# Heat Pipes used as Heat Flux Transformers and for Remote Heat Rejection

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## Abstract

Heat pipes are commonly used as a tool to improve thermal performance when conduction through solid metal (aluminum and/or copper) alone is unable transfer heat within the temperature drop budget. Heat pipes can be embedded into aluminum spreaders to significantly improve thermal performance by accepting the high heat flux generated by the electronics and spreading it to a level that can be managed by the ultimate heat sink. Heat pipes can also be used to transfer heat to remote fin stacks when geometry and environmental constraints do not allow for local heat rejection. These applications of heat pipes are becoming more valuable as electronics become more powerful and compact packaging becomes a primary design goal.

## 1. Background

High performance electronics are increasing the amount of waste heat generated and the trend toward smaller packages amplifies the need for thermal solutions capable of rejecting high heat fluxes. Reliable operation and optimum performance depend on a thermal management solution capable of meeting system demands. Typical heat spreaders are made from aluminum or copper since they are low cost, easily machined and have high thermal conductivities of 180 W/m-K and 380 W/m-K, respectively. As heat flux requirements increase, conduction gradients become the largest contributor in the thermal resistance network. Heat pipes can be used as a cost effective enhancement to traditional spreaders without adding significant weight or volume.

### 1.1 Heat Pipes

Heat pipes transport heat by two phase flow of a working fluid [1,2]. Shown in Fig. 1, a heat pipe is a vacuum tight device consisting of a working fluid and a wick structure. The heat input vaporizes the liquid working fluid inside of the wick in the evaporator section. The vapor, carrying the latent heat of vaporization, flows towards the cooler condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The vapor space of the heat pipe is at saturated conditions, so the temperature difference within the vapor space is driven be the pressure difference between the evaporator and condenser ends of the heat pipe. This means that the end-to-end heat pipe temperature difference is driven largely by the conduction losses through the pipe wall which is typically on the order of a few degrees Celsius [3,4].

Copper/water heat pipes are standard for electronics cooling. Water and copper are known to be compatible for long term operation. In the temperature range of typical electronics cooling environments (25°C to 125°C), water has the best combination of physical properties (surface tension, latent heat, viscosity, etc.) for heat pipe performance. Copper also has the highest thermal conductivity of any engineering metal, making it ideal for heat transfer applications. Copper's flexibility makes it ideal for conforming to different desirable geometries, allowing them to be bent (at a bend radius as tight as 3x the pipe O.D.) and flattened (up to 2/3 of the pipe O.D.) to conform to flat input surfaces or avoid structures.

Since heat pipes are essentially isothermal along their length, their effective thermal conductivity can range from 10,000 to 200,000 W/m-K [5].

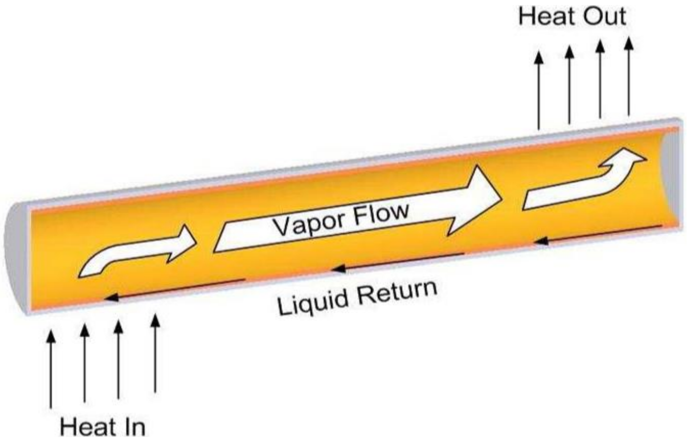

Fig. 1. The operation of a heat pipe is illustrated. Heat applied to one end of the heat pipe evaporates liquid off a wick. The vapor carrying its heat of vaporization moves toward the colder end of the heat pipe where it condenses. The wick returns fluid to the evaporator.

