

ATS Engineering eBook

Selected Technical Articles on Vapor Chambers and
Their Roles in the Thermal Management of Electronics

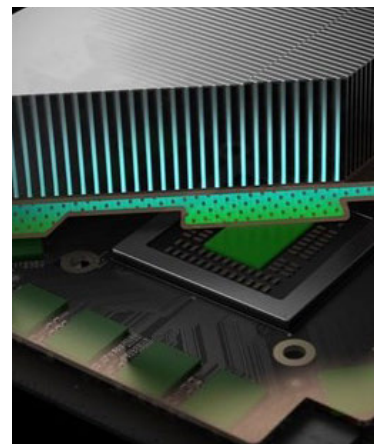
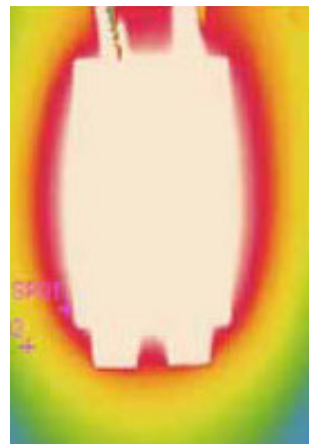
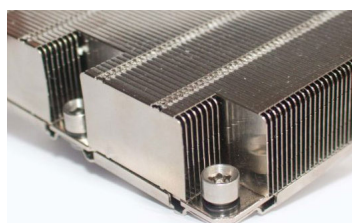
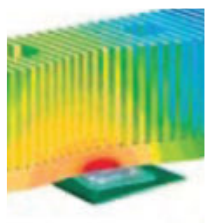


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Applications of Vapor Chambers in Thermal Management of Electronics

The use of vapor chambers in the thermal management of electronics has grown exponentially since Advanced Thermal Solutions, Inc. (ATS) first wrote seven years ago about their ability to spread heat uniformly across the base of a heat sink, reducing the spreading resistance and enhancing the heat sink's heat transfer capabilities when applied to high-powered components.

In a two-part series published originally in 2010 and based on an article from Qpedia Thermal eMagazine entitled, "Vapor Chambers and Their Use in Thermal Management," it was explained that "a vapor chamber (VC) is basically a flat heat pipe that can be part of the base of a heat sink. It is vacuumed and then injected with just enough liquid (e.g. water) to wet the wick." [1]

Similar to heat pipes, "The heat source causes the liquid to vaporize on the evaporator side. The resulting pressure increase in this area forces the vapor into the condenser side, which is the base of the heat sink. Here, the vapor transfers the heat to the heat sink, and it then condenses back to liquid. The liquid is pumped back to the base through the capillary action of the wick structure."

In Fig. 1, two heat sinks are shown. One has a solid base and the other has a vapor chamber in its base and it is clear from the temperature distribution that the vapor chamber spreads out the heat across the base and distributes heat to a larger portion of the heat sink.

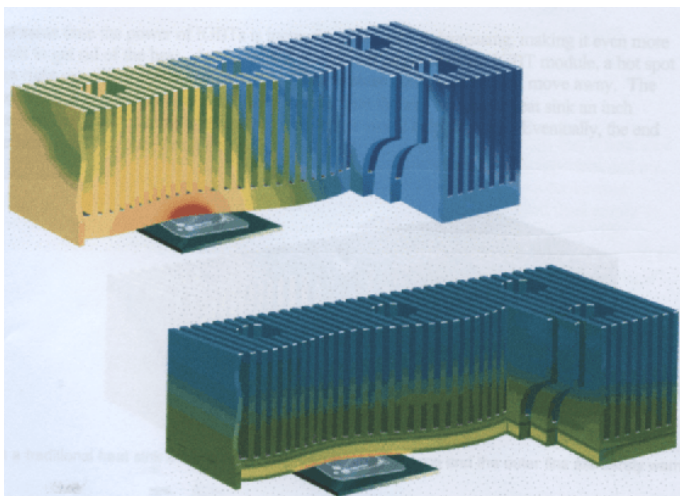


Figure 1. Schematic View of Heat Sinks with (a) Solid Base and (b) Vapor Chamber Base. [1]

As the original article explained, "The very high equivalent thermal conductivity of the vapor chamber has spread the heat uniformly, leading to more efficiency from the heat sink."

The second article runs through some of the equations that define the effective thermal conductivity of the wicking structure inside the vapor chamber and the impact that changing the wick material can have on its efficiency.

"This article shows that while a vapor chamber presents exciting technology, some calculations should be made to justify its use," it continued. "In some situations, a solid copper block might provide better thermal performance than a vapor chamber. To use a vapor chamber instead of solid copper must be justified, for example, to reduce weight.

Another issue with vapor chambers presented by the article was that "some vapor chambers have a power limit of 500 watts. Exceeding this value might cause a dry out, as with a heat pipe, and could increase the vapor temperature and the pressure. The increase in internal pressure can deform the VC surfaces, or cause leakage from the welded joints."

The study of vapor chambers has developed in the past seven years and, although some of the same issues remain, they are now thinner and lighter than ever and engineers are finding many new ways of incorporating them into cooling systems. Vapor chambers are now frequently used in applications ranging from hard drive disk cooling, PC cooling (not just for gamers and overclockers, but also for office computers), graphic card cooling, server cooling, high heat flux chips (IGBT and MOSFET), LED, and in consumer products (particularly mobile devices such as cell phones and tablets).

In addition to the benefits explained above, vapor chambers are critical in applications where height is limited, which is an increasing problem in today's era of miniaturization, and where power densities are high. Vapor chambers are also important in applications where there are hotspots, where weight is a concern, and where there is a high ambient temperature or low airflow.

Hard Drive Disk Cooling

Several manufacturers in the hard drive market have turned to vapor chambers because of increases in spindle speed. In the past, many manufacturers and designers limited the thermal management of hard drives to using the aluminum case as a heat sink to dissipate the excess heat from the device, but as drives began working at 7,200 RPM and higher another option was required to ensure the reliability and longevity of the drive. [2]

A 2013 study that was published in International Communications in Heat and Mass Transfer explored the use of vapor chambers to cool hard drives in personal computers. The researchers found that adding vapor chambers to the cooling system could reduce the hard drive temperature by as much as 15.21%. [3]

Gaming, Overclocking, Personal Computing

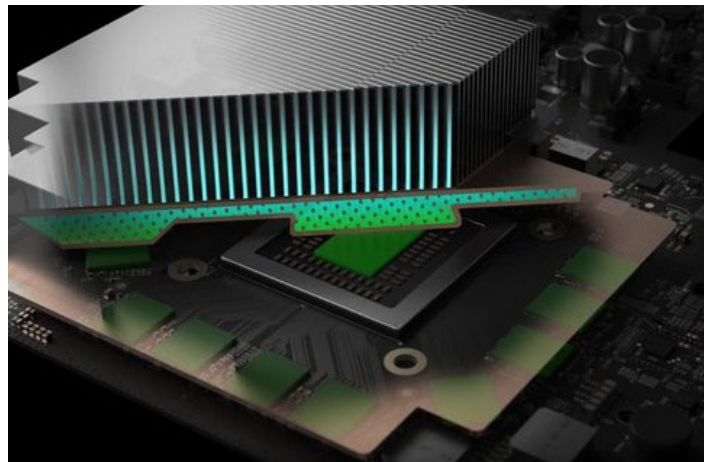
The gaming and overclocking community has turned towards liquid cooling in recent years, as evidenced by a recent survey from KitGuru that showed 51% of its readers had already or would shortly be using liquid cooling for their personal computers. [4] While there is a trend in that direction, just under half (49%) of the respondents were also sticking with convection cooling options and many companies are incorporating vapor chamber technology in elaborate cooling devices (many with fans and heat pipes) for the PC market.

