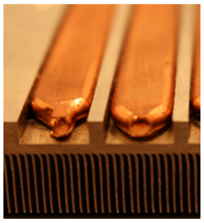
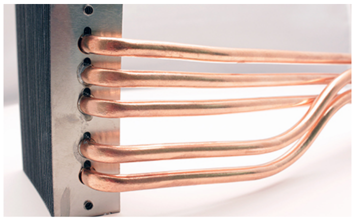
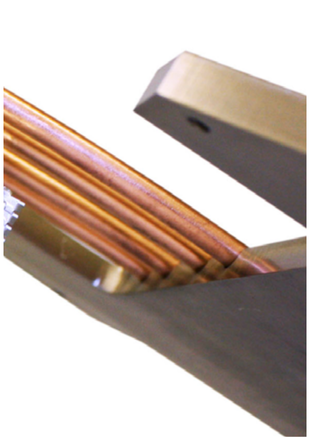
ATS Engineering eBook

Collection of Technical Articles on Heat Pipes and Their Roles in the Thermal Management of Electronics

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Heat Pipes: Heat Super Conductors

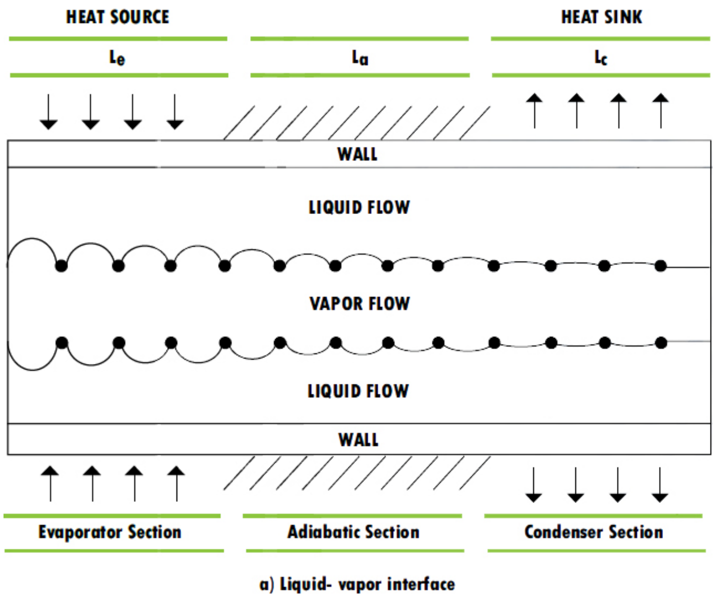

Figure 1. Schematic View of a Heat Pipe [1].

Heat pipes are transport mechanisms that can carry heat fluxes ranging from 10 W/cm^2 to 20 KW/cm^2 at a very fast speed. Essentially, they can be considered as heat super conductors. Heat pipes can be used either as a means to transport heat from one location to another, or as a means to isothermalize the temperature distribution.

The first heat pipe was tested at Los Alamos National Laboratory in 1963. Since then, heat pipes have been used in such diverse applications as laptop computers, spacecraft, plastic injection molders, medical devices, and lighting systems. The operation of a heat pipe is described in Figure 1.

A heat pipe has three sections: the evaporator, adiabatic, and condenser. The interior of the pipe is covered with a wick, and the pipe is partially filled with a liquid such as water. When the evaporator section (Le) is exposed to a heat source, the liquid inside vaporizes and the pressure in that section increases. The increased pressure causes the vapor to flow at a fast speed toward the condenser section of the heat pipe (L_c). The vapor in the condenser section loses heat to the integral heat sink and is converted back to liquid by the transfer of the latent heat of vaporization to the condenser. The liquid is then pumped back to the evaporator through the wick capillary action. The middle section of the heat pipe (La), the adiabatic portion, has a very small temperature difference.

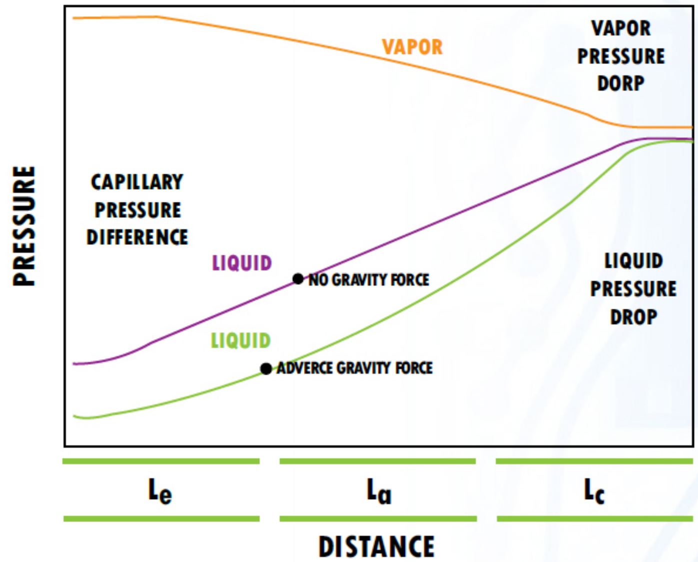

Figure 2. Pressure Drop Distribution in a Heat Pipe [1].

Figure 2 shows the pressure drop distribution inside a heat pipe. In order for the capillary force to drive the vapor, the capillary pressure of the wick should exceed the pressure difference between the vapor and the liquid at the evaporator. The graph also shows that if the heat pipe is operated against the force of gravity, the liquid undergoes a larger pressure drop. The result is less pumping of the wick with reduced heat transfer. The amount of heat transfer decrease depends on the particular heat pipe. A typical heat pipe is made of the following:

1. **Metallic pipe** The metal can be aluminum, copper or stainless steel. It must be compatible with the working fluid to prevent chemical reactions, such as oxidation.
2. **Working fluid** Several types of fluids have been used to date. These include methane, water, ammonia, and sodium. Choice of fluid also depends on the operating temperature range.
3. **Wick** The wick structure comes in different shapes and materials. Figure 3 shows the profiles of common wick types: axial groove,

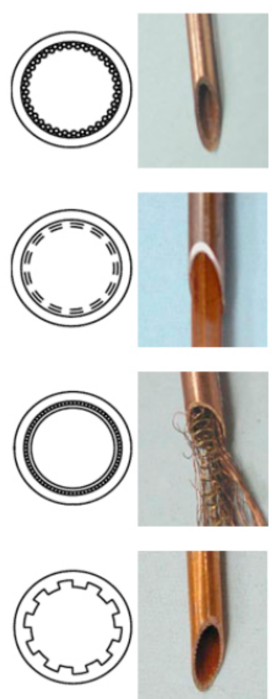

Figure 3. Different Wick Structures

3. **Wick (continued)** fine fiber, screen mesh, and sintering. Each wick has its own characteristics. For example, the axial groove has good conductivity poor flow against gravity, and low thermal resistance. Conversely, a sintering wick has excellent flow in the opposite direction of gravity, but has high thermal resistance.