## 1.2 Heat Pipe Application Guidelines

A properly designed heat pipe will exhibit the following properties:

- Adverse gravity operation
- Freeze/thaw tolerance
- Shock/vibration tolerance

Operation in an adverse gravity orientation refers to any configuration in which the heat input area of the heat pipe is above the heat rejection area with respect to gravity. In this orientation the liquid return must overcome gravitational forces proportional to the vertical height difference between the evaporator and condenser sections. This is achieved by utilizing capillary action through a porous wick structure.

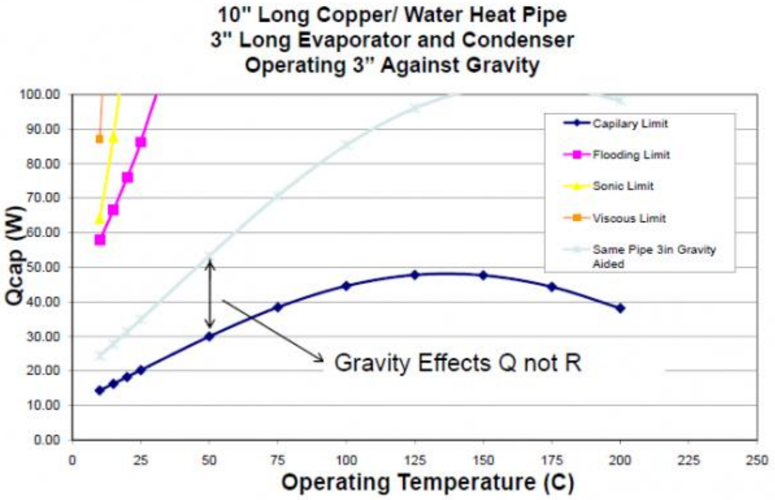

Fig. 2. Performance curves for a nominal heat pipe operating horizontal and against gravity show a difference in the maximum power handling capability. However, the thermal resistance of the heat pipe is unchanged and the expected DT across the pipe will be identical.

When the wick structure is designed properly, the heat pipe will continue to operate at the same thermal resistance (R) regardless of the orientation. However, it should be noted that adverse gravity orientations do affect the maximum amount of heat (Q) that the heat pipe can carry, as seen in Fig. 2. This simply means that when designing a heat pipe for a particular application the maximum power and worst case orientation must be considered. If the pipe is designed properly to perform at the worst case power and orientation it is virtually guaranteed to perform equally or better at all other conditions.

A common misconception about heat pipes that utilize water as the working fluid is that they are limited to applications in which the environment never drops below freezing (i.e. >0°C). The concern in this situation is that the water inside of the heat pipe will expand during freezing and result in bulging or complete failure of the heat pipe envelope. This is not actually the case when a heat pipe is properly manufactured. The working fluid inside of a heat pipe should fully saturate the wick structure without making a puddle of excess fluid. With the fluid completely contained within the wick, it is not able to bridge the gap across the inside diameter of the heat pipe. This allows multiple freeze thaw cycles to occur without any signs of deformation.

The authors routinely subject heat pipes to thermal cycling and typical freeze thaw tests are conducted from temperatures ranging from -20 to +20°C and -40 to +80°C. A typical cycle for such tests is shown in Fig. 3 which illustrates a thermal ramp rate of about 120°C per hour. The authors have tested heat pipes up to 1,200 cycles, but 50-300 cycles are a more standard practice. Heat pipes may be thermally cycled prior to installation into assemblies or the entire heat pipe assemblies can be thermally cycled as units to assure system level performance.