Cooler Master has introduced the V8 GTS CPU Air Cooler, which strongly resembles a car engine and has a horizontal vapor chamber and eight heat pipes. [5] The vapor chamber spreads the heat evenly from hotspots in the CPU and the heat pipes draw that heat into the tower's heat sink.



The Cooler Master GTS V8 has a distinct car engine look and uses vapor chambers, heat pipes, and heat sinks to cool PCs. (Cooler Master/YouTube)

ID Cooling has introduced several products that boast vapor chamber technology, including the HUNTER, and FI (which stands for Finland) Series CPU coolers. [6] Even gaming systems have gotten into the act with the recently announced, high-powered Xbox One Scorpio expected to include a vapor chamber array as part of its thermal management. [7] Microsoft's announcement that it was using vapor chambers in Project Scorpio was not surprising because of the technology's ability to fit into the tight confines of the gaming system.



Microsoft's Project Scorpio introduced a new, higher-powered gaming system that required an array of vapor chambers to keep it cool. (Microsoft)

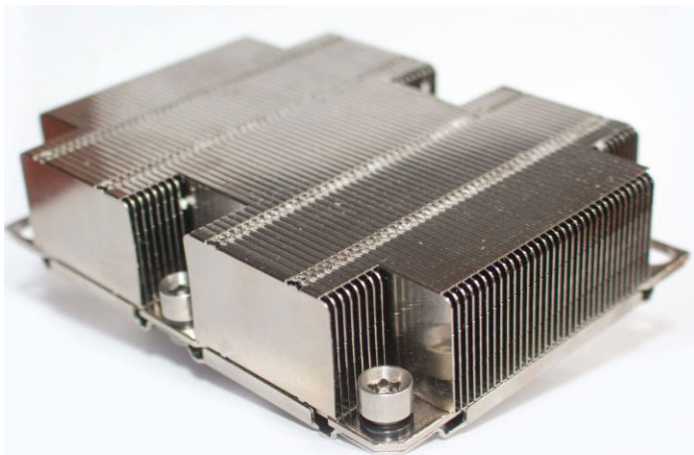
Also, the increasing capabilities and power of next-generation graphics cards has led to a trend in the industry to use vapor chambers as part of a package to cool these components. Nvidia is one of the biggest names in graphic cards and for both the Titan X and the GeForce GTX 1080 (each launched in 2016) vapor chamber are used with a blower to dissipate the increased power of the devices. [8]

It is not only the gaming community that is benefiting from vapor chamber cooling. Hewlett Packard (HP) has also explored using vapor chambers for multiple purposes. HP released a white paper last year about using 3-D vapor chambers in its Z Coolers to enhance their thermal efficiency as well as reduce the acoustic impact of the fans. [9] Also last year, HPE Labs released a study of vapor chambers for cooling multiple chip modules dissipating 250 W and operating temperatures up to 45°C and found that "VC (vapor chamber) performs better for: high power, power density, off center or asymmetric heat sources." [10]

Server Cooling

Much like in graphic cards or gaming systems, vapor chambers are increasingly used in server cooling applications because their size and weight allows them to fit into tight spaces, particularly in applications with high component density. For example, Rugged has released an M120 1-U server rack that includes vapor chambers to spread the heat evenly and high-speed fans to pull the heat out of the system. [11]

A study by Aavid Thermacore from the 2007 ASME InterPACK Conference explained that in blade processors that need to dissipate 100-300 W with heat sinks lower than 30 mm, vapor chambers could be used as the base of the heat sink to improve effective spreading and improve performance by 25-30%. [12] Radian's Intel Skylake heat sink that is intended for server chips installed in a 1-U chassis put this into practice with a vapor chamber in its base that enhances the effective thermal conductivity of the stamped aluminum fins. [13]



Radian's Intel Skylake heat sink uses a vapor chamber in the base to evenly spread the heat and improve the heat transfer through the fins of the heat sink. (Radian)

LED Cooling

A more recent development in the use of vapor chambers is their inclusion in LED packages. A 2016 study from the 37th International Electronic Manufacturing Technology Conference outlined the use of vapor chambers along with finned heat sinks in the thermal management of LED to enhance the thermal performance and provide a "more economical" process than making the heat sink larger or using more expensive materials. [14]

Advanced Cooling Technologies (ACT) also released a case study about cooling high-powered LED applications, such as ultraviolet (UV) cutting devices,

which said, "Vapor Chambers are an important tool in LED thermal management, since they act as flux transformers, spreading the high input heat flux over the entire surface of the vapor chamber. This allows the heat to be removed from the vapor chamber by conventional cooling methods." [15] ACT added that it developed C.T.E matched vapor chambers that allow for direct bonding with the LED and "dissipate heat fluxes as high as 700 W/cm² and 2kW overall."

Vapor chambers are also being used in automotive LED applications to prevent failures by spreading the heat quickly from the source. A study from the 2011 International Heat Pipe Symposium found that a vapor chamber with distilled water dropped the LED temperature from 112.7°C to 80.7°C, reduced thermal resistance by 56%, and reached steady state faster than conventional systems. [16]

Mobile Devices

The most obvious market for vapor chambers is mobile devices. Last fall, the news was filled with stories about Samsung cell phone batteries reaching thermal runaway and airplane passengers being forced to turn off the phones for concern about a midair fire. With their thin design and low weight, vapor chambers can be used to spread the heat quickly from batteries or high-powered processors in phones, laptops, tablets, etc. and reduce the risk for catastrophic failures.

A 2016 study from the International Journal of Heat and Mass Transfer described vapor chambers being used to reduce hotspots to improve the comfort of users, which is a problem unique to mobile devices. [17] The researchers proposed a "biporous condenser-side wick design" that "facilitates a thicker vapor core, and thereby reduces the condenser surface peak-to-mean temperature difference by 37% relative to a monolithic wick structure."

A recent story from EE Times noted that the combined shipments of mobile devices was expected to decline in 2017, marking the third straight year of reduced shipments [18], but with companies expending resources to develop 5G technology there is still a need for superior cooling options moving forward and vapor chambers appear to be a perfect fit in mobile thermal management systems.

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Vapor Chambers and Solid Material as a Base for High Power Devices

Microelectronics components are experiencing ever-growing power dissipation and heat fluxes. This is due to dramatic gains in their performance and functionality. To cope with the heat issues of tomorrow’s technology, more efficient cooling systems will be required.

It should be noted that as computer systems continue to compact, the components adjacent to the processors are experiencing an increase in power dissipation.

As a result, ambient temperatures local to the microprocessor heat sinks have increased, and temperatures in excess of 45°C have been reported. [1] Improvements are needed in all aspects of the cooling solution design, i.e., packaging, thermal interfaces, and air-cooled heat sinks. The article discusses the use of vapor chamber technology as a heat spreader to help cool high-power devices.

