The Benefits of Liquid Cooling over Air Cooling for Power Electronics

Designers of power electronics have long favored cooling heat-generating devices with air rather than with liquid. Some advantages of cooling with air are its abundant availability, high dielectric strength, and ease of employment for heat removal. Up until now, liquid cooling posed the risk of damage to the delicate electronics in the event of a leak, and the complexity of the hardware required to control and circulate the liquid brought added design and build costs.

In spite of its broad market appeal, however, air cooling will not keep pace with the needs of tomorrow's more powerful systems, with their increased heat generation, higher outputs, and smaller package sizes.

Air Cooling

Historically, forced- and natural-convection air cooling has been the predominant method of cooling electronics. If natural airflow is insufficient for direct cooling without an extended surface, a heat sink will improve the thermal transfer, reducing the temperature of the heat-generating device. If additional cooling is necessary, a fan will increase the airflow over the heat sink to dissipate more heat. With the exception of a fan or other air-moving device, basic air cooling of electronics requires no external equipment. Liquid cooling, on the other hand, requires auxiliary support equipment.

As power levels and the density of this power (watts/sq. inch) increase, today's electronics generate more waste energy in the form of heat. Therefore, air-cooled heat sinks must have more surface area to effectively transfer the increased heat load and control the temperature of the semiconductor package. Although innovative constructions increase the surface area without substantially increasing the volume of the heat sink, heat sinks must ultimately become larger as the required surface area expands. In turn, to cool a high-density heat sink, a fan must be large enough to overcome significant backpressures. Using a fan in conjunction with the heat sink provides additional cooling, but fills valuable space with the fan, the fan mount, and airflow entry and escape paths. In an environment that demands maximum functionality out of every bit of real estate, the extra space that is required for air cooling becomes a necessary evil.

Liquid Cooling

Liquid cooling counters almost every drawback of air cooling. It can dissipate more heat with considerably less flow volume, maintain better temperature consistency, and do it with less local acoustic noise.

The physical properties of the cooling media form the basis of heat removal in convection cooling. Because of its low density, air has a reduced ability to carry heat per pound (specific heat). In comparison, water is denser and is capable of carrying a considerable amount of heat per pound. The combination of a cooling medium's density and its specific heat equal its ability to carry and remove heat. The details of the physical properties of air and water can be found in Table 1.

Medium	Specific Heat	Mass Density
Water	4217 J/kgÂ·Â°C	998 kg/m^3
Air	1060 J/kgÂ·Â°C	1.2 kg/m^3

Table 1: Properties of Common Cooling Media

The ability to remove and carry heat is important when used in combination with the following basic mass flow equation:

Temp. rise of fluid = Power (in watts)/(Specific Heat x Mass Density x Flow Volume)

As an example, the following calculations show the difference in the flow volume required to dissipate 1000 watts of heat with a 10Â° C temperature rise in the fluid:

Air
Flow Volume m^3/sec = 1000 watts/(1060 J/kgÂ·Â° C x 1.2 kg/m^3 x 10Â° C)
Flow Volume = 0.079 m^3/sec = 79 liters/sec

Water
Flow Volume m^3/sec = 1000 watts/(4217 J/kgÂ·Â° C x 998 kg/m^3 x 10Â° C)
Flow Volume = 0.000024 m^3/sec = 0.024 liters/sec

Air must flow at 167 cubic feet per minute to carry 1000 watts of heat with a maximum temperature rise of 10Â° C in order to achieve sufficient cooling. Conversely, water requires only 0.36 gallons per minute (0.049 cubic feet per minute) to dissipate the same amount of heat with the same temperature rise, a significant reduction in flow volume when compared to air.

Another factor when considering the benefits of liquid cooling is the impact that elevation has on air cooling performance. As elevation above sea level increases, air changes density. Because air-moving devices, such as fans, are constant volume pumps, whereas cooling is dependent upon mass flow, this density change will have a significant effect on the resulting temperature of an air-cooled device. An increase of 5000 feet above sea level, for example, means a 14% reduction in the performance of an air-cooled heat sink. On the other hand, elevation has no adverse impact on the performance of liquid-cooled heat sinks, because they utilize a constant mass pump.

Heat Sink Volume Comparison

The surface area exposed to the cooling airstream determines the size of an air-cooled heat sink. The basic convection heat transfer equation defines that the effective heat transfer times the exposed surface area is directly equal to the amount of heat that can be removed. This detailed equation shows the effect that surface area and the amount of heat transferred per square foot have on the amount of heat removed:

Q = H x A x Dt

Where:

Q = heat removed in watts

H = heat transfer coefficient (heat transferred per square meter)

A = surface area (square meters)

DT = temperature difference (rise in temperature of the cooling medium

A typical heat-transfer coefficient for forced-air cooling is 20 watts/meter^2 Â° C, and a typical heat-transfer coefficient for moving water is 9000 watts/meter^{2}Â° C. Since liquid has a much higher heat-transfer rate, the amount of surface area necessary for heat dissipation decreases significantly. To cool the example used above, the following equations would apply:

For air cooling: Area = Q/(Hair Â· DT) = 1000 W/(20 W/m^{2}Â°C Â· 10Â°C) = 5 m^2

For water cooling: Area = Q/(Hwater Â· DT) = 1000 W/(9000 W/m^{2}Â°C Â· 10Â°C) = 0.011 m^2

The surface area that is required with water cooling is hundreds of times smaller than that required with air cooling. The net effect of this difference in cooling surface area is the reduction of the overall volume of the heat sink. In strict comparison, an air-cooled heat sink, based on standard manufacturing techniques, would have an approximate volume of over 5000 cubic inches. A liquid-cooled heat sink achieves the same level of cooling in a volume of less than 15 cubic inches.

Acoustic Noise Comparison

In order to achieve significant heat transfer in forced-air convection cooling, the speed of the air past the fins of the heat sink must be sufficient to promote turbulent flow patterns. Air velocities for cooling high-power products typically exceed 1000 linear feet per minute (LFM) between the fins of the heat sink. Airflow at this speed generates noise from two sources: the air mover (from the motor and the fan), and the friction of air moving between the cooling fins. Because the higher power devices are demanding larger fans, the increased local acoustic noise is reaching the point where it is unacceptable in an office environment.

Liquid-cooled electronics, on the other hand, remove most of the noise-producing sources from the electronics rack to a site remote from the day-to-day user. The circulation pump used to supply liquid flow moves a much smaller volume of fluid, which also reduces the noise. Liquid in the cooling channels typically travels at less than 400 LFM, and is completely enclosed inside the cold plate. Remote location of the support equipment (circulation pump, heat exchanger, and cooling fan) allows the area immediately surrounding the power supply to remain quiet.

Conclusion

No matter what advantages air may have over liquid, it simply will not remove sufficient heat from the more powerful, tightly configured systems that are on today's drawing boards. This leaves designers few alternatives but to examine liquid cooling for tomorrow's hot electronics. A liquid-cooled heat sink that reduces the risk of leakage and incorporates less obtrusive, more cost-effective support equipment is providing designers with the optimal cooling solution for these difficult applications.