Table 1 shows experimental data for the operating temperature and heat transfer for three different types of heat pipes [1].

Working Fluid	Operating Temp (°C)	Wick Design	Wall Material	Axial Heat Transport, (W)
Methane	-140	Circumferential mesh	Stainless steel	12
Water	100	Axial grooves	Copper with rectangular cross section	70
Sodium	430-790	Circumferential stainless steel screen	Stainless steel	1309

Table 1. Heat Pipes with Different Structures and Operating Conditions [1]

Certain factors can limit the maximum heat transfer rate from a heat pipe. These are classified as follows:

1. Capillary limit Heat transfer is limited by the pumping action of the wick
2. Sonic limit When the vapor reaches the speed of sound, further increase in the heat transfer rate can only be achieved when the evaporator temperature increases
3. Boiling limit High heat fluxes can cause dry out.
4. Entrainment limit High speed vapor can impede the return of the liquid to the condenser

A heat pipe has an effective thermal conductivity much larger than that of a very good metal conductor, such as copper. Figure 4 shows a copper-water heat pipe and a copper pipe dipped into an 80°C water bath. Both pipes were initially at 204°C temperature. The heat pipe temperature reaches the water temperature in about 25 seconds, while the copper rod reaches just 30°C after 200 seconds. However, in an actual application when a heat pipe is soldered or epoxied to the base of a heat sink, the effective thermal conductivity of the heat pipe may be drastically reduced due to the extra thermal resistances added by the bonding. A rule of thumb for the effective thermal conductivity of a heat pipe is 4000 W/mK.

Heat pipe manufacturers generally provide data sheets showing the relationship between the temperature difference and the heat input. Figure 5 shows the temperature difference between the two ends of a heat pipe as a function of power [2].

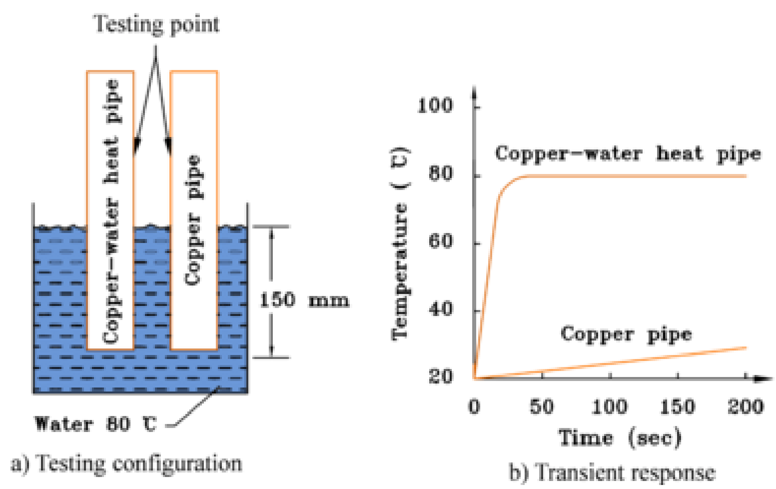

Figure 4. Experiment Comparing Speed of Heat Transfer Between a Heat Pipe and a Copper Pipe [1].

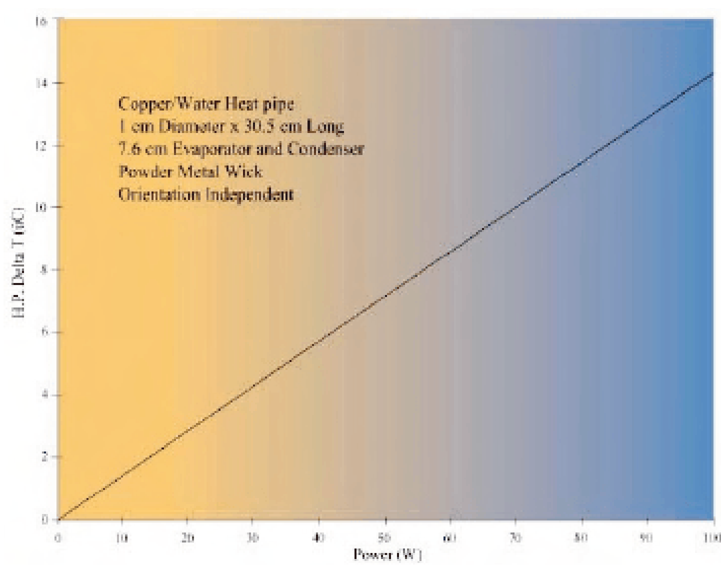

Figure 5. Temperature Difference Between the Evaporator and the Condenser in a Heat Pipe [2].

There are many heat pipe shapes in the market, but the most common are either round or flat. Round heat pipes can be used for transferring heat from one point to another. They can be applied in tightly spaced electronic components, such as in a laptop. Heat is transferred to a different location that provides enough space to use a proper heat sink or other cooling solution. Figure 6 shows some of the common round heat pipes available in the market.

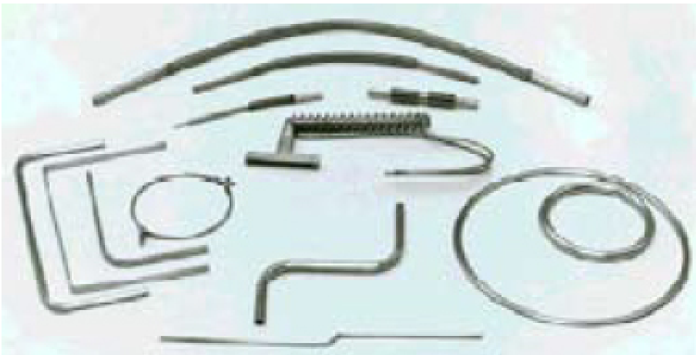

Figure 6. Typical Round Heat Pipes in the Market.

Flat heat pipes (vapor chambers) work conceptually the same as round heat pipes. Figure 7 shows a flat pipe design, they can be used as heat spreaders. When the heat source is much smaller than the heat sink base, a flat heat pipe can be embedded in the base of the heat sink, or it can be attached to the base to spread the heat more uniformly on the base of the heat sink. Figure 8 shows some common flat heat pipes.

