Heat Pipe Reliability in High-Power Applications

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A well-designed, carefully built and appropriately applied heat pipe can achieve an operating life in excess of 15 years. With short-term, high- temperature screening and numerical analysis, heat pipe life can be predicted.

Over the past decade, the use of heat pipes in electronic cooling applications has increased dramatically, primarily in notebook computers. In fact, virtually every notebook computer manufactured today uses at least one heat pipe assembly. Typically used to carry less than 25 W of power, these parts are low in cost and highly reliable.

Use of heat pipes in high-power (>150 W) cooling applications has been limited to custom applications requiring either low thermal resistance or having a severely restricted enclosure area. The cost of these larger diameter heat pipes was high due to a limited number of manufacturers and handmade assembly times.

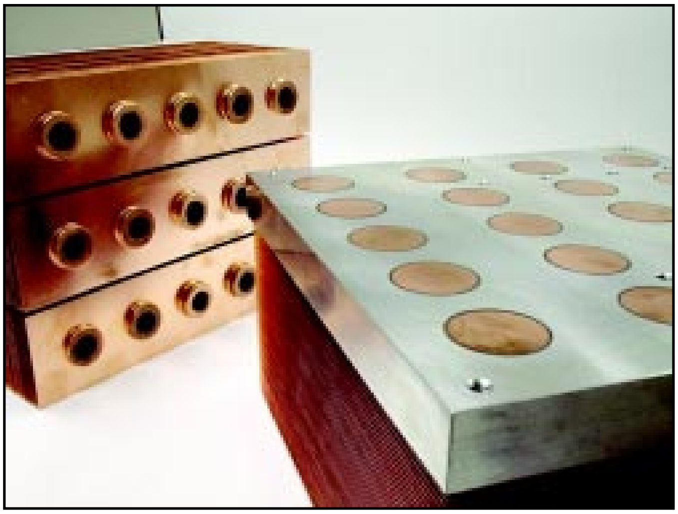

Fig. 1. *The extreme heat loads and flux densities experienced by the latest generation of semiconductor power modules demand the use of heat pipes to enhance base-plate heat spreading. When heat pipes are mounted in the Z-axis of the heatsink, perpendicular to the base-mounting surface (as shown above), they can boost fin efficiencies by nearly 100%.*

Enter now the latest generation of IGBT and other semiconductor power modules. These modules offer high-power outputs and even more challenging power densities—cooling of the modules at full rated output power is virtually impossible. As in modern microprocessors, the removal of waste energy in the form of heat has arguably become the most challenging engineering task of the mechanical design effort.

These heat loads and flux densities are so high that in many cases conventional air-cooled aluminum extrusion and even bonded fin heatsinks will not provide sufficient cooling. Using forced air-cooling, they cannot remove heat fast enough to keep the module from exceeding its maximum recommended junction temperatures. The introduction of a solid copper heat spreader (copper has 2X the conductivity of extruded aluminum) into the base of an extrusion also will not suffice.

Historically, some high-power systems have used heat pipes to enhance base-plate heat spreading in different modes as the solution to keep systems using air-cooling and keep them away from liquid cooling (Fig. 1). A heat pipe has an apparent conductivity many times greater than copper and relies on the latent heat of vaporization of a working liquid inside a heat pipe to operate.

Reliability and longevity of these closed-loop coolers and the systems they are used in now become a large issue. What will happen if the heat pipe stops working? What MTBF can be expected from these large diameter heat movers? Is there any way to ensure they keep working up to and beyond the expected life of the system?

Heat Pipe Operation

Basically a heat pipe is a partially evacuated, closed vessel that recirculates a small amount of working fluid, which through the addition of heat, changes from liquid to gas.

Condensing that gas back to a liquid and releasing the absorbed heat requires additional cooling surface or other means of heat removal.

In operation, a heat pipe absorbs significant amounts of heat in the evaporator section as it reaches a set temperature. The working fluid and the partial pressure inside the pipe set this temperature. Heat of vaporization of the liquid allows for high quantities of heat to be absorbed at a given temperature. This is similar to liquid water at 100°C vs. steam at 100°C. The additional heat absorption is required to change phase.

Heated gas moves to the cold end of the heat pipe at nearly the speed of sound and under nearly isothermal conditions. At the condenser section the gas cools slightly, releasing the heat gain, reverting back to a liquid. This entire cycle usually happens with less than a 5°C differential from one end of the pipe to another.

Operation takes place at virtually the same temperature and does not depend on where the heat enters or leaves the heat pipe. Depending on pipe diameter, this process can move hundreds of watts a distance of many inches, offering an apparent thermal conductivity of thousands of W/mK (Fig. 2).