Introduction

Spreading resistances exist whenever heat flows from one region to another in a different cross-sectional area. For example, with high performance devices, spreading resistance occurs in the base plate when a heat source with a smaller footprint is mounted on a heat sink with a larger base plate area. The result is a higher temperature where the heat source is placed.

The impact of spreading resistance on a heat sink’s performance must not be ignored in the design process. One way to reduce this added resistance is to use highly conductive material, such as copper, instead of aluminum. Other solutions include using heat pipes, vapor chambers, liquid cooling, micro thermoelectric cooling, and the recently developed forced thermal spreader from Advanced Thermal Solutions, Inc. (ATS).

In the case of vapor chambers (VC), the general perception has been that phase change technologies provide more effective thermal conductivity than solid metals. The spreading resistance of the base for both solid metal and conventional VC heat spreaders is defined as:

$$\theta_{sp} = \frac{T_s - \bar{T}_{b,top}}{P} \quad [^{\circ}\text{C} / \text{W}]$$

Where T_s [°C] is the temperature of the hottest point on the base, and $\bar{T}_{b,top}$ [°C] is the average temperature of the base top surface. [1]

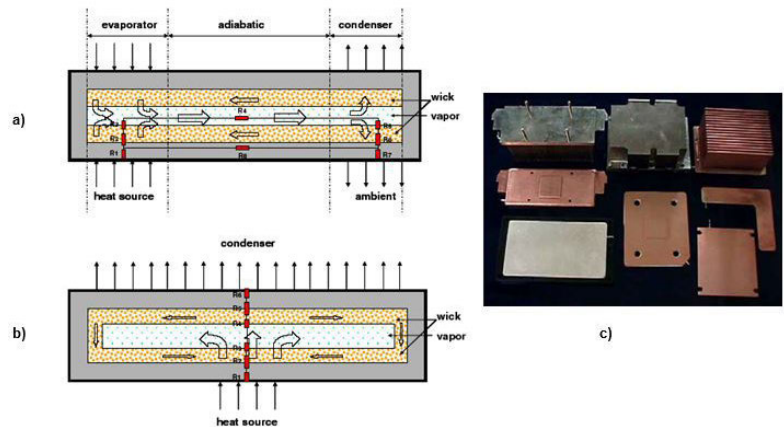


Figure 1. Schematics of a) Heat Pipe and b) Vapor Chamber [2], with c) Photo of Vapor Chambers. [3]

Table 1 shows the thermal conductivity of different materials in spreading the heat at the base. Heat pipes and VC emerged as the most promising technologies and cost effective thermal solutions due to their excellent uniform heat transfer capability, high efficiency, and structural simplicity. Their many advantages compared to other thermal spreading devices are that they have simple structures, no moving parts, allow the use of larger heat sinks, and do not use electricity. This article’s emphasis is on vapor chambers.

*Is a heat pipe considered a material?
Should we include vapor chambers in this table?*

The principle of operation for VC is similar to that of heat pipes. Both are heat spreading devices with highly effective thermal conductivity due to phase change phenomena. A VC is basically a flat heat pipe that can be part of the base of a heat sink. Figure 1 shows the schematics of a typical heat pipe and VC. [2]

Material	Thermal Conductivity (W/m°C)
Heat Pipe	50,000 – 200,000
Aluminum	180
Copper	386
Diamond	2,000

A VC is a vacuum vessel with a wick structure lining its inside walls. The wick is saturated with a working fluid. The choice of this fluid is based on the operating temperature of the application. In a CPU application, operating temperatures are normally in the range of 50-100°C. At this temperature range water is the best working fluid. [3]

As heat is applied, the fluid at that location immediately vaporizes and the vapor rushes to fill the vacuum. Wherever the vapor comes into contact with a cooler wall surface it condenses, releasing its latent heat of vaporization. The condensed fluid returns to the heat source via capillary action, ready to be vaporized again and repeat the cycle.

The capillary action of the wick enables the VC to work in any orientation, though its optimum performance is orientation dependent. The pressure drop in the vapor and the liquid determines the capillary limit or the maximum heat carrying capacity of the heat pipe. [4] For electronics applications, a combination of water and sintered copper powder is used. [2]

A VC, as shown in Fig.1 (b), is different from a heat pipe in that the condenser covers the entire top surface of the structure. In a VC, heat transfers in two directions and is planar. In a heat pipe, heat transmission is in one direction and linear.

The VC has a higher heat transfer rate and lower thermal resistance. In the two-phase VC device, the rates of evaporation, condensation, and fluid transport are determined by the VC's geometry and the wicks' structural properties. These properties include porosity, pore size, permeability, specific surface area, thermal conductivity, and the surface wettability of the working fluid. [5] Thermal properties of the wick structure and the vapor space are described in the next section.

Effective Thermal Conductivity

Wick Structure

Heat must be supplied through the water-saturated wick structure, at the liquid-vapor interface, for the evaporation process to happen. With water and sintered copper powder, the water becomes a thermal

barrier due to its much lower thermal conductivity compared with the copper. [2]

There are several ways to compute the effective thermal conductivity of the wick structure.

For parallel assumption:

$$K_W = (1 - \varepsilon)K_S + \varepsilon K_I \quad (2)$$

(2)

For serial assumption:

$$K_W = \frac{1}{(1 - \varepsilon)/K_S + \varepsilon/K_I} \quad (3)$$

(3)

For sintered wick structure, Maxwell gives: [2]

$$K_w = K_s \left[\frac{2 + K_I / K_s - 2\varepsilon(1 - K_I / K_s)}{2 + K_I / K_s + \varepsilon(1 - K_I / K_s)} \right] \quad (4)$$

(4)

Chi gives: [2]

$$K_w = \frac{\pi}{8} \left(\frac{r_c}{r_s} \right)^2 K_s + \left[1 - \frac{\pi}{8} \left(\frac{r_c}{r_s} \right)^2 \right] \left[\frac{K_I K_s}{\varepsilon' K_s + K_I (1 - \varepsilon')} \right] \quad (5)$$

(5)

Where:

$$\varepsilon' = \frac{\varepsilon}{1 - \frac{\pi}{8} \left(\frac{r_c}{r_s} \right)^2} \quad (6)$$

(6)

In the equations above, K_I and K_S are the thermal conductivities of water and copper, respectively, ε is the porosity of the wick, r_c and r_s are the contact radius (or effective capillary radius) and the particle sphere radius, respectively.

Table 2 shows a comparison of effective thermal conductivity (W/m°C) for the wick using equations 2—5. It appears that Equation 5 gives a more realistic value. This is also the typical value used in Vadakkan et al. [6]

Eq. 2	Eq. 3	Eq. 4	Eq. 5
200	1.2	160	40

Table 2. Effective Thermal Conductivity for the Wick Structure.