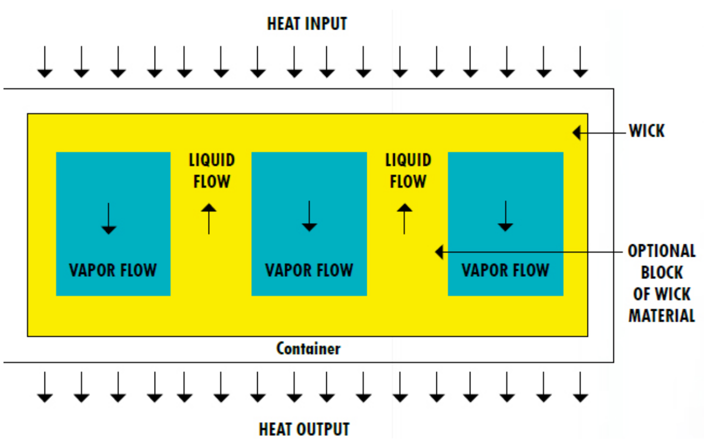

Figure 7. Conceptual Design Schematic of a Flat Heat Pipe [1].

Figure 8. Commonly-used Flat Heat Pipes.

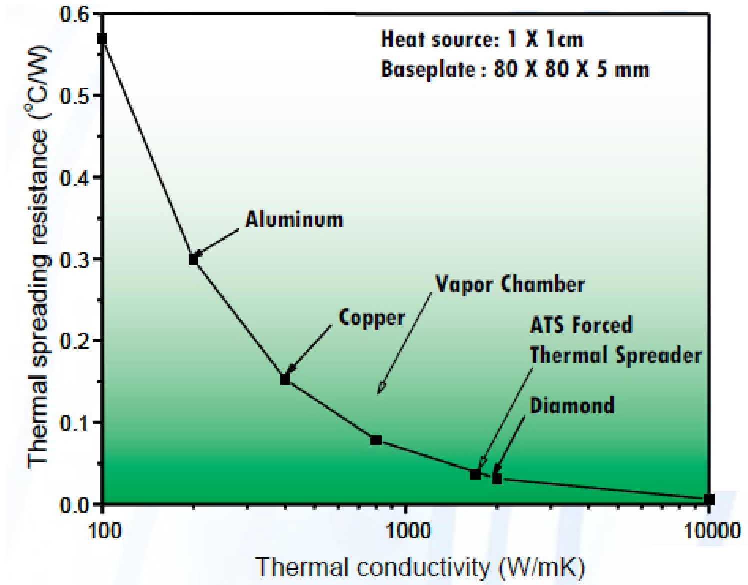

Figure 9. Thermal Spreading Resistances for Different Materials.

Although a vapor chamber might be helpful in minimizing spreading resistance, it may not perform as well as a plate made from a very high conductor, such as diamond. A determining factor is the thickness of the base plate. Figure 9 shows the spreading resistance for 80 x 80 x 5 mm base plate of different materials with a 10 x 10 mm heat source. The vapor chamber has a spreading resistance that is better than copper, but worse than diamond. However the price of the diamond might not justify its application. Figure 9 also includes the spreading resistance from the ATS Forced Thermal Spreader (FTS), which is equal to that of diamond at a much lower cost. The FTS uses a combination of mini and micro channels to minimize the spreading resistance by circulating the liquid inside the spreader.

Heat pipes have a very important role in the thermal management arena. With projected lifespans of 129,000-260,000 hours (as claimed by their manufacturers), they will continue to be an integral part of some new thermal systems. However, with such problems as dry out, acceleration, leakage, vapor lock and reliable performance in ETSI or NEBS types of environments, heat pipes should be tested prior to use and after unsatisfactory examination of other cooling methods.

References:

1. Faghri, A. Heat Pipe Science and Technology Taylor & Francis, 1995.

2.Thermacore Internation, Inc., www.thermacore.com.

3. Xiong, D., Azar, K., Tavossoli, B., Experimental Study on a Hybrid Liquid/Air Cooling System, IEEE, Semiconductor Thermal Measurement and Management Symposium 2006.

Fundamentals:
Effective Thermal Conductivity Of A Heat Pipe

Introduction

The question often arises that what is the effective thermal conductivity of a heat pipe. The correct answer depends on the construction and the wick material inside the heat pipe. To understand this better, consider figure 1 which shows all the resistances from the hot source on the evaporator side to the cold side which is the condenser.

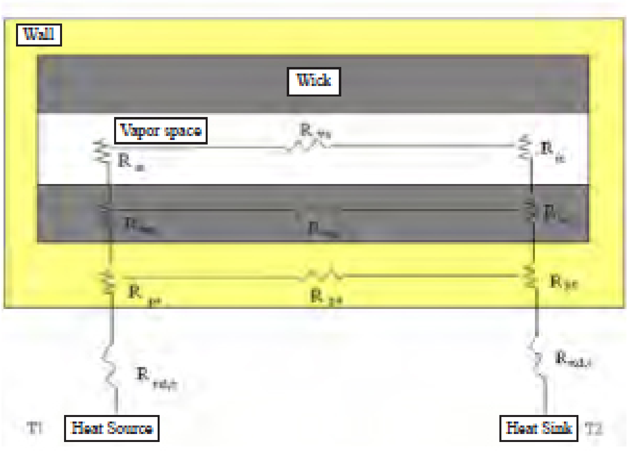

Figure 1. Thermal Resistances of a Heat Pipe [1]

The various thermal resistances are defined as follows:

$R_{ext,e}$ = Contact resistance between hot source and the heat pipe

R_{pe}, R_{pc} = Conduction resistance of the heat pipe wall in the radial direction

R_{we},R_{wc} = Resistance of the wick liquid structure in the radial direction

R_{pa} = Conduction resistance of the heat pipe wall in the axial direction

R_{wa} = Resistance of the wick liquid structure in the axial direction

R_{ie},R_{ic} = Resistance of the liquid vapor interface

R_{va} = Resistance of the vapor phase

The total resistance of the heat pipe is a combination of series and parallel resistances and can be calculated as follows:

$$\frac{1}{R_{tot}} = \frac{1}{R_{pe} + R_{we} + \dfrac{1}{\dfrac{1}{R_{va}} + \dfrac{1}{R_{pa}} + \dfrac{1}{R_{wa}}} + R_{wc} + R_{pc}} \qquad (1)$$

Considering that the thermal resistance of the vapor space is extremely small in the range of 10-8 °C/W, equation 1 can be simplified to:

$$R_{tot} = 2(R_{pe} + R_{we}) \qquad (2)$$

To gain a better understanding a simple calculation can reveal some insight. Assume a 6cm long heat pipe with inner and outer diameters of 5mm and 6mm respectively having two layers of #500-mesh copper screens with wire diameters of 0.0215mm. Calculations show that:

R_{pe} = 3.618X10^{-3} °C/W
R_{we} = 1.474°C/W

Substituting these values into equation 2 results in:
R_{total} = 2.95°C/W

When you compare it to a solid copper with the same sizes results in R = 5.3°C/W, almost a factor of two better, with the added advantage that the heat pipe is much lighter. This results in an effective thermal conductivity of this heat pipe to be 730 W/m·K

Equation 2 shows the importance of the wick structure resistance and is clear that it is one of the dominant factors in the overall thermal performance of the heat pipe.