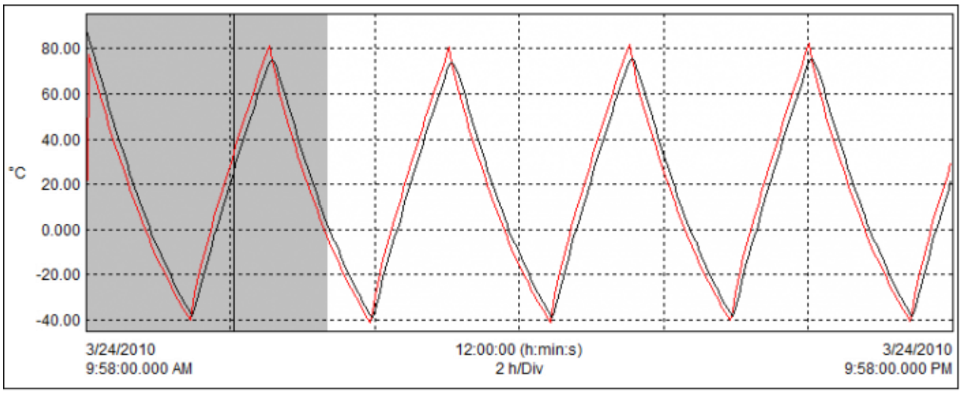

Fig. 3. Typical heat pipe freeze thaw testing criteria showing numerous cycles between 80°C and -40°C at a ramp rate of around 120°C per hour.

Another common concern regarding the use of heat pipes in some applications is in regards to the shock and vibration tolerance of the devices. It is often thought that the passive nature of heat pipes (i.e. there are no moving parts) makes them susceptible to failure under random shock or vibrational loading. In fact, heat pipes exhibit little or no change in performance when exposed to shock loads up to 9,000 lbf and 4,500 lbf of sustained vibration loads. The authors have tested numerous types of heat pipes in shock and vibration environments similar to those presented in Fig. 4 and have witnessed no degradation in thermal performance.

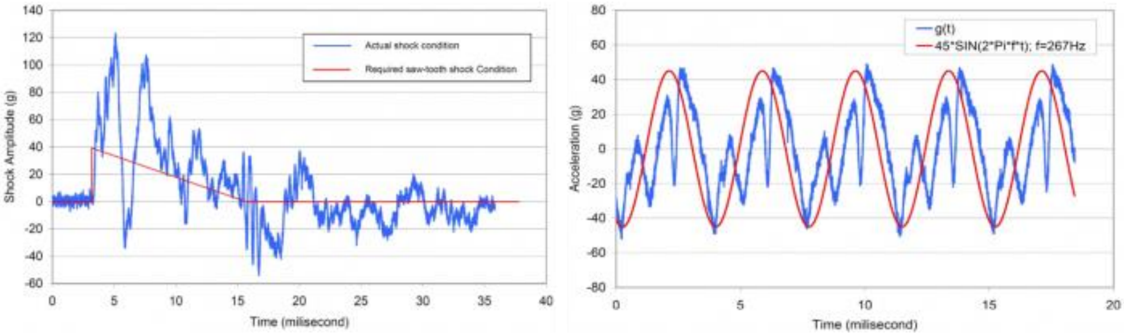

Fig. 4. Typical heat pipe testing curves for Shock Amplitude vs. Time and Acceleration vs. Time.

The reason for the sustained performance under these harsh conditions can be attributed to the wick structure. The working fluid inside of the heat pipe is protected from the external perturbations by the capillary pressure of the porous material. The surface tension forces are strong enough that the shock and vibration loads cannot dislodge the working fluid from the pores which is known as depriming the wick. It is worth noting that if an acceleration vector is sustained in a direction that opposes the flow of the working fluid back to the evaporator section the performance of the heat pipe could be hindered. This is very similar to the effect that gravity has on the operation of a heat pipe and the device would have to be designed accordingly to withstand this operating condition.

## 2. Remote Heat Rejection

In applications where local heat rejection is limited, heat pipes can be used to transfer heat to a location where there is sufficient volume. A common example is a luminaire design where the ceiling or wall fixtures are based on a pre-existing design using non-LED technologies. These designs commonly have both restricted space for heat dissipation through conduction and limited air flow to remove heat via convection. In cases where there is space to remotely dissipate the heat, heat pipes can be used to transport the heat from the device to a remote heat sink. Fig. 5 shows a photograph and an infrared (IR) image of a heat pipe transporting heat to a remote sink, clearly demonstrating the transport of heat isothermally from the heat source to the heat sink and the even distribution of heat to the heat sink.