Vapor Space

Effective thermal conductivity for vapor chambers used in remote cooling applications has been derived from Prasher [4], based on the ideal gas law, and from the Clapeyron equation for incompressible laminar flow conditions.

$$K_{\text{vapor}} = \frac{H_{fg}^2 P \rho d^2}{12R\mu T^2} \quad (7)$$

Where H_{fg} is the heat of vaporization (J/Kg), P is pressure (N/m²), ρ is density (kg/m³), d is the vapor space thickness (mm), R is the gas constant per unit mass (J/K.Kg), μ is the dynamic viscosity (N.s/m²), and T is the vapor temperature (°C).

$$\theta_{sp} \cong \theta_{ev} \cong \frac{1}{h_{ev} \times A_{ev}}$$

As shown in Equation 7, effective thermal conductivity is a function of thermodynamic properties and vapor space thickness. Larger vapor space thickness reduces the flow pressure drop, and thus increases the effective thermal conductivity. Note that the effective thermal conductivity is relatively low at low temperatures. This has significant implications for low heat flux applications or start-up conditions [2].

Drawbacks

There are a few drawbacks to using a VC instead of solid copper. Some VC have a power limit of 500 watts. Exceeding this temperature might cause a dry out and could increase the vapor temperature and pressure.

An increase in internal pressure can deform the VC surfaces or cause leakage from the welding joints. Other factors to be addressed include cost, availability, and in special cases, the vapor chamber's manufacturability.

When to Use a Vapor Chamber

The early design stages are when to decide if it makes sense to use a heat pipe/VC instead of copper or other solid materials to better spread heat. To predict the minimum thermal spreading resistance for a VC, a

simplified model was developed by Sauciuc et al. [1]. Their model assumes that the minimum VC spreading resistance θ_{sp} is approximately the same as the evaporator (boiling) resistance θ_{ev} .

$$\theta_{sp} \cong \theta_{ev} \cong \frac{1}{h_{ev} \times A_{ev}} \quad (8)$$

Here, h_{ev} [W/m²K] is the boiling heat transfer coefficient and A_{ev} [m²] is the area of the evaporator (heat input area). It is also assumed that the boiling regime inside the VC is nucleate pool boiling. This is a conservative assumption, since in reality the spreading resistance in a VC is greater than just the boiling resistance. If the spreading resistance calculated from this simplified model is higher than that of a solid copper base, then a VC should not be used. [1]

The boiling model is based on Rohsenow's equation for nucleate pool boiling on a metal surface, and is given by: [7]

$$q = \mu_f h_{fg} \left[\frac{g(\rho_f - \rho_g)}{\sigma} \right]^{1/2} \left[\frac{c_{p,f}}{C_{s,f} h_{f,g} Pr_f^n} \right]^3 \Delta T^3 \quad (9)$$

Where μ_f is the dynamic viscosity of the liquid, h_{fg} is the latent heat, $g(\rho_f - \rho_g)$ is the body force arising from the liquid-vapor density difference, σ is the surface tension, $c_{p,f}$ is the specific heat of liquid, $C_{s,f}$ and n are constants that depend on the solid-liquid combination, Pr_f is the liquid's Prandtl number, and $\Delta T = [T_s - T_{sat}]$, which is the difference between the surface and saturation temperatures.

It can be seen that the heat flux is mainly a function of fluid properties, surface properties, and the fluid/material combination, and that superheat is required for boiling. For electronics cooling applications, it is widely accepted that water/copper is the optimum combination for VC fabrication [1].

The evaporator heat transfer coefficient definition is:

$$h_{ev} = \frac{q}{(T_s - T_g)} \quad (10)$$

The ratio of phase change spreading over copper spreading can be estimated for the base of conventional rectangular heat sinks using Rohensaw's equation and conventional modeling tools, Figure 2 from [1] shows the relationship of this ratio versus base thickness (solid metal heat sink only) for different footprint sizes. The heat input area is kept constant for this plot. This figure shows that for spreading resistance ratios greater than 1.0, the ratio decreases with increasing condenser size.

This implies that the VC type base is better situated for larger condenser sizes. The figure also indicates that ratio 1.0 occurs at greater base thickness for larger condensers. For example, with a 200×200 mm footprint, a VC would outperform a corresponding copper base heat sink (with a thickness of 10 mm or less). However, with a 50×50 mm footprint the sink's base thickness would have to be less than about 2.5 mm for the VC to make the same claim. [1]

Figure 2 also shows that there is a "worse case point" when comparing the thermal performance of a VC and a solid copper base heat sink. This is identified by the maximum in the curve for the 50×50 mm footprint at a base thickness of 10 mm. At this point the spreading resistance ratio is at its largest value, which indicates the worst performance for the VC (when compared with the corresponding solid copper base). In general, there will be a maximum base thickness (dependent on heat source size and footprint) in considering a VC base.

Unless weight is a major concern, with a base thickness above this maximum, a VC base should not be considered. Conversely, for a heat sink base thickness below this maximum, a VC base is a viable option.

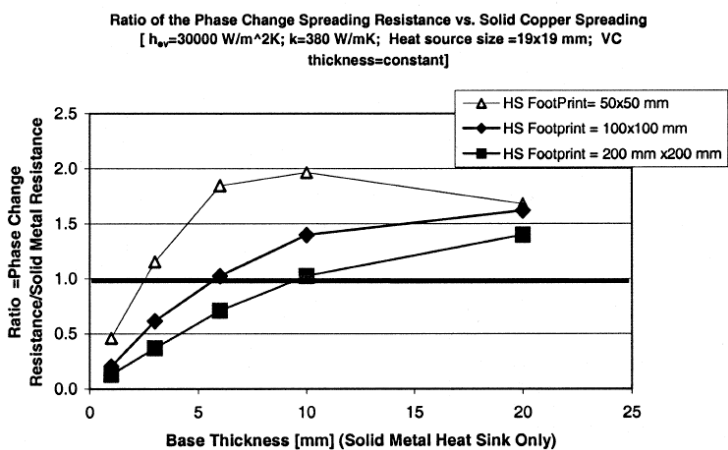


Figure 2: Ratio of Phase Change Resistance (Rohensaw's Equation) Versus Solid Metal Resistance. [1]

Summary

Although a VC enhances heat spreading through high effective thermal conductivity, some modeling needs to be considered early in the design stage. Because a VC is a liquid filled device, cautions need to be exercised in its deployment in electronics. The dry out or loss of liquid due to poor manufacturing will render the VC as a hollow plate, thus adversely impacting device thermal performance.

In some situations as shown earlier, a solid copper base might provide better spreading of heat without the potential pitfalls of a VC.

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Vapor Chambers and Their Use in Thermal Management

Increasing heat fluxes and decreasing sizes pose a major challenge for keeping electronic components below their critical junction temperatures. To cool a high power device with a small footprint requires a heat sink larger than the component.

This size difference creates an added thermal resistance, called spreading resistance, which is usually in the same order of magnitude as the heat sink thermal resistance.

Spreading resistance is observed in combinations of very high performance heat sinks and small heat source sizes, e.g. 10 x 10 or 15 x 15 mm. There are many ways to reduce this added resistance. One is to use a highly conductive material, such as copper. It has a smaller spreading resistance than aluminum, although it is much heavier and costlier. Other ways to lower spreading resistance include the use of heat pipes, liquid cooling, vapor chambers, micro TECs (thermoelectric coolers), and the recently developed Forced Thermal Spreader (Advanced Thermal Solutions, Inc.). The focus of this article, however, will be the use of vapor chambers.

A vapor chamber (VC) is basically a flat heat pipe that can be part of the base of a heat sink. It is vacuumed and then injected with just enough liquid, e.g. water, to wet the wick. The theory of operation for a vapor chamber is the same as for a heat pipe. The heat source causes the liquid to vaporize on the evaporator side. The resulting pressure increase in this area forces the vapor into the condenser side, which is the base of the heat sink. Here, the vapor transfers the heat to the heat sink, and it then condenses back to liquid. The liquid is pumped back to the base through the capillary action of the wick structure.