The above mentioned arguments show that the common assumption of a very high conductivity around 40,000 W/m·K for the heat pipe is not correct. The correct way is to accurately calculate the different thermal resistances based on the geometry of the heat pipe, wall material, wick structure and the liquid to find the total thermal resistance and hence the effective thermal conductivity. If the information is not readily available, the best option is to test the heat pipe to calculate its thermal resistance.

Reference:

Peterson, G.P, “An introduction to Heat pipes – Modeling, Testing and Applications”, New York: John Wiley and sons, 1994

How Wicks and Orientation Affect Heat Pipe Performance

Introduction

A heat pipe is a device with very high thermal conductance that can transport large quantities of heat with small temperature difference between its hot and cold ends. It is normally used to transport heat from one area to another or to smooth the temperature distribution on a solid surface. Heat pipes are widely used in aerospace applications, military devices, temperature control systems, and now in personal computers.

A heat pipe is a self-driven, two-phase device. A schematic view is shown in Figure 1. At its hot end (evaporator) the liquid evaporates and turns to vapor. This vapor flows to the cold end (condenser) where it liquefies. The liquid is driven back from the cold end to the hot end by capillary forces within the heat pipe's wick structure.

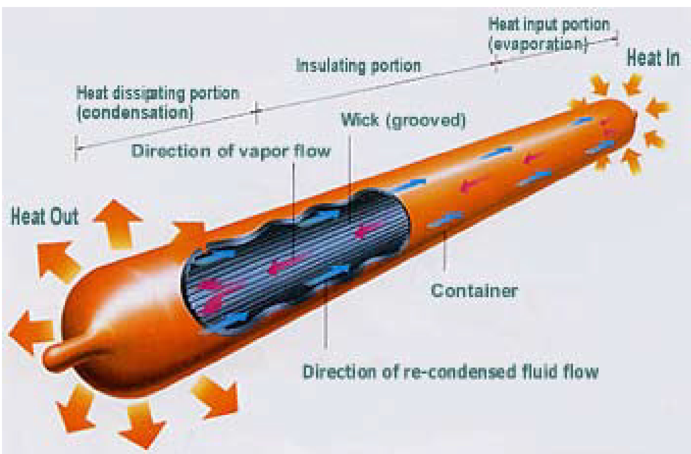

Figure 1. Typical Heat Pipe [1].

The heat transfer ability of a heat pipe is determined by its diameter, fluid type, wick structure, and orientation. The heat flux limitations of a heat pipe are governed by the following factors (Figure 2):

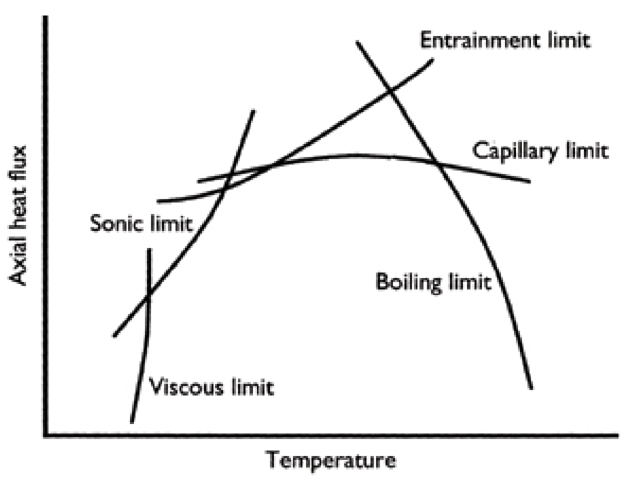

Figure 2. Limits to Heat Transfer in a Heat Pipe [2].

1) Viscous Limit. At low temperature, the vapor pressure difference between the evaporator and the condenser may not be enough to overcome viscous forces.

2) Sonic Limit. This occurs when the vapor velocity reaches sonic speed at the evaporator and any increase in the pressure difference will not speed up the flow.

3) Entrainment Limit. At high vapor velocities, droplets of liquid are torn from the wick and entrained in vapor. The droplets flow to the condenser with the vapor, which results in drying out on the evaporator.

4) Capillary Limit. This is reached when the capillary

$$\Delta P_{capillary} \geq \Delta P_v + \Delta P_l + \Delta P_g$$

If this condition is not met, the wick on the evaporator will dry out and the heat pipe will overheat. The maximum allowable heat flux $\Delta P_{capillary\_max}$ is referred to as the capillary limit. In typical operating conditions, the capillary limit determines the maximum heat transfer rate of the heat pipe.

For a heat pipe, the pumping power $\Delta P_{capillary}$ occurs on the gas and liquid interface of the wick structure due to surface tension differences. Pore radius and permeability are the two most important characteristics of a wick structure. The pore radius determines the pumping pressure that the wick can develop. The smaller the pore radius, the larger the pumping power. The permeability determines the fractional pressure losses of the working fluid ΔP_l. The pressure drop ΔP_V is directly related to the rate of vapor traveling from the evaporator to the condenser.

The heat transfer rate is also affected by the diameter and the length of the heat pipe. In a large diameter heat pipe, the cross sectional area will allow higher vapor volume to be transported from the evaporator to the condenser than in a small diameter pipe. The cross sectional area of a heat pipe affects the sonic limit and entrainment limit, as well. In general, heat pipes with larger diameters transport more heat. The gravitational pressure head ΔP_g is determined by the relative positions of the evaporator and condenser.

If the angle between a straight heat pipe and horizontal is f (f is positive when the evaporator is lower than condenser), the gravitational pressure head ΔP_g can be calculated as follows:

$$\Delta P_g = - \rho_l g l \sin ø$$

Where ρ_l is liquid density and l is heat pipe length.

The most commonly used wick structures for heat pipes are simple and homogeneous, such as grooves, wire mesh, sintered metal powders, and fiber. Other composite wick structures are included in Figure 3 [2]. Each wick structure has its advantages and disadvantages.

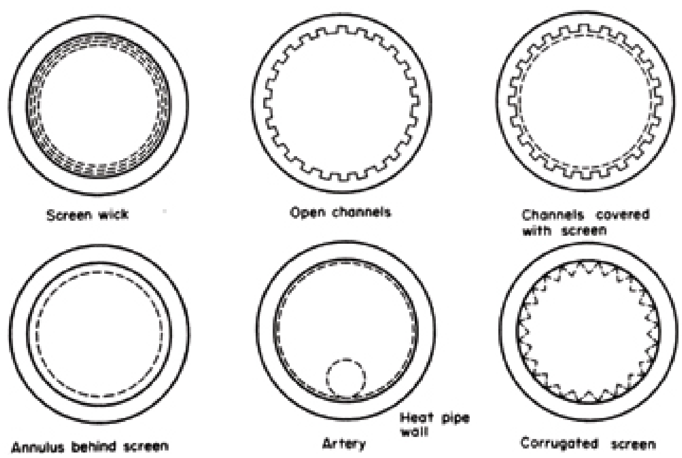

Figure 3. Heat Pipe Wick Structures [2].