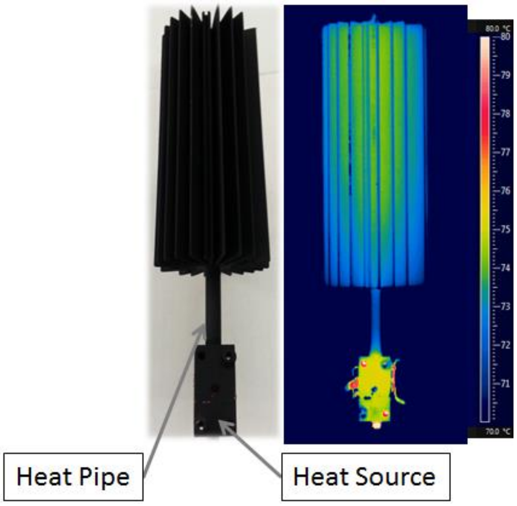

Fig. 5. IR image and photograph of remote cooling with a heat pipe embedded radial heat sink. The temperature distribution clearly demonstrates that the heat pipe can transport heat almost isothermally, and then deliver it uniformly to the heat sink.

Heat pipes can also be bent and manipulated to clearance multiple obstructions in a given assembly as shown in the two examples in Fig. 6. In this case the form factor that must be packaged in between the heat source and heat sink is simply the outer diameter of the heat pipe. This enables more compact packaging options and minimizes the number of components that may need to be displaced when implementing a thermal solution. The ultimate heat sink does not necessarily need to be an air-cooled heat sink. As shown in the figure on the right in Fig. 6, the ultimate heat rejection medium could be a central cold rail that could be cooled by a circulated liquid.

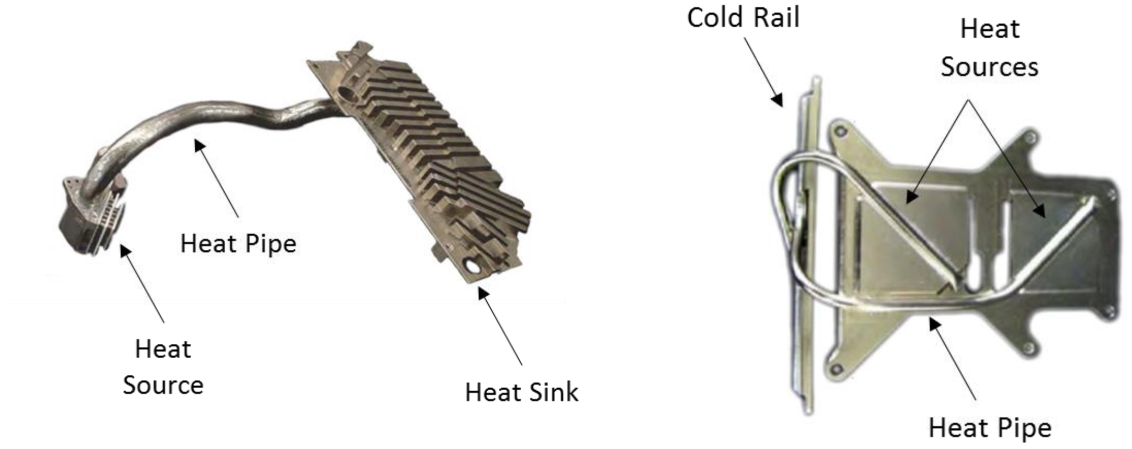

Fig. 6. (left) A heat pipe and heat sink assembly with multiple bends used to remove the waste heat from a thermoelectric device. (right) Heat pipes embedded in aluminum spreader plates and connected to a cold rail for heat rejection.

