blocks with and without thermoelectric modules, has occurred in the past 18 months. Some of these coolers use sophisticated jet impingement and microchannel designs, while others are relatively primitive.

This paper discusses the major design issues for this application and the challenges of high heat flux loads for thermoelectric solutions. The most successful designs are described and experimental performance testing of several of the best in class models is presented.

Introduction

SIZZLING SEMICONDUCTORS
growth of watts per square centimeter in microprocessors

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<th>Year</th>
<th>7W/cm²</th>
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*Could be higher, depends on level of integration.
SOURCE: HWJET- PICKARD LABS

Fig 1. The growth of CPU power density

Interest in CPU cooling has become more significant as CPU speed increases generate levels of heat that are becoming more and more difficult for thermal engineers to control. Figure 1 above (sourced from Electronic Business on-line) is indicative of the CPU heat flux levels predicted into the future.

Moore’s Law appears to be still holding and as CPU speed increases exponentially, so does the heat generated. Worse, feature sizes have recently shrunk from 0.25microns to 0.1microns leading to a 6 times smaller area. Computer chip manufacturers have publicly called for wider efforts to address the thermal issues which threaten to restrict computer performance in the future.

Common CPU failure mechanisms tend to be mechanical (wire bond failure, die fracture, corrosion) and electrical (overstress, migration and diffusion, gate oxide breakdown) Following the Arrhenius equation, (for die temperatures operating in the range of -20ºC to 140ºC) every 10ºC decrease in temperature reduces the failure rate by approximately a factor of 2. We can therefore expect a reduction in chip failure rates with lower operating temperatures.

For all of these reasons it has become apparent that heat fluxes are reaching levels that air cooling techniques cannot handle and there has been a consequent shift towards water cooling in the last 12 months. Initially concentrated in the niche “overclockers” sector, water cooling has moved into the mainstream. Notable examples include the recently released Apple G5 and the Sony VAIO RA810G. Beyond this current liquid cooling phase there is a window of opportunity for thermoelectrics to provide active cooling solutions, particularly when a two or three year horizon is considered. CPU heat could increase several times over today’s levels in this period.

Hydrocool Pty Ltd has been researching water-cooling and specifically the application of water-cooling to thermoelectrics since the mid 1990’s with great success. The company has licensed technology to Matsushita Refrigeration Company (MARCO) for applications such as mini-bars, wine storage cabinets and truck cabin refrigerators. Further collaboration with MARCO led to the development of a 126L thermoelectric refrigerator/freezer prototype that rivaled the efficiencies of current vapour compression technology with the added bonus of light weight, low noise and no CFC’s [1]. Not content with this world first Hydrocool achieved further technical success by producing a commercial liquid heat exchange system for a thermoelectric module that has a thermal resistance of 0.01°C/W.

There are particular problems associated with cooling CPU chips, not least of which is the small footprint, (AMD 14.6 x 10 mm), and the consequent high heat fluxes. Specialized designs are required to handle these high heat fluxes with low thermal resistance heat exchangers needed to minimize die temperatures. Hydrocool has found an application for its highly effective heat transfer systems in the burgeoning CPU cooling market. The recently released simple water block (‘HydroStream’) was developed for liquid CPU cooling applications, and is followed by the thermoelectric ‘Hydro-TEC’ active cooler.

These designs are suitable for today’s CPU’s but future thermal loads require a more sophisticated approach. This paper presents descriptions of low
thermal resistance heat exchangers for CPU cooling and thermoelectric system designs for a more advanced cooling capacity.

**Present Solutions: Liquid Cooling and Direct Thermoelectrics**

Up until recently, air-coolers have been able to meet the cooling needs of a CPU through increased size & air velocity. However, further increases in size offer diminishing returns as conductive resistance increases, and further increases in air-velocity are limited by noise considerations. Typical aircoolers have a thermal resistance to a CPU die of 0.4°C/W whereas state of the art heat pipe devices with high speed fans can get as low as 0.2°C/W. As illustrated in Figure 2, the next logical step, which is already starting to be implemented, is liquid-cooling.

Liquid-cooled systems have much higher heat transfer coefficients than air systems, typically 500-1,000 W/mK compared to 50 – 100 W/mK, significantly reducing the thermal resistance at the cpu die. The heat is efficiently transferred through a “waterblock” into a liquid – typically water-based. The liquid is then pumped to a radiator, where the heat is conducted to air-cooled fins and out to ambient air. Radiators alleviate the need for high air velocities by more effective use of the fins, and the availability of larger fin arrays. Thus water-cooling solutions overcome both conduction resistance & airflow limitations, and will allow another generation of die size decreases & CPU power increases.

**Fig 2. Typical values for CPU Cooling solutions**

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**Fig 3. HydroStream Liquid Cooler (cross-section)**

Figure 3 shows Hydrocool’s implementation of the liquid cooling solution in the form of its commercial product, the HydroStream. It is essentially a microchannel heat exchanger consisting of a large number of slender fins. The trade offs between channel heights, channel widths and wall thickness were computationally modeled as detailed by Chandratilleke et al [2].

**Fig 4. CPU Die Test Rig**

Figure 4 shows the experimental setup used to test the efficacy of the waterblocks in a typical CPU cooling environment. Three 50W electrical resistors were attached to a copper block, which spreads the heat evenly produced by the resistors. A small section, 15mm x 15mm, protrudes from the block to simulate the area of CPU die heat generation. The cooling unit under test is joined to the die block with a thermal interface material. A thermocouple measures the temperature of the CPU die block near its cooled interface and inlet and outlet water temperature are measured, as is input power to the heaters. The difference between the average water temperature and the CPU die temperature divided by the heat inputted allows us to calculate a Thermal Resistance to giving an overall measure of performance.