The HP-1 is a series of high performance, sintered wick structure heat pipes produced by Thermacore. These pipes are available in diameters of 6.4 mm (1/4"), 9.5 mm (3/8"), 12.7 mm (1/2") and 15.9 mm (5/8"). Thermacore Corporation tested these 304.8 mm (12") long heat pipes with 76.2 mm (3") evaporator and 76.2 mm (3") condenser sections at a 100˚C operating temperature. The results are presented in Figures 4 and 5 [3].

Figure 4 shows the temperature difference between evaporator and condenser at different power levels when the heat pipes are vertical. Compared to small diameter heat pipes, large diameter heat pipes transport more heat with the same ΔT. Figure 5 illustrates the relationship between power and the inclination angle for different heat pipes. Clearly the sintered wick structure pipes are better with the help of gravity. When the inclination angle is larger than 10˚, the heat flux that the heat pipes can transport does not vary much. As the inclination angle gradually decreases from 10˚C, the heat flux decreases as well. At a -90˚ angle, the heat flux is less than half of that at 10˚.

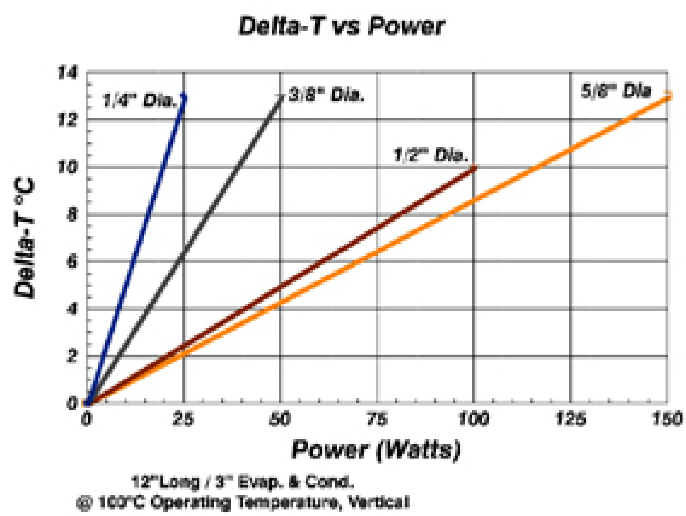

Figure 4. HP-1 Delt-T vs. Power [3].

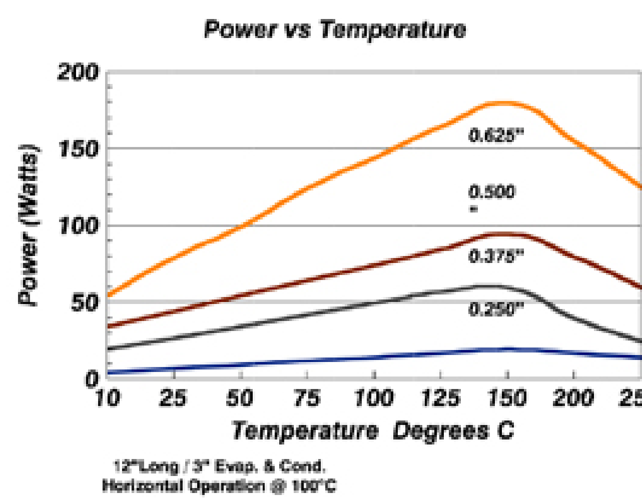

Figure 4. HP-1 Delt-T vs. Power [3].

Loh et al [4] experimentally studied the effects of wick structure and orientation on heat pipe performance. The bench they used for the tests is shown in Figure 6. The heat pipes they tested were 4, 5, and 6 mm in diameter.

The pipes were 200 mm long with a 35 mm evaporator and a 35 mm condenser. Each test started with an inclination angle f of 90°, the vertical position at which the evaporator block was located at the bottom. The tests ran through a 180° rotation that paused at each of the following inclination angles: 60°, 30°, 0° (horizontal), -30°, -60° and –90°.

Figures 7, 8 and 9 show the temperature differences between evaporator and condenser for mesh, groove and sintered metal powder heat pipes, respectively.

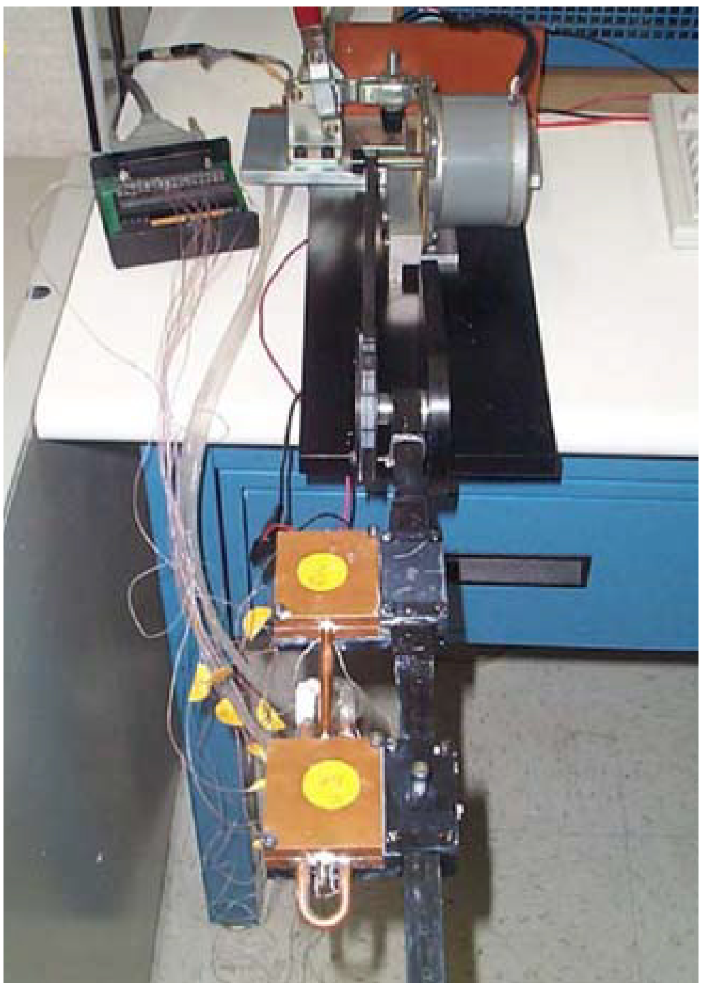

Figure 6. Photo of Heat Pipe Test Bench [4].

