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Liquid-Cooled Heatsinks

Enable Smaller, Cooler Devices

- Evolution of Smart Power Relays
- Bypass Capacitors for Point-of-Load Architecture
- Synthesis of Near-Zero Emissions Power Converter—Part 4
- Improving Efficiency with Active Clamp Technique

A PRIMEDIA PUBLICATION

Liquid-Cooled Heatsinks

Image courtesy of **Ferraz Shawmut Inc.**, Newburyport, Mass.

Careful consideration of mechanical, hydraulic, power, and cost requirements helps determine the best thermal management solution for high-power applications.

Enable Smaller, Cooler Devices

By **Jean-Christophe Bertrand**, Ferraz Shawmut Inc., Newburyport, Mass.

Although today's advanced microelectronic technology enables the design of ever-smaller semiconductor devices, the size limits and operating performance of these new devices are largely determined by the amount of heat [W/m^2] that can be removed from the unit. Industrial components such as high-power drives for paper mills, large rectifiers for aluminum processing plants and large induction generators are built using the latest technology. These high-power semiconductors include silicon-controlled rectifiers (SCRs) and insulated gate bipolar transistors (IGBTs) that frequently have current ratings of 1000A and up along with very high commutation frequencies. To keep the power semiconductor operating below its maximum junction temperature and prevent possible damage or decreased life expectancy of the device, on-state power losses and power switching losses must be dissipated.

Modern heatsinks (see **Photos 1** and **2**) serve to manage this thermal challenge by controlling the temperature of the power semiconductor and keeping the application running below its thermal limits.

Heatsink Design Options: Air or Liquid-Cooled?

In designing any type of heatsink, there will always be a compromise between the required thermal resistance (Rth) and the acceptable pressure drop for the given application. This is because no matter what cooling medium is used, all heatsinks will have a thermal resistance and pressure drop in function of the coolant flow. Although air is the most readily available medium to use, certain disadvantages to air-cooled heatsinks make it an impractical solution for some high-power applications. Heat removal is proportional to the surface area of the device and the volume of coolant moving along the heat transfer surface. Compared to water or other liquids, air has a very poor heat transfer coefficient (**Fig. 1**, on page 16). With high-power semiconductors, the fans required to move the necessary volume of air across the heatsink fins generate a substantial amount of unwanted noise. The use of water or other liquids not only cools more efficiently, they minimize nuisance noise.

Although liquid-cooling has traditionally been avoided in some industries, high-energy applications such as induction heating demand the

Photo 1. *Brazed cold plate used in a bolt-in design and a brazed cold plate for a press-pack semiconductor assembly.*

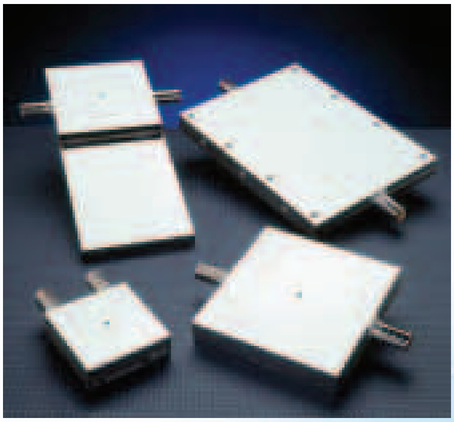

Photo 2. *Several different brazed cold plate designs.*

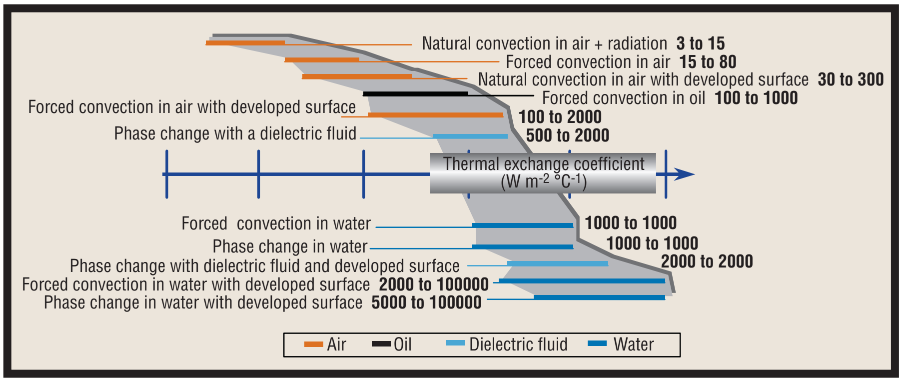

Fig. 1. *Graph depicting heat transfer properties of air, oil, dielectric fluid and water.*