It has been shown that for electronics cooling applications, sintered copper and water are the best choices for the chamber material and its internal liquid. The advantages of water are its high thermal conductivity, high surface tension, and non-toxicity.

$$\theta_{sp} = \frac{T_s - \bar{T}_{b,top}}{P} \quad [^{\circ}\text{C} / \text{W}]$$

A vapor chamber is generally used to spread heat more uniformly than with a solid metal block. This is due to the chambers high equivalent thermal conductivity. Figure 1 shows the temperature distribution in two heat sinks: one

has a solid base and the other has a vapor chamber in its base. The heat sink without the VC shows temperature concentrated on top of the heat source, while the major portion of the heat sink is running cold. The result is low thermal performance. On the other hand, the heat sink with the VC in its base shows a very uniform temperature distribution. The very high equivalent thermal conductivity of the vapor chamber has spread the heat uniformly, leading to more efficiency from the heat sink.

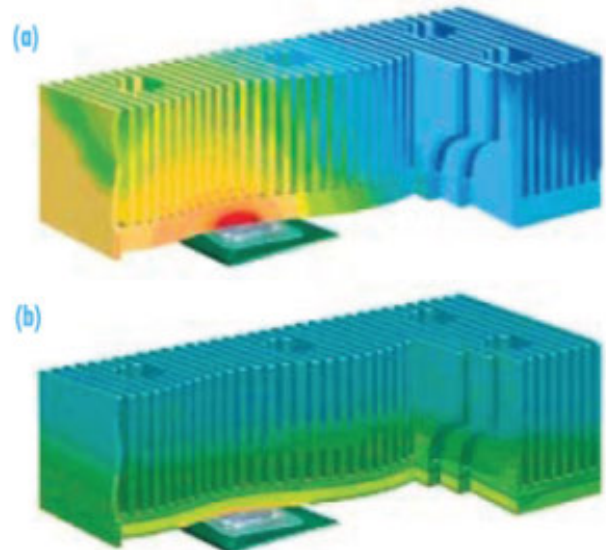


Figure 1. Schematic View of Heat Sinks with (a) Solid Base and (b) Vapor Chamber Base [1]

Figure 2 gives a schematic view of a typical vapor chamber. Its successful performance depends on many factors, as explained in the following paragraphs.

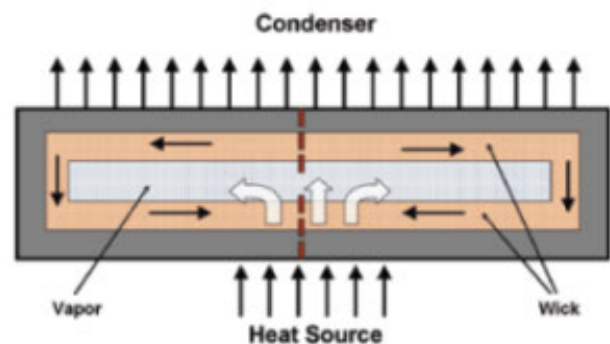


Figure 2. Schematic of a Vapor Chamber

The thermal conductivity of a vapor chambers wick has a strong influence on its overall effectiveness. Wicks are typically made from copper powder. Heat must travel through the wick structure to vaporize the water. The low thermal conductivity of water compared to that of copper powder can degrade the chambers performance.

The effective thermal conductivity of a wick can be expressed as shown below [2]:

$$K_w = \frac{\pi}{8} \left(\frac{r_c}{r_s}\right)^2 K_s + \left[1 - \frac{\pi}{8} \left(\frac{r_c}{r_s}\right)^2\right] \left[\frac{K_1 K_s}{\epsilon K_s + K_1(1 - \epsilon)}\right] \quad (1)$$

$$\epsilon = \frac{\epsilon}{1 - \frac{\pi}{8} \left(\frac{r_c}{r_s}\right)^2} \quad (2)$$

Where

K_w = Wick effective thermal conductivity

K_1 = Water thermal conductivity, W/m°C

K_s = Copper thermal conductivity, W/m°C

R_c = Capillary radius, m

R_s = Particle sphere radius, m

The above equation yields a value of 40 W/m°C for water inside a sintered copper wick.

Another variable to consider is the effective thermal conductivity of the vapor space [3]:

$$K_{vapor} = \frac{H_v^2 P \rho d^2}{12 R \mu T^2}$$

Where

K_{vap} = Vapor space effective thermal conductivity

H_{fg} = Heat of vaporization, J/Kg

P = Pressure, N/m²

ρ = Density, Kg/m³

d = Vapor space thickness, mm

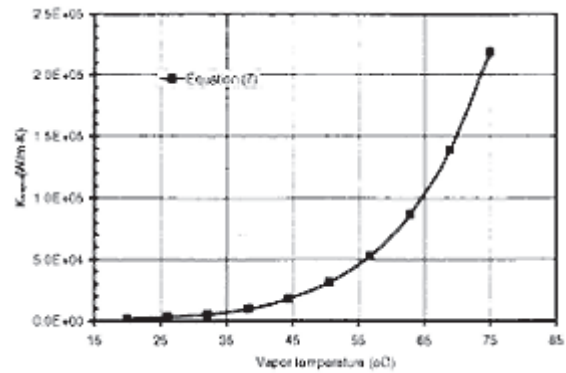
R = Gas constant per unit mass, J/K.Kg

μ = Dynamic viscosity, N·sec/m²

T = Vapor temperature, °C

As shown in Figure 3 below, when plotted against temperature, the above equation demonstrates that the effective vapor space conductivity is very low at low

temperatures. This has a significant implication for low heat flux or start up conditions [4]



To address the effects of different variables on the performance of a vapor chamber, a conduction model was put together as shown in Figure 4 [4]. In this model, a 10 x 10 mm heat source was mounted on a 42.5 x 42.5 mm ceramic chip carrier. The model was analyzed using Flotherm computational fluid dynamics (CFD) software. Different layers of the resistance network were constructed using their effective thermal conductivities, which were known or could be calculated as shown in the previous equations. The vapor chamber was modeled as a combination of the vapor chamber wall, wick structure, and vapor space. An effective heat transfer coefficient of 1,400 W/m²K was assigned based on the performance of the heat sink. The ambient air temperature was assumed to be 35°C and a uniform heat flux of 100 W/cm² was applied at the base. Figures 5 and 6 reveal some interesting findings about the performance of the vapor chamber.

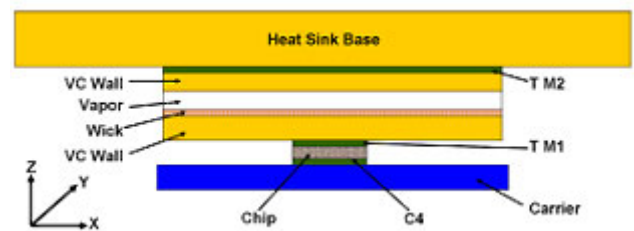


Figure 4: Schematic of a Vapor Chamber Physical Model for CFD

Figure 5 shows the junction temperature (T_j) as a function of wick effective thermal conductivity. The vapor space thermal conductivity was assumed to be 30,000 W/mK. The graph shows that the chip junction temperature drops from 97°C to 93.5°C for wick conductivities of 30 and 60 W/mK,

respectively. In other words, the performance of the vapor chamber is strongly influenced by wick thermal conductivity. However, Figure 6 shows that junction temperature is a very weak function of vapor space thermal conductivity. This is due to the fact that even an equivalent thermal conductivity of 5,000 W/mK, the lowest on the X-axis, is still a large number. However, if the vapor temperature is below a certain value, such as 35°C, then the vapor space effective thermal conductivity will drop drastically, impacting the junction temperature.