## 3. Heat Flux Transformers

### 3.1 HiK™ Plates

Heat pipes can be embedded into conventional spreaders to take advantage of their superior heat transport capabilities and increase the overall effective thermal conductivity (k). When heat pipes are embedded into aluminum, they are known as HiK™ plates. Heat pipes are typically embedded into aluminum instead of copper for several reasons. First, since the heat pipes are the primary means of heat transfer the copper provides marginal thermal improvement at a significant weight penalty. Secondly, aluminum has superior mechanical properties when compared to copper. These are maintained after heat pipes are installed. Finally, aluminum is a low-cost material that is easily machined and extruded.

Fig. 7 shows a design challenge where electronics mounted to a conventional aluminum heat spreader were overheating. Here large thermal gradients in the heat spreader results in a maximum base plate temperature of 91°C, which is above the 80°C max case temperature levied by many electronics. By embedding heat pipes within the plate the thermal gradient of the spreader was reduced to 70°C. The high heat flux components located in the upper corners of the plate are already located close to the edge of the spreader where heat is rejected. Using heat pipes to spread heat along the edge transformed the heat flux to a manageable level and minimized the thermal bottleneck at the clamping interface. The hot spot located at the bottom center is a result of high conduction gradients. The high effective thermal conductivity of the heat pipes reduced this gradient to maintain a safe base plate temperature. With the design complete the heat pipe solution was fabricated and is shown in the image to the right of Fig. 7.

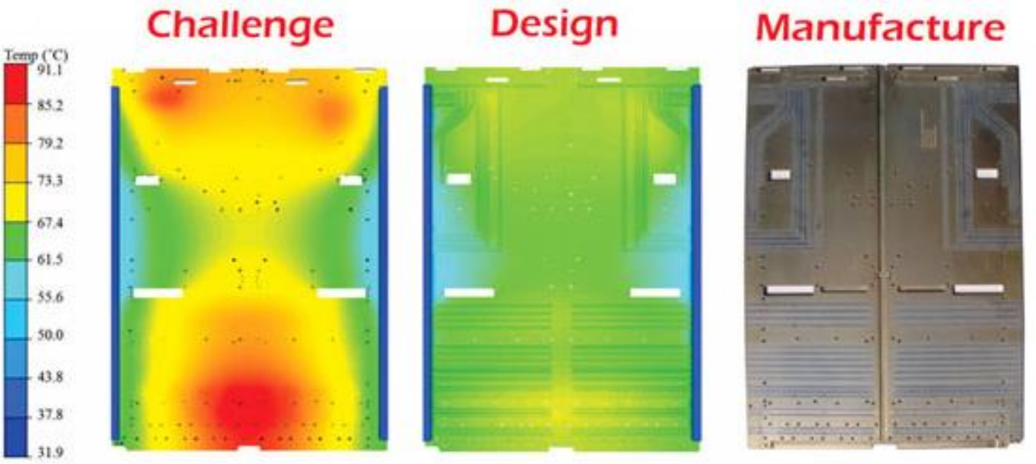

Fig. 7. The thermal model on the left shows the design "Challenge", a heat spreader made of aluminum. The thermal model in the center shows the heat pipe enhanced "Design". The image on the right shows the "Manufactured" heat spreader.

## 3.2 Vapor Chambers

Vapor chambers are effectively flat heat pipes which operate under the same principles by evaporating and condensing a working fluid inside of a vacuum tight enclosure. The main difference between a heat pipe and vapor chamber is the geometry. Heat pipes are typically cylindrical devices while vapor chambers are flat with parallel evaporator and condenser sections. The benefit to this configuration is that very effective heat spreading can be achieved. As shown in Fig. 8, the vapor spreads to the entire inner volume and condenses over a much larger, cooler surface of the vapor chamber. The condensed liquid is transported back to the heat input area in the wick structure lining the vapor chamber inner wall. In some cases, vapor chambers are referred to as a "heat flux transformers" because of this ability to convert higher heat fluxes into lower heat fluxes. Depending on the design of the wick structure, heat fluxes up to 1000 W/cm$^2$ can be achieved.