most efficient thermal management available and frequently rely on liquid-cooled designs. These applications push semiconductors to their limits, and the only viable solution to the increasing thermal stress is to use liquid-cooled systems. Plus, as device sizes continue to shrink, the advantages of liquid-cooled heatsink designs become even more clear.

In the United States, the power electronics industry generally requires copper to be used in its liquid-cooled systems because copper buss bars are also cooled by the same water. The following paragraphs detail the different liquid-cooled heatsink designs available in the U.S. market. Please note that as every application is unique, accurately quantifying and comparing the many different thermal management methods would require detailed testing to be performed on the same device using all the techniques available. For these reasons, we will constrain our discussion here to the basic technologies and principles behind each technique, and the advantages and disadvantages of each method.

Embedded or Pressed Copper Tube in Aluminum Plate

Embedded or pressed copper tube in aluminum plate is one of today's most widely used thermal management techniques. The basic process for manufacturing heatsinks employing this method is to machine a groove in an aluminum plate and insert a copper tube inside the groove. A bonding agent, such as epoxy, is then added to the component to secure the copper tube to the aluminum plate. Finally, the plate is then skin-cut to achieve a flat surface.

The advantages inherent to the embedded or pressed copper tube technique are that the resulting heatsinks are generally quite light and fairly inexpensive, depending on the geometry of the design (the configuration/layout of the groove machined into the aluminum). In addition, this method offers a low pressure drop. Some manufacturers have made further improvements by using copper tubing with rough inside walls. This increases the turbulence within the copper tubing and improves the heatsink's heat transfer capabilities. The combination of the light package and inexpensive design make this an attractive option (**Fig. 2**).

However, it's important to recognize several disadvantages when contemplating the use of the embedded copper tube technique. For one, there are issues concerning the uniformity of the device's cooling performance. Depending upon the geometry of the design, the cooling provided may not be uniform across the surface of the semiconductor. For double-sided applications, the thermal characteristics of both sides of the heatsink may not be exactly the same. Also, the way in which these heatsinks are constructed can present potential issues. For example, the epoxy or compound used to bond the copper tube to the aluminum plate is known to increase the device's thermal resistance. Over time, both of the compound's mechanical characteristics and thermal resistance can change, possibly altering the heatsink's performance. Also, the fly-cutting operation used to make the copper and aluminum flush can possibly weaken the tubing's walls and compromise the integrity of this heatsink design.

To address these issues, Ferraz Shawmut has developed a brazing technique to bond the copper tube to the aluminum plate. This technique minimizes the resistance of the heat transfer from the tube to the aluminum plate and provides stable mechanical and thermal characteristics.

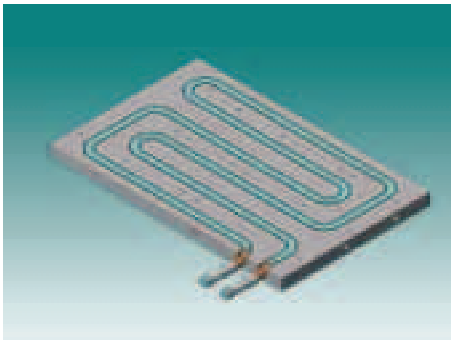

Fig. 2. *Typical copper tube embedded in aluminum plate heatsink design.*

Expanded Copper Tube in Aluminum Plate

The use of an expanded copper tube in an aluminum plate is another accepted thermal management solution. This design consists of copper tubes placed in gun-drilled holes in an aluminum plate. The tubes are expanded to provide a good mechanical connection with the aluminum, and finally linked together to create the liquid path. The advantages of this type of design are that there is no need to use epoxy or other compounds to bond the copper to the aluminum and that the fly-cutting operation will not weaken the copper tube's walls. In addition, heatsinks employing this design will have the same thermal resistance on both sides—an obvious advantage for applications requiring double-sided cooling. As possible downsides, the cooling may not be uniform along the entire heatsink surface, the extra connections required to link the copper tubes can raise the potential for leaks, and the tubes outside the plate add unnecessary volume to the heatsink package.