As a system CPU watercooler thermal resistance is the sum of the radiator and the waterblock resistances. Independent review of the HydroStream waterblock rated it as the most efficient CPU water cooler on the market today [3]. From this benchmark we can assume that state of the art waterblocks such as the HydroStream will have thermal resistances of ~0.08°C/W and a large radiator will have a resistance of ~0.02°C/W. This gives a total thermal resistance of ~0.1°C/W for cutting edge watercooling today.

Unfortunately, watercooling is limited by the conduction and convection resistances in the water-block and by the space available for the hot side radiators. Inevitably, these limitations will be reached, necessitating an active cooling solution to service higher cpu heat loads in the future.

Thermo-electrics offers some unique advantages compared to other active cooling technologies. These include:

- Low cost and long service life
- Low energy consumption
- No special skills required for installation or servicing
- Environmentally friendly & safe.
- Compact, quiet and lightweight
- Highly controllable cooling power

Depending on the manner of implementation some, or all of these advantages, may be lost.

The first application of thermoelectrics to CPU cooling considered here involves a thermoelectric module bonded to a plate of conductive material, adjacent to the CPU. The function of this plate is to spread the heat from the CPU to the cold side of the module. The heat is then dispersed from the module hot side into the fluid stream and from there into ambient air via a radiator. This application method shall be referred to as direct thermoelectric cooling. Figure 5 shows a schematic of this direct thermoelectric system.

![Fig 5. Direct Thermoelectric CPU Cooler Schematic](image)

Figure 6 shows Hydrocool’s implementation of the direct thermoelectric cooling solution the form of its commercial product, the HydroTEC.

![Fig 6. HydroTEC Direct Thermoelectric CPU Cooler (cross-section)](image)

It is essentially the same microchannel heat exchanger used in the HydroStream product soldered to a commercial thermoelectric module which itself is soldered to a copper ‘spreader’ plate.

The experimentally determined performance of the HydroTEC utilizing a Kryotherm 08 module (dTmax 69K) at 24V (Qmax) is shown in Figure 7. A radiator of thermal resistance 0.02°C/W was used.

![Fig 7. HydroTEC Direct Thermoelectric CPU Cooler Performance](image)

It is apparent from these results that for a power consumption of 245W this direct thermoelectric device can maintain a 93W processor at ambient temperature (25°C).

Future Solutions: Thermoelectric Chillers

In many ways the direct thermoelectric solution above does not fully exploit the advantages of thermoelectrics. CPU die areas are typically 7 times smaller than thermoelectric modules (15x15mm as opposed to 40x40mm). Attempts to use spreader plates to remedy this situation eventually will be limited by the conduction resistance of the spreader.

![Fig 8. HydroTherm Thermoelectric CPU Cooler](image)

Figure 8 presents a more elegant solution in the form of a thermoelectric unit that chills a fluid that is then passed through a conventional waterblock onto the CPU die. The core of the system is a bank of multiple thermoelectric modules run at or close to their...
maximum COP bonded to high efficiency microchannel heat exchangers. This design is under development at Hydrocool and known as the “HydroTherm”.

**Figure 9.** Thermoelectric CPU Chiller Schematic

Figure 9 shows a schematic of a thermoelectric chiller as applied to a CPU cooling application. Thermoelectric CPU chillers have several implicit advantages. They overcome the limitations of conduction resistance by lowering the temperature of the conductive medium that is adjacent to the CPU die, thus increasing the driving temperature differential. Both the hot and the cold side of the modules have access to highly effective heat transfer devices. Additionally they utilize the entire heat transfer surface of the module and distribute the load over several modules, allowing improved COPs.

The performance of the above system was modeled using four of the same Kryotherm Drift 0.8 modules as for the direct thermoelectric system (HydroTEC) each run at 12V (close to their optimum COP) instead of 24V. These were bonded in series to the same microchannel heat exchanger used in the HydroStream, which has a thermal resistance of 0.015°C/W (heat transfer coefficient of 41600 W/m²K) across a full 4cm x 4cm interface. A radiator of thermal resistance 0.02°C/W. The results are shown in Figure 10.

**Fig 10.** HydroTherm Thermoelectric CPU Chiller Performance

The results of careful design now become clear. In contrast to the direct thermoelectric design, the thermoelectric chiller can maintain an 180W processor at ambient temperature (25°C) for a power consumption of 220W. Or in other words, for slightly less power the new design can cool a processor twice as ‘hot’.

Prototype construction of the HydroTherm system is currently underway to confirm modeled expectations as well as further modeling to investigate the system sensitivity to ZT as well as different quality’s of radiators and liquid heat exchangers.

**Conclusions**

To enjoy the benefits of increasing computing power in the next few years creative heat transfer solutions are required to control rapidly increasing CPU heat loads.

The evolution of CPU cooling has passed from forced convective air cooling to liquid cooling. It is likely that in the next few years even high efficiency water coolers such as those developed by Hydrocool Pty Ltd will be superceded by active cooling technologies.

Thermoelectrics is ideally placed to take a leading role in this phase of CPU cooling but careful design of this application is required. An example of a well designed thermoelectric chiller system has been presented which allowed a doubling in the cooling ability of the direct thermoelectric cooling option.

**References**

3. As reported at time of publication on: http://www.overclockers.com/articles373/wbsum.asp