A heat pipe with a mesh wick structure has the largest thermal impendence. The orientation has a large effect on its heat transfer, but it manages to work at low and moderate heat flux even at a -90° angle. A heat pipe with a groove wick has the smallest thermal impendence among three wick structures when the inclination angle is positive. However, its temperature difference increases dramatically when the inclination angle changes to negative, even at low heat flux. It fails at a negative inclination angle when the heat flux is larger than 15 W.

The performance of a heat pipe with sintered metal powder is not affected much by its orientation when the heat flux is less than 15 W. At moderate heat flux, the sintered metal powder heat pipe can still work against gravity with an increased temperature difference. At high heat flux (>25 W), it can only work with help of gravity.

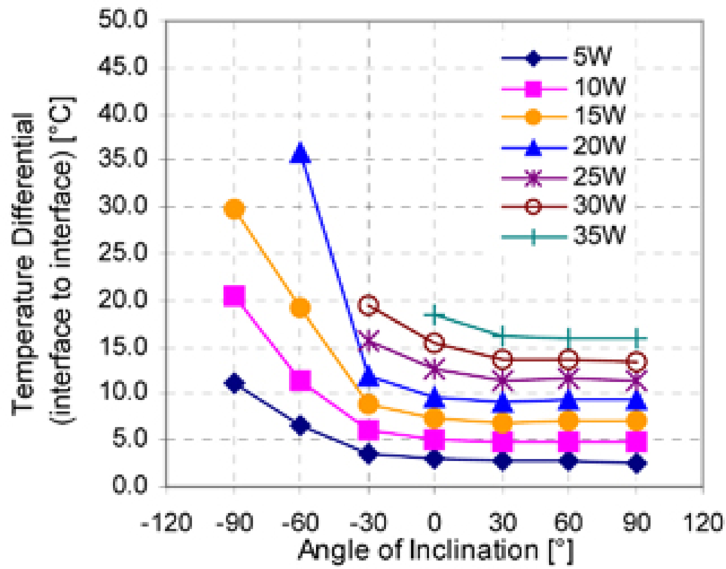

Figure 7. ΔT of a 6mm Mesh Heat Pipe at Different Inclination Angles [4].

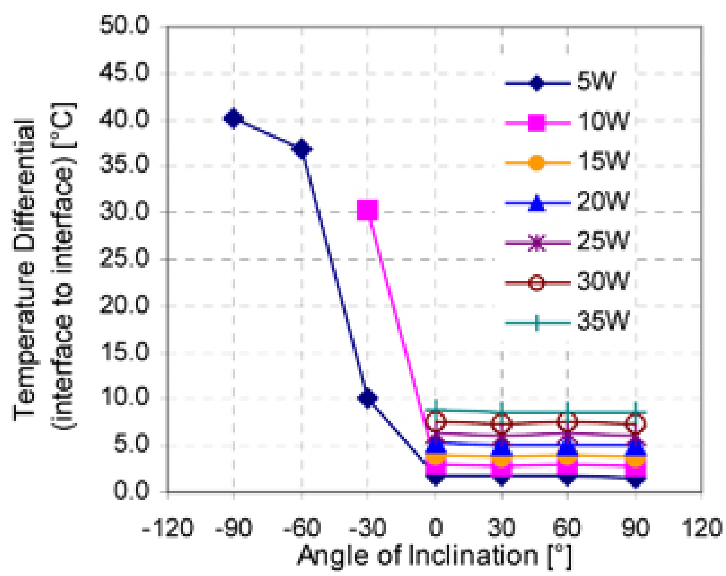

Figure 8. ΔT of a 6mm Groove Heat Pipe at Different Inclination Angles [4].

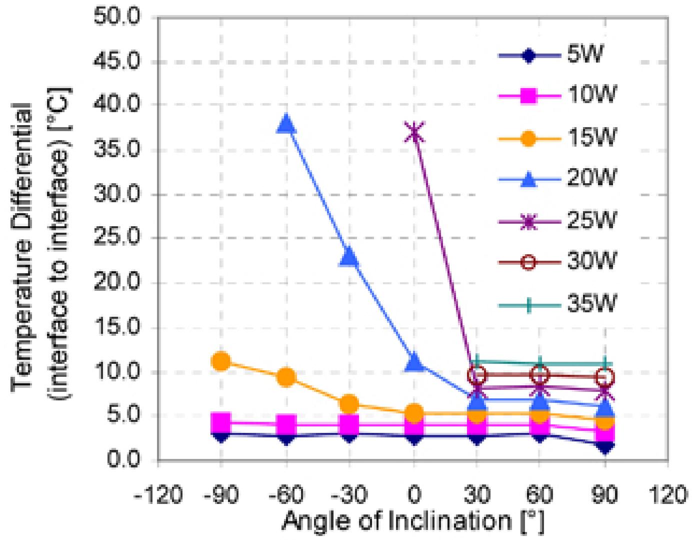

Figure 9. ΔT of a 6mm Sintered Metal Powder Heat Pipe at Different Inclination Angles [4].

It is important to select the proper wick structure for heat pipes based on their real application. If a heat pipe works in conditions with favorable gravitational force and a few bends, the grooved wick heat pipe is a good choice because of its superior thermal performance. If a heat pipe has complex geometry and works at a small or negative tilting angle, sintered powder metal is the optimum wick structure. For cooling electronic components in telecommunications devices and computer products, the sintered powder metal wick is the best choice because such applications require a compact heat sink size with many turns and bends. The high capillary pumping pressure achieved by using a sintered powder metal wick due to its small pore size, allows a heat pipe to operate in any orientation. Other wick structures do not work as well in non-vertical orientations because they cannot lift the returning working fluid along the length of the heat pipe against gravity.

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1. http://www.lightstreamphotonics.com/technology.htm
2. Reay, D. and Kew, P., Heat Pipes: Theory, Design and Applications, 5th Edition, Butterworth-Heinemann, 2006.
3. HP-1 Heat pipe specification, www.thermacore.com.
4. Loh, C., Harris, E. and Chou, D., Comparative Study of Heat Pipes Performances in Different Orientations, Semiconductor Thermal Measurement and Management Symposium, 2005.

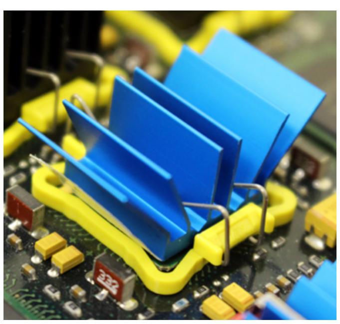
Integrated Heat Pipe Technology for Thermal Management of Electronics

Introduction

Increasingly, consumers and industry are demanding more functionality and better performance, along with increased miniaturization, from electronics products. The decrease in size of the new generation of electronic devices imposes a severe constraint on their incorporated thermal management devices. Since the cooling hardware has become large in size relative to the components to be cooled, serious challenges are ahead for the design of future products.