Gun-Drilled Copper Plate

The gun-drilled copper plate method consists of a thick copper plate gun-drilled at different angles and locations parallel to its surface. The holes are then plugged, or tubes are added, to create the liquid path. Offering thermal performance similar to that of the expanded copper tube in aluminum plate technique, this method is also widely used.

The upside of this thermal management technique is that both sides of the heatsink will offer the same thermal resistance. The potential downsides to this design include that the thermal performance may not be entirely uniform across the heatsink's surface, and any liquid paths drilled into the plate at a 90° angle will produce a much higher pressure drop than other available heatsink designs. In addition, heatsinks incorporating the gun-drilled copper plate method tend to be heavy, which may be undesirable for certain applications.

One-Piece Castings

Heatsinks employing one-piece castings are primarily used to cool press-pack semiconductors. In this type of design, the semiconductor unit is sandwiched between the heatsinks and the pressure ensures that the available current flows smoothly through the device. One-piece castings offer high-performance cooling that is uniform across the entire semiconductor surface. This method is also reliable, as the heatsink unit is free of any seams.

Despite these performance advantages, some cost and application considerations must be made. One-piece castings are expensive for low-volume cooling. Also, new designs require new tooling, raising costs and limiting the flexibility of this type of design.

Direct Cooling

Direct cooling method involves making the semiconductor unit a physical part of the heatsink. IGBTs are well suited for use with this type of thermal management. In this scenario, the semiconductor case becomes the top part of the heatsink, and an o-ring ensures the unit is watertight. The final assembly is bolted together to form a complete component.

While the direct cooling method's integrated design reduces thermal resistance and allows for uniform cooling across the entire semiconductor surface, there are often concerns about the long-term integrity of this type of design. For example, in the event of an IGBT case rupture, a leak could occur that may damage equipment.

Bolted Cold Plate

The bolted cold plate method of thermal management consists of two machined copper plates bolted together. Similar to the direct cooling method, an o-ring is used to ensure that the unit is watertight. This technique is generally a low-cost solution, as no bonding agent or brazing of the plates is required to join the two halves of the heatsink. Heatsinks incorporating the bolted cold plate technique should allow uniform cooling across the entire semiconductor surface.

Possible disadvantages inherent to this technique include the weight of the heatsink, which can be heavy and less-than-ideal for certain applications. In addition, the reliability of the seal between the two halves of the heatsink is questionable. Over time, the o-ring may fail, exposing components to a possible leak and further failure. If the device is in the presence of vibrations from surrounding equipment, the risk of failure is increased even further.

Brazed Cold Plate

Finally, recent developments in the brazed cold plate technique have made this method a high-performance, highly reliable thermal management solution for today's demanding application requirements. Manufacturers looking for the best cooling device available are likely to choose this technique. The basic design of heatsinks incorporating the brazed cold plate technique is similar to that of bolted cold plate designs, with the exception being that the top and bottom halves of the machined copper

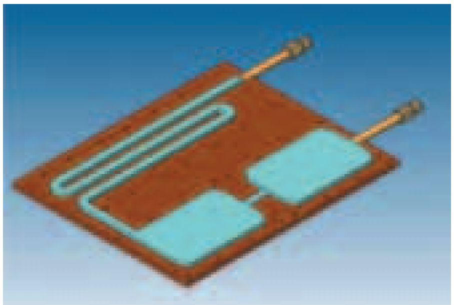

Fig. 3. *Brazed cold plate heatsink design; liquid path geometry detailed.*

plates are brazed, rather than bolted, together. Along with eliminating the need for an O-ring and potentially compromising the integrity of the heatsink, the advantages of brazing the plates together are many.