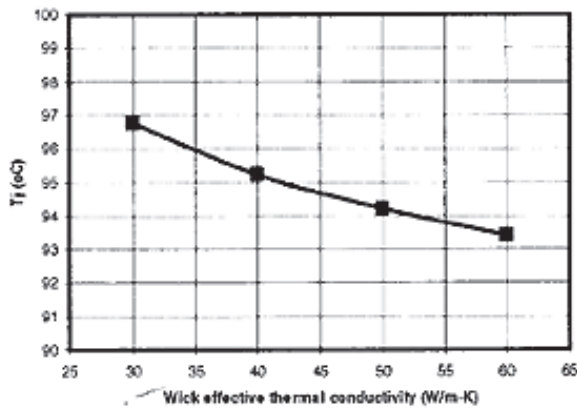


Figure 5: Junction Temperature as a Function of Wick Effective Thermal Conductivity [1]

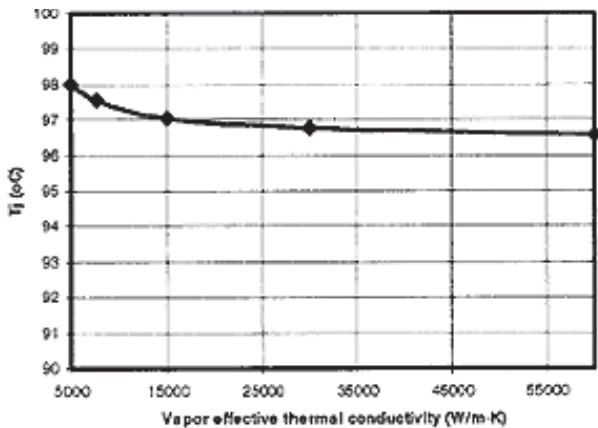


Figure 6: Junction Temperature as a Function of Vapor Space Thermal Conductivity [1]

Figure 7 shows junction and case temperatures as a function of vapor chamber size (lid) using examples that compare a solid heat sink base and a vapor chamber. The graph shows that for this particular configuration, a solid copper block outperforms a vapor chamber below the 40 mm lid size. But, above 40 mm the vapor chamber is a better choice. The superior performance of the VC over

solid copper is due to its enhanced lateral heat spreading on larger surfaces.

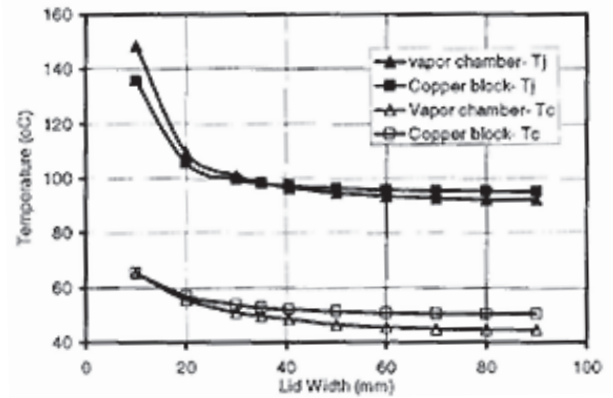


Figure 7: Junction Temperature as a Function of Lid Size for Vapor Chamber and Solid Copper Base [1]

Figure 8 shows the temperature as a function of lid size for heat transfer coefficients of 400 and 50,000 W/m²K. These extreme values of heat transfer coefficients represent low performance and very high performance heat sinks. The graph shows that with a low performance heat sink, the cross over point between the copper block and the vapor chamber is at 40 mm. From here the VC starts to outperform the copper block. For a very high heat transfer coefficient, such as with a liquid cooled cold plate, the size of the VC needs to be much larger to have an advantage over the copper block. In other words, if a large (80 x 80 mm) liquid cooled plate is used, a solid copper block will provide the same performance as a vapor chamber.

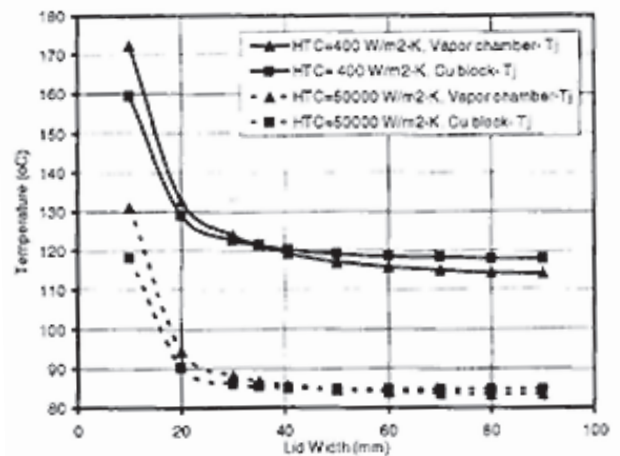


Figure 8: Junction Temperature as a Function of Lid Size for Vapor Chamber and Solid Copper Base for 400 and 50,000 W/m² Heat Transfer Coefficients [1]

Conclusion

This article shows that while a vapor chamber presents exciting technology, some calculations should be made to justify its use. As shown above, in some situations a solid copper block might provide better thermal performance than a VC. To use a VC instead of solid copper must be justified, for example, to reduce weight. Some vapor chambers have a power limit of 500 Watts. Exceeding this value might cause a dry out, as with a heat pipe, and could increase the vapor temperature and the pressure. The increase in internal pressure can deform the VC surfaces, or cause leakage from the welded joints. Other factors that need to be addressed include, cost, availability, and in special cases, the vapor chambers manufacturability.

Parameters Affecting Vapor Chamber Performance

Vapor chambers are flat heat pipes with very high thermal conductance. The idea of heat pipe was first proposed by Gaugler [1]. However, only after its invention by Grover [2, 3] in the early 1960s, were the remarkable properties of heat pipe realized by scientists and engineers.

In electronics cooling, heat pipes are generally used to move the heat from electronics to heat dissipation devices. For example, in a desktop computer, multiple heat pipes are used to transfer heat from a CPU to an array of cooling fins, which dissipate the heat to ambient environment through convection. Vapor chamber are generally used to spread heat from a small size device to a larger size heat sink, as it is shown in Figure 1.