The vast majority of cooling solutions have been developed to be either attached on existing electronic products or managed through packaging techniques. As no integrative effort has been made, all these devices remain essentially adds on (Figure 1 [1]). The devices presented in Figure 1 are well embraced by the industry, especially from an assembly and cost point of view.

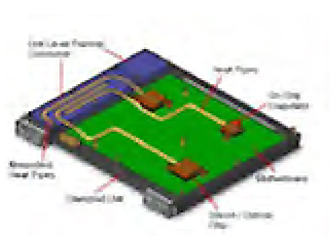
However, such solutions prevent significant progress in the design of electronic products. A radical new way of thermal management can be achieved by integrating thermal design criteria early into the electronic design process. This approach will allow the design of a printed circuit board with full integration of the thermal management hardware, with the aim of reducing thermal gradients inside electronic products.



a) ATS maxiFLOW™ heat sink

b) Corsair[2] A50 heat sink with heat pipes

c) ThermoShuttle[3] SVH001 vapor chamber



d) On board heat pipes by McGlen et al.[4]

Background

Before addressing the specifics of the heat pipe PCB integration let us briefly present basic background information about heat pipes and PCB technologies. A heat pipe is a heat transfer device consisting of a sealed vessel containing a small amount of working fluid. It has three sections: evaporator, adiabatic transport section and condenser. In order for the device to function, the condensate must return to the evaporator in a timely manner. This function is served by a capillary or wick structure that must be placed on the walls of the enclosure. The wick enables the liquid return from the condenser to the evaporator through the capillary pressure caused by the difference in curvature of the liquid menisci. In order for a heat pipe to operate, the following condition must be satisfied:

$$\Delta P_{cap} \geq \Delta P_v + \Delta P_l + \Delta P_g \qquad (1)$$

where,

ΔP_{cap} = capillary pressure (Pa)

ΔP_v = pressure drop of vapor flow (Pa)

ΔP_l = pressure drop of liquid flow (Pa)

ΔP_g = pressure drop due to gravity (Pa)

So, the capillary pressure provided by the wick must overcome the pressure drops due to vapor and liquid flows. The capillary limit refers to the maximum heat that a heat pipe can transfer and this can be expressed as:

$$\dot{Q}_{cap,\max} = \frac{\dfrac{2\sigma\cos\theta}{r_{eff}} - \rho_l g L \sin\gamma}{L_{eff}\left(\dfrac{\mu_l}{A_w \varphi \rho_l H_{fg} K} + \dfrac{2(f\,\mathrm{Re})_{h,v}\mu_v}{D_{h,v}^2 A_v \rho_v H_{fg}}\right)}$$

where,

σ = surface tension of working liquid (N/m)

r_{eff} = effective pore radius of the wick (m)

θ = mesh wall - working liquid contact angle (degrees)

g = gravitational constant (m/s2)

L = heat pipe length (m)

γ = heat pipe's inclination angle (degrees)

φ = porosity of the wick

fRe = Reynolds based friction factor

A_v = vapor space cross-sectional area (m2)

μ_l = viscosity of the liquid (Pa•s)

μ_v = viscosity of the vapor (Pa•s)

L_{eff} = effective length (m)

K = permeability of the wick (m2)

A_w = wick cross-sectional area (m2)

ρ_l = density of the liquid (kg/m3)

ρ_v = density of the vapor (kg/m3)

H_{fg} = latent heat of vaporization of the working fluid (J/Kg)

Since the heat pipes presented in this paper have a rectangular cross-section, hydraulic properties are used in equation (2).

In general, a PCB serves as a carrier, providing mechanical support and enabling electrical connections between all mounted electronic components. A typical PCB consists of several polymeric layers (such as FR4) laminated together. Conductive patterns (traces) need to be etched in order to interconnect the electronic components. Usually, several layers are laminated together, forming a multilayer PCB.

The process of manufacturing a PCB can be presented sequentially as follows:

a) individual layers are patterned

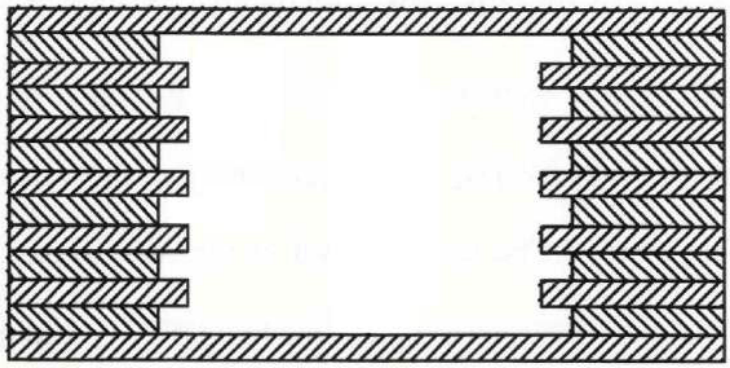
b) layers are stacked with intermediate bonding layers

c) the entire stack is laminated in a special press at an elevated temperature

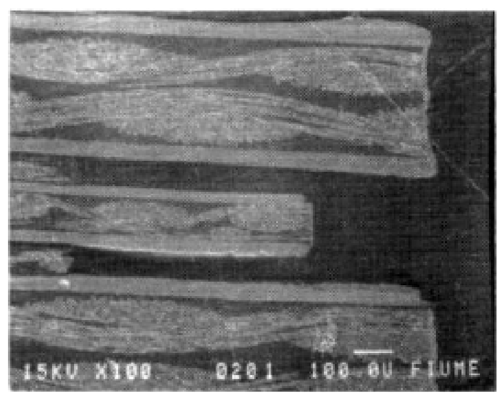
Advances in Technology Integration

In recent years, significant advances in integrating the heat pipe technology and PCB technology have been made. Jones et al. [2] proposed embedded micro heat pipes in laminate substrates with the wick microgrooves placed vertically in a staggered lay-up (Figure 2).