The brazed cold plate method enables reliable, uniform cooling across the entire semiconductor surface. Moreover, because its design involves two distinct cold plate halves that will later be securely fitted together, it opens up many possibilities for the geometry of the internal liquid path. This latitude allows the greatest application flexibility so heatsinks incorporating this technology will provide the optimum thermal performance. When such a part is being developed, depending on the component wattage that must be dissipated, a multitude of liquid path designs can be applied, enabling the best thermal resistance for the required pressure drop allowed. When all engineering considerations are made at the early stages of the project, a very effective cold plate can be designed within a compact footprint.

For example, in a custom-made brazed cold plate designed to cool four IGBTs (double-sided) and various other power electronics components, the four IGBTs require the removal of a large number of watts. To achieve this goal, the liquid channel covers the entire surface where the IGBTs will be located with a design allowing a maximum of turbulence and internal surface area to remove heat. Since the other half of this cold plate does not require the same performance, a standard U-shape channel is sufficient, which in turn reduces the pressure drop of the entire system

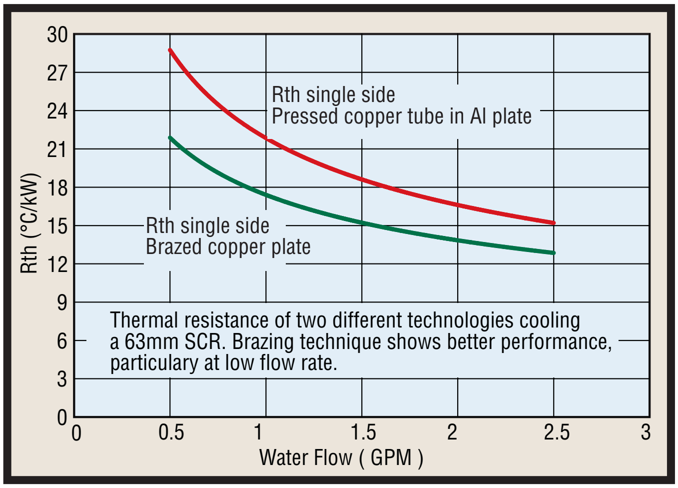

Fig. 4. *The brazing technique shows better performance than the pressed copper tube in aluminum plate technique, as you can see in this comparison between the two technologies.*

(**Fig. 3**, on page 21).

Many times, equipment manufacturers already have their own cold plates but have reached the thermal limits of their existing designs and must remove even more heat from their component. In these cases, custom cold plates can be designed to meet the customer's specific needs. Again, the greatest advantage of brazed cold plate technology lies in the nearly unlimited variations of liquid path designs that can be achieved. We've learned the liquid path designs that provide the most heat exchange and limit the component's pressure drop the most. This is particularly important when using liquid with a higher viscosity than water. The liquid path can be designed so the heatsink can withstand the pressure when mounted on press-pack assemblies.

One of the main difficulties behind brazed cold plate technology is ensuring a good brazing of the two cold plate halves. To eliminate possible clogging due to excessive brazing and promote an exceptional mechanical bond and watertightness, excellent process quality control is required. Heatsinks employing this technique are generally of a higher density, and larger heatsinks are more expensive to make due to the brazing operation; however, for the most demanding applications, this technique is an excellent choice in thermal management (see **Fig. 4**).

Today's advanced microelectronic technology is pushing semiconductor devices to their thermal limits, underscoring the importance of a well-designed, reliable heatsink. Unlike fuses and semiconductors that can be standardized in size and performance, high-power thermal management is always customized for each individual application. To select the thermal management method that best meets the needs of application at-hand, the OEM should collaborate closely with the heatsink manufacturer at the earliest possible stages of the design project. After carefully considering the application's mechanical, hydraulic, power, and cost requirements, the OEM and heatsink manufacturer will together be able to design a solution that delivers the optimum combination of performance, size, and cost. **PETech**

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