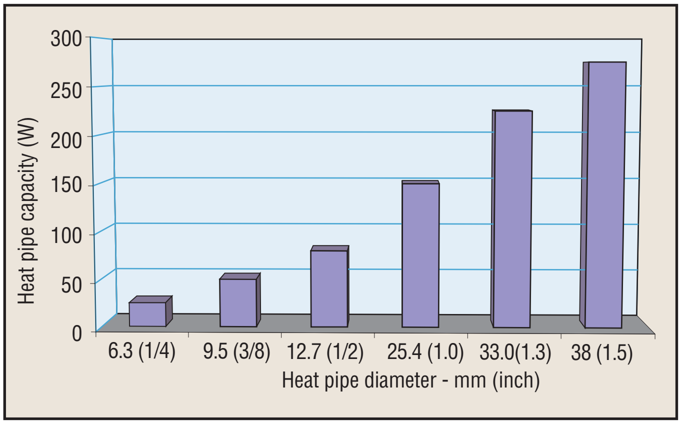

Fig. 2. *Heat pipe capacity as a function of diameter.*

> To make it operational, a heat pipe must have as much cooling surface area in form of fins as the equivalent-size air-cooled heatsink without a heat pipe.

Heat pipes offer many advantages in their use and operation. First, a heat pipe by itself does not remove or dissipate heat. It is only a conduit through which heat can be moved from one point to another with a low thermal resistance. To make it operational, a heat pipe must have as much cooling surface area in form of fins as the equivalent-size air-cooled heatsink without a heat pipe. It must also have a high conductivity thermal contact to the heat source to bring heat into the heat pipe.

Heat pipes are orientation-sensitive in relationship to gravity. Heat pipes will carry large amounts of heat when they operate in a heat-down, cooling-up attitude. This orientation allows for the rapid return of cooled liquid to the evaporator. Heat pipes also will operate with little loss of conductivity in a horizontal attitude. However, operation in a heat-up/cooling-down orientation must be carefully engineered. Depending on the style of wick or liquid return capillary, most heat pipes will lose some efficiency.

Z-axis Heat Removal

Most high-power heat pipe applications have used heat pipes or vapor chambers (a flat heat pipe) to help heat spreading under the base of a power module. Many times a series of round heat pipes are embedded in a heatsink base to help average the temperature of the aluminum mounting plate.

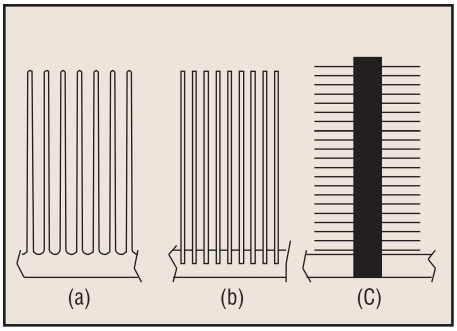

Fig. 3. *A comparison of fin efficiency for a high ratio extrusion heatsink (a), a bonded-fin heatsink (b), and a heatsink with heat pipe assembly embedded in the Z-axis (c). Overall thermal performance varies from 100% for the extrusion to 150% for the bonded-fin heatsink to greater than 200% for the heatsink with heat pipe assembly.*

Although this is a positive step, it still leaves conventional air-cooled fins or extended cooling surfaces operating at fin efficiencies often as low as 50% to 60%. Heat pipes used in the Z-axis, perpendicular to the base-mounting surface, can offer fin efficiencies approaching 100%.

Fig. 3 shows a comparison of fin efficiencies and overall thermal performance for three types of heatsinks—a high ratio extrusion, a bonded-fin heatsink, and a heatsink with a heat-pipe assembly mounted in the Z-axis.

For an extrusion with a fin area of 1X, the fin efficiency is 70% to 90%, and the overall thermal performance of the heatsink is 100%. For a bonded fin heatsink of the same size, a fin area of 1.5X is achieved, which produces a fin efficiency of 60% to 80% and an overall thermal performance of 150%. In the case of the heatsink with heat-pipe assembly, a fin efficiency of 3X is possible. This heatsink achieves a fin efficiency as high as 90% to 95% and an overall thermal performance greater than 200%.

Heat pipes with the ability to move heat with near-zero temperature rise are employed as conduits to eliminate this fin efficiency problem. Z-axis cooler design uses large diameter heat pipes mounted through a base plate heat spreader, perpendicular to the heatsink mounting surface. Heat spreaders integral to the heat pipes are positioned in the base plate to make maximum contact to the high heat flux sites (die positions) under the power module.

The heat pipes move heat away from the base plate and use a series of thin, copper fins attached to the pipes to dissipate this heat into a forced air stream. Due to the effects of the heat pipe, the copper fin furthest from the base plate will have virtually the same fin efficiency as the closest fin. This allows significant increases in fin count and cooling surface over an extrusion type heat sink. In many cases Z-axis coolers can increase cooling of a power module (IGBT or similar device) by up to 100%.

Heat Pipe Reliability

Over the past 40 years of heat pipe design and manufacture, reliability and consistency of performance have always been issues. Do heat pipes leak over long periods of time? Can they continue to operate at their limits for years? What are their limits?