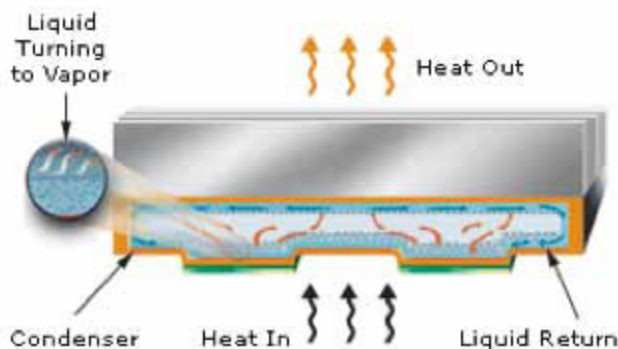


Figure 1. Vapor Chamber [4]

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Just like heat pipes, vapor chambers use both boiling and condensation to maximize their heat transfer ability. A vapor chamber generally has a solid metal enclosure with a wick structure lining the inside walls. The inside of the enclosure is saturated with a working fluid at reduced pressure. As heat is applied to one side of the vapor chamber, the fluid at locations close to the heat source reaches its boiling temperature and vaporizes. The vapor then travels to the other side of the vapor chamber and condenses to liquid. In the process of condensation, it releases its latent heat. The condensed fluid returns to the hot side via the gravity or capillary action, ready to vaporize again and repeat the cycle. By using boiling and condensation, the vapor chamber can transfer and spread heat from one side to another side with minimum temperature gradient.

Compared to copper heat spreaders, vapor chambers have the following merits. They have much higher effective thermal conductivity. The pure copper has a thermal conductivity of 401 W/m°C and the best conductive material (i.e., diamond) has a thermal conductivity of

1000-2000 W/m°C. The effective thermal conductivity of a well designed vapor chamber can exceed 5000 W/m°C, which is an order of magnitude higher than that of pure copper. The density of the vapor chamber is much lower than copper. Due to its hollow structure, the heat spreaders designed for vapor chambers are much lighter than those made of copper. These properties make the vapor chamber the ideal candidate for high heat flux and weight sensitive heat spreading applications. However, the cost of the vapor chambers is much higher than copper heat spreaders. Some design limitations also limit the usage of vapor chambers. Vapor chambers don't perform better than copper heat spreaders in some application and this paper will address the research on the parameters affecting vapor chamber performance.

Wei and Sikka [5] used a conduction model built in FLOTHERM to study the thermal performance of a vapor chamber heat spreader and compared its performance with that of a copper heat spreader. In the FLOTHERM model, the vapor chamber is represented by multiple layers of material with effective thermal conductivities. The schematic of the vapor chamber model is shown in Figure 2.

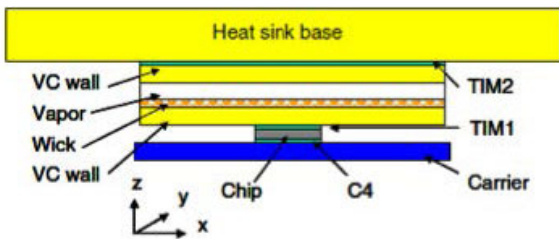
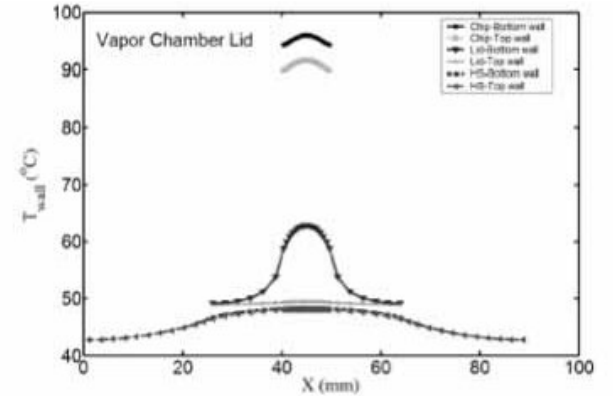


Figure 2. Vapor Chamber Model [5]

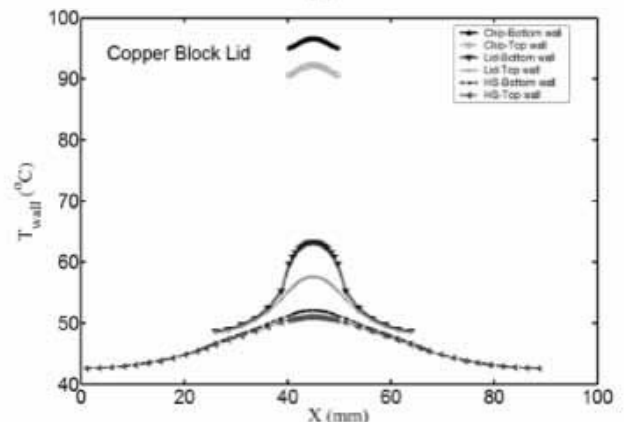
Parts	Model	Material/Thermal conductivity (W/m-K)	Dimension (mm)
Carrier	Cuboid	Ceramic/21	42.5x42.5x2
C4	Collapsed cuboid	Solder+underfill/5	10x10x0.075
Chip	Cuboid	Silicon/117 at 100°C	10x10x0.785
TIM1	Cuboid	Thermal Paste/3.8	10x10x0.114
VC wall-bottom	Cuboid	Cu/385	40.5x40.5x1.5
Wick	Cuboid	Sintered Cu powder/30	40.5x40.5x0.5
Vapor	Cuboid	Water vapor/30000	40.5x40.5x1.0
VC wall-top	Cuboid	Cu/385	40.5x40.5x1.0
TIM2	Cuboid	Thermal Paste/3.8	40.5x40.5x0.1
HS base	Cuboid	Cu/385	90x90x4

Table 1. Model Component Information [5]

The size of the vapor chamber is 40.5 × 40.5 × 4 mm and the size of chip is 10 × 10 × 0.785 mm. The component information is shown in Table 1. In the model, all the boundary walls are assumed to be adiabatic except the top surface of the heat sink base, where an effective heat transfer coefficient of 1400 W/m²°C is applied. A uniform heat flux of 100 W/cm² is applied at the bottom side of the chip and the ambient temperature is assumed to be 35°C. The effective thermal conductivities of vapor and sintered wick are assumed to be 3000 W/m°C and 30 W/m°C, respectively.



(a)



(b)

Figure 3. Temperature Distribution Along the Model Centerline (a) Vapor Chamber Heat Spreader (b) Copper Heat Spreader [5]

Figure 3(a) shows the temperature distribution along the centerline of the model with the vapor chamber as the heat spreader. Figure 3(b) shows the temperature distribution along the centerline of the model with a copper block (40.5 × 40.5 × 4 mm) as the heat spreader. Test results show that the die junction temperature is close for two cases. Across the heat spreader thickness, the vapor chamber has the larger temperature drop because of the low thermal conductivity of the wick (30 W/m°C). However, the vapor section of the vapor chamber heat spreader enhances the lateral heat spreading. Thus, it results in

a much more uniform temperature at the bottom of the heat sink. In the simulation, the temperature drop across the TIM1 is largest among all components. Due to its low thermal conductivity, the wick structure of the vapor chamber causes the largest temperature drop across the vapor chamber. To understand the effect of the wick structure, Wei and Sikka [5] did a sensitivity study by changing the wick structure's effective thermal conductivity while maintaining the vapor thermal conductivity at 30000 W/m°C. The simulation results are shown in Figure 4. By doubling the wick thermal conductivity to 60 W/m.oC, the junction temperature drops 3.5°C. The results of another sensitivity study by changing the vapor effective thermal conductivity while maintaining wick thermal conductivity at 30 W/m°C is shown in figure 5. Clearly the junction temperature is less sensitive to change of vapor effective thermal conductivity. So in the vapor chamber, the thermal resistance of the wick structure is the dominant factor