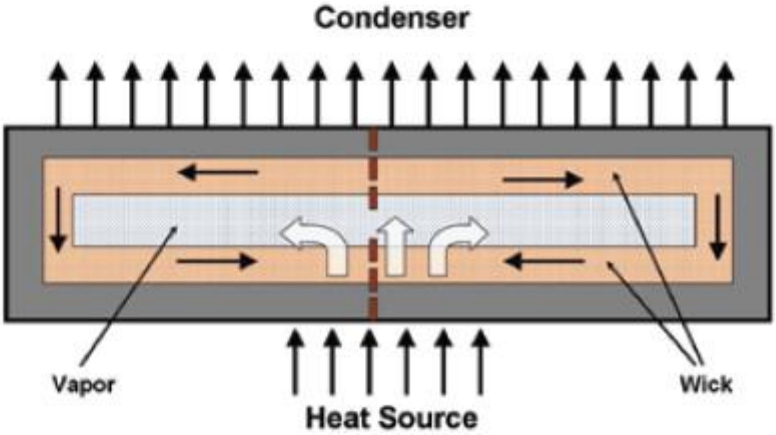

Fig. 8. A vapor chamber is essentially a flat heat pipe where the heat input area is substantially smaller than the heat rejection area. Image courtesy of [6].

The authors have fabricated advanced vapor chambers that are manufactured with low coefficient of thermal expansion (CTE) materials that enable direct solder attachment and high heat flux capability. The advanced wick structure is shown in Fig. 9, which allows for efficient liquid return to the evaporator section while maintaining low thermal resistance. Most vapor chambers also contain an internal support structure to provide rigidity and allow for more robustness (shown in Fig. 9). Typical vapor chamber thicknesses are on the order of 3-5mm which provides highly efficient and compact heat spreading for a wide variety of applications.

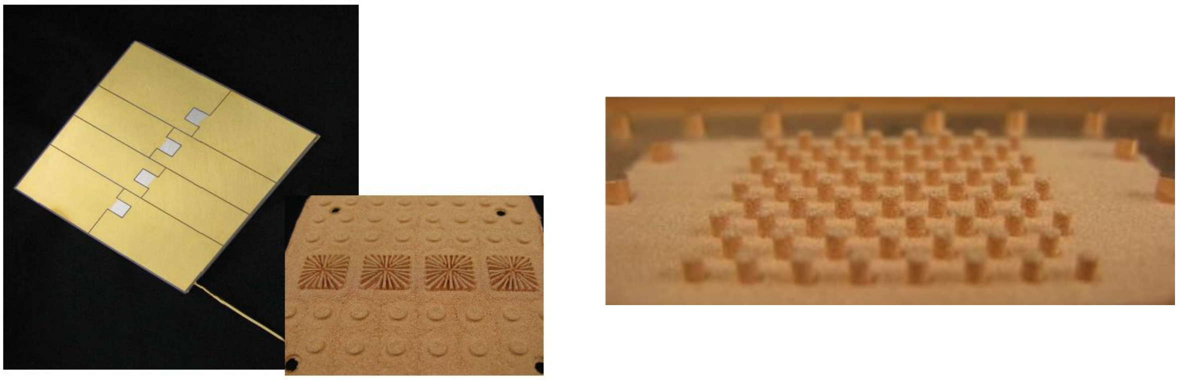

Fig. 9. (left) CTE-matched vapor chamber with advanced wick structure capable of handling 1000 W/cm$^2$. (right) Internal support structure to provide structural integrity to the otherwise hollow vapor space.

## 4. Summary

Heat pipes transfer heat very efficiently and can be used to enhance the performance of conventional heat spreaders without compromising mechanical properties or significantly adding weight. Heat pipes are capable of accepting high heat fluxes and spreading them to a manageable level. Their high effective thermal conductivity allows designers to incorporate heat sinks of sufficient volume remotely when other geometry constraints don’t allow for local heat rejection. Heat pipes are freeze/thaw and shock and vibration tolerant and can operate in any orientation when designed appropriately.

## 5. References

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