To understand heat pipe longevity and potential failure, it is necessary to understand the manufacturing steps and design for reliability. Virtually 100% of prematurely failed heat pipes come from:

- Improper cleaning/oxidation of the interior.
- Improper filling or charging.
- Poor sealing or potential leakage over time.
- Incompatible materials.
- Overtemperature during assembly.

Failures also can be seen as the result of designers not understanding the limitations of heat pipes in application and long-term use. In terms of longevity, how a heat pipe is applied is just as important as how it is assembled. In short these failure modes are:

- Dry-out (high heat loads/heat fluxes).
- Improper orientation to gravity.
- Sealing/crimp problems.
- Flex failure due to shaping.
- Catastrophic failure due to too high temperature at assembly or in operation (Fig. 4).

Predicting Operational Life

Heat pipes are similar to semiconductor electronics in that they demonstrate higher failure rates at start-up, due to initial infant mortality, and at the end of life, due to wear-out. After passing the first few hours of operation, a heat pipe will normally operate for many tens of thousands of hours before failure occurs.

In many real-life, high duty-cycle applications, large diameter heat pipes have been in operation for more than 20 years without failure. These applications include steel-wheel locomotive and traction drive, electrically powered people movers, as well as wind power generators, high-horsepower ac motor drives and region buses.

One predictor of potential heat pipe life is the use of short-term, high-temperature testing to induce failure and mathematically predict wear-out. The use of controlled temperature chambers to accelerate the heat pipe destruction can be used along with predictive models to demonstrate this long-term reliability. As per a recently published MTBF model*, the following life model can offer a reasonably predictive model. Operating life at 60°C can be predicted by operation time. This example uses 36 hours as an indicator.

MTBF hours of operation at 60°C = Test time at 180°C × $2^{(\Delta T/10)}$

MBTF hours of operation at 60°C = 36 hours × $2^{(180-60)/10}$

36 hours at 180°C is equivalent life of 147,456 hours
or ~ 17 years at 60°C

This type of accelerated life has its roots in the extensive work in predicting the life and reliability of semiconductor electronics. Based on “weeding out” infant mortality in populations of electronic components, the same principles of temperature-induced stress hold true for heat pipes.

Use of burn-in or stress-screening techniques similar to those used for PC boards can be used on heat pipes. Short-term, high-temperature screening of full production lots can help to eliminate the infant mortality problems seen in the first few hours of use. This can increase lot reliability and virtually eliminate field failures.

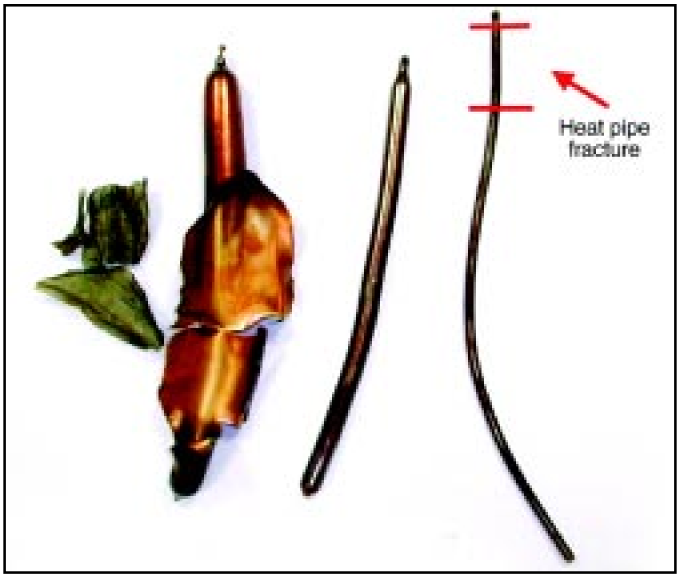

Fig. 4. *Testing heat pipes at the upper limits of temperature screening—seven hours at 300°C—reveals the worst-case examples of catastrophic heat pipe failure.*

The use of and need for heat pipes in high-power applications exists today and is growing as the semiconductor power outputs increase. The use of heat pipes or other high conductivity materials is a growing necessity in state-of-the-art electronic cooling designs. This is true, in part, because of:

- Increased heat outputs from power modules is driving high-technology cooling solutions.
- The market’s avoidance of water or other cooling liquids due to cost and maintenance concerns.
- Innovative use of heat pipes to remove heat in the Z-axis direction from a power module will increase heatsink efficiency and provide an increased level of air-cooling.
- Heat pipe reliability, like air mover reliability, is key to system reliability.
- Service life of a well-designed, carefully built and appropriately applied heat pipe will be in excess of 15 years.
- Based on short-term high-temperature screening, heat pipe life can be predicted using numerical analysis similar to semiconductor life. **PETech**

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* Heat pipe reliability test method from 13th IEEE SemiTherm Symposium.