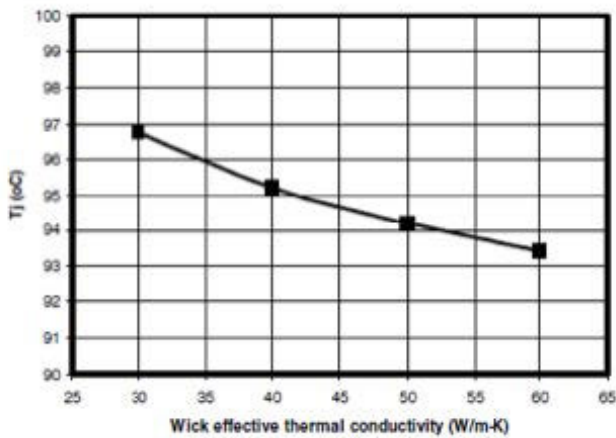


Figure 4. Effects of Wick Thermal Conductivity on Junction Temperature [5]

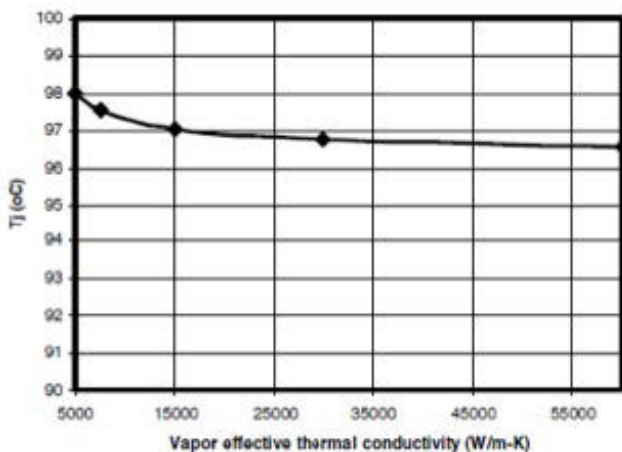


Figure 5. Effects of Vapor Thermal Conductivity on Junction Temperature [5]

of heat sink on junction temperature for vapor chambers and copper heat spreaders. The results are shown in Figure 6. When the heat sink has a low convection heat transfer coefficient, the vapor chamber outperforms the copper heat spreader. With an increase of the convection heat transfer coefficient, the difference between two heat spreaders narrows and the copper heat spreader even outperforms the vapor chamber at a high convection heat transfer coefficient. It is obvious that the vapor chambers are best suited for aircooled heat sinks and copper heat spreaders are good for liquid- cooled cold plates.

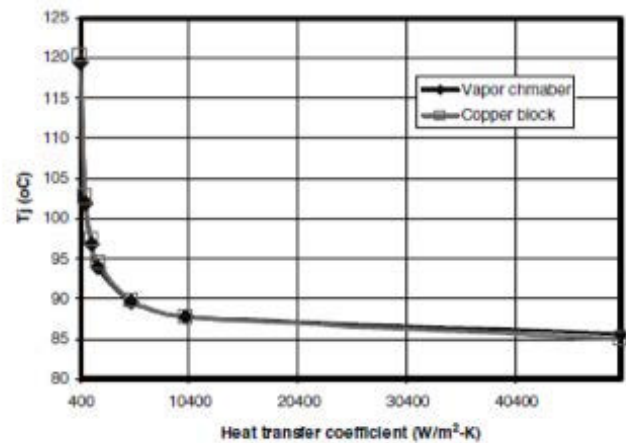


Figure 6. Effects of Heat Sink Convection on Junction Temperature [5]

The effects of the size of heat spreader on die junction temperatures are shown in Figure 7. As shown below, the vapor chamber outperforms the copper heat spreader with its large heat spreader size, which enables it to fully utilize its lateral heat spreading ability performance of a vapor chamber and a copper heat spreader. They utilized Infra Red (IR) imaging to visualize the temperature distribution

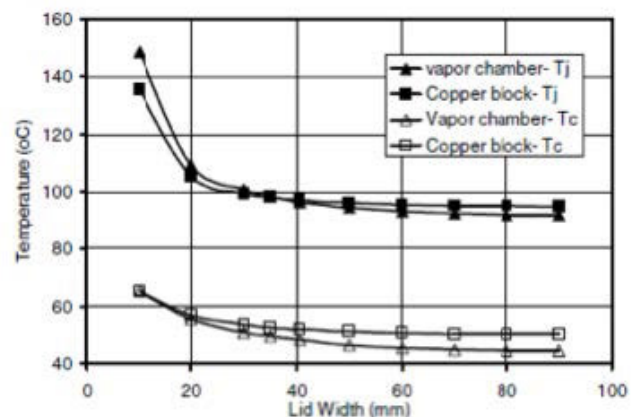


Figure 7. Effects of Heat Spreader Size on Junction Temperature [5]

of different heat spreaders under the same heat flux. The dimensions of the vapor chamber and copper heat spreader they studied is 250 × 200 × 5 mm. An electric heat cartridge was embedded in an aluminum block (100 × 50 mm) as a heat source. The aluminum block was mounted at the center of the heat spreaders. The surface temperature distributions of the tested vapor chamber and copper heat spreader at 40 W/cm² heat flux are shown in Figures 8 and 9, respectively. Clearly, the temperature on the vapor chamber surface is lower and more uniform. Because the heat spreading area ratio is larger, the vapor chamber fully demonstrates its superiority over the copper heat spreader.



Figure 4. Effects of Wick Thermal Conductivity on Junction Temperature [5]

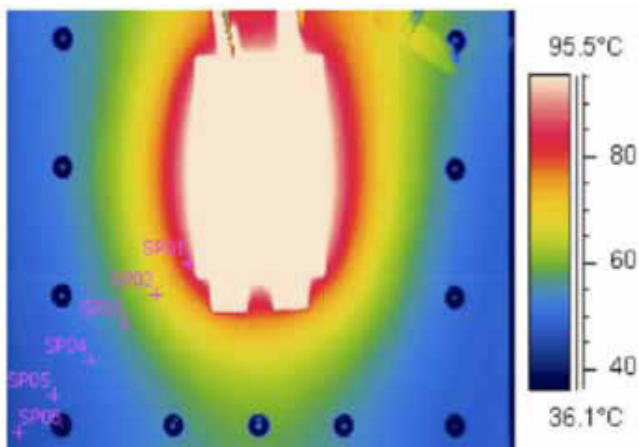


Figure 5. Effects of Vapor Thermal Conductivity on Junction Temperature [5]

To select an appropriate heat spreader for a demanding application, engineers should understand that the performance of the heat spreader is affected by a many parameters, such as device and heat sink size, heat sink

thermal resistance and heat spreader thickness. In most high heat flux cases, the vapor chamber is a better choice than the copper heat spreader in terms of performance. They can lower device temperature and make heat sink temperatures more uniform, which will reduce the heat sink thermal resistance. But, in some cases, as mentioned in this paper, the performance differences between a vapor chamber and a copper heat spreader are very small. If the cost and weight of the heat spreader are critical for the application, engineers have to find some intuitive ways or make a compromise to choose or design the right heat spreader.

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