The staggered lay-up introduces an additional constraint on the board design. As heat pipe performance is a function of the number of PCB layers, additional, electronically non-functional layers must be introduced. Water was used as working fluid and the cavity was made of copper. To reduce the contact angle and, therefore, increase the capillary pressure, a cleaning method was used. A reduction in contact angle from 104 degrees to 56 degrees was achieved. In terms of thermal performance, heat pipe failure occurred around 10W, due to delamination of the PCB.



a) staggered lay-up (schematically)

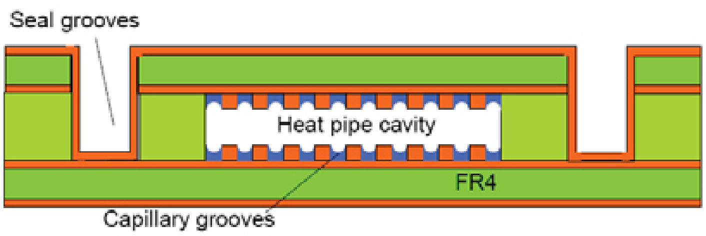


b) microgrove detail

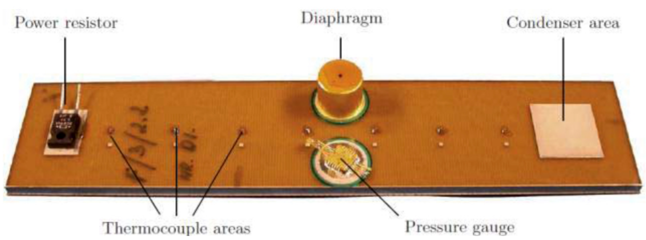
Figure 2. Integrated Heat Pipe [2]

Wits et al. [3] proposed another way of integrating a heat pipe into the PCB. In their design, the microgroove wick was placed on the top and bottom layers of the internal cavity (Figure 3). The grooves are manufactured using a metallic plating technique based on conventional dry film lithography, commonly used in electronics manufacturing. The working fluid was also water and the cavity was made of copper. Figure 3 b) shows the technology demonstrator. The heat transfer in and out of the heat pipe was accomplished with thermal vias.

The heat pipe pictured in Figure 3 b) was tested using the experimental set up illustrated in Figure 4. The heat pipe was insulated and clamped in a hinge to allow testing in various orientations. The power input was raised in steps. After reaching steady state, readings were made and the next step was implemented. The experimental run was terminated when the heat pipe would experience a sudden rise in temperature, signaling a dry out condition.



a) integrated heat pipe structure



b) technology demonstrator

Figure 3. Copper Mesh Used for Ultra-Thin Heat Pipes [3]

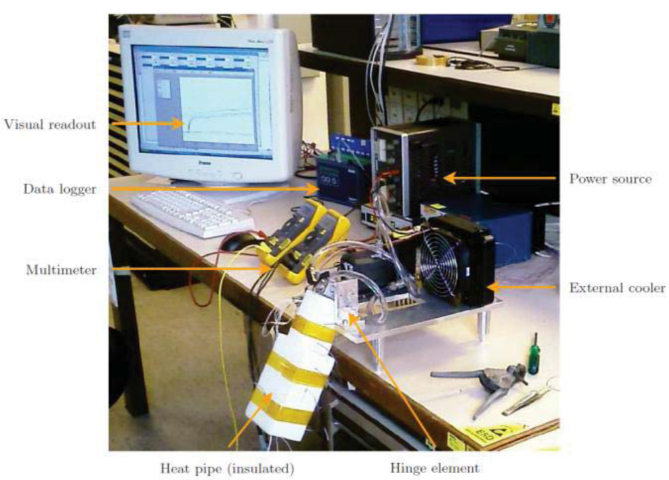


Figure 4. Experimental Setup [3]

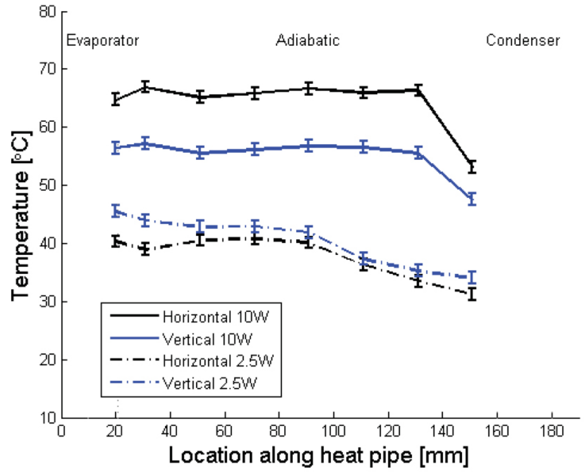


Figure 5. Temperature Distribution Along The Heat Pipe [3]

Figure 5 presents some of the test results, for two power input levels (2.5 W and 10 W), and for two orientations (horizontal and vertical). The vertical orientation refers to the condition whereby the working fluid returns to the evaporator assisted by gravity. For 2.5 W input power, the thermal performance for both orientations is similar. At the evaporator end, the temperature profile is fairly Figure 5. Temperature Distribution Along The Heat Pipe [3] flat. However, just over the mid-way point, the temperature starts to drop, indicating the presence of non-condensable gases (air). Vertically, the heat pipe was able to transport a maximum of 12 W of heat.

When tested with the working fluid ascending against gravity, the prototype did not function at all. The capillary microgrooves were not able to pump the working fluid back up to the evaporator. However, the PCB did not delaminate as in the Jones et al. [2] case.

Integration Challenges

Based on a thorough analysis of the previously proposed designs, the following three challenges have been identified for the design of a PCB with an integrated heat pipe:

a) operation against gravity: microgroove structure must be improved

b) lower thermal resistance from the top to the bottom of the PCB in the normal direction

c) minimize the amount of dead volume (bonding layers in contact with heat pipe cavity)

To address the first challenge, it is useful to take a look at Equation (2). In the numerator, the first term, indicating capillary pressure, must be enlarged in comparison with the second term, corresponding to pressure losses due to gravity. The capillary microgrooves of both presented designs failed to transport the working fluid against gravity; therefore, a different wick structure, with a smaller pore radius, should be chosen. Both microgroove designs had an effective pore radius of about 50-100 μm. A screen mesh, sintered media or metal foam will yield lower pore radii. Also from Equation (2), it is clear that for a chosen mode of operation, geometry and working fluid, only the internal distribution of vapor and liquid areas and the wick structure remain at the designer's discretion.

Based on this discussion, a new PCB prototype was built by Wits et al. [1] (Figure 6). The PCB features an insertable wick structure with a smaller pore diameter, to address the first challenge. The wick is positioned inside the cavity with the aid of copper inserts, which are also lowering the top to bottom thermal resistance. Therefore, the second challenge is addressed as well.

the multilayer board, each layer is given a surface finish to enhance the bonding strength. Since the surface finish also enhances the wettability, the wick structure is also treated with this surface finish. The wick structure is placed inside the heat pipe cavity and the copper inserts are placed in the evaporator and condenser areas.

The third challenge can be overcome by introducing an intermediate process step during the construction of the PCB. For instance, the bottom and intermediate layers can be assembled first to allow overplating and the sealing of the intermediate permeable zones from the inside. The second process step will then include stacking and laminating the bottom half of the board with the wick structure, copper insert and top layer. Finally, a seal groove needs to be machined and plated Figure 6. Prototype Heat Pipe Design [1] to seal the remaining top intermediate permeable zone.

The theoretical maximum amount of heat that can be transported with a PCB such as this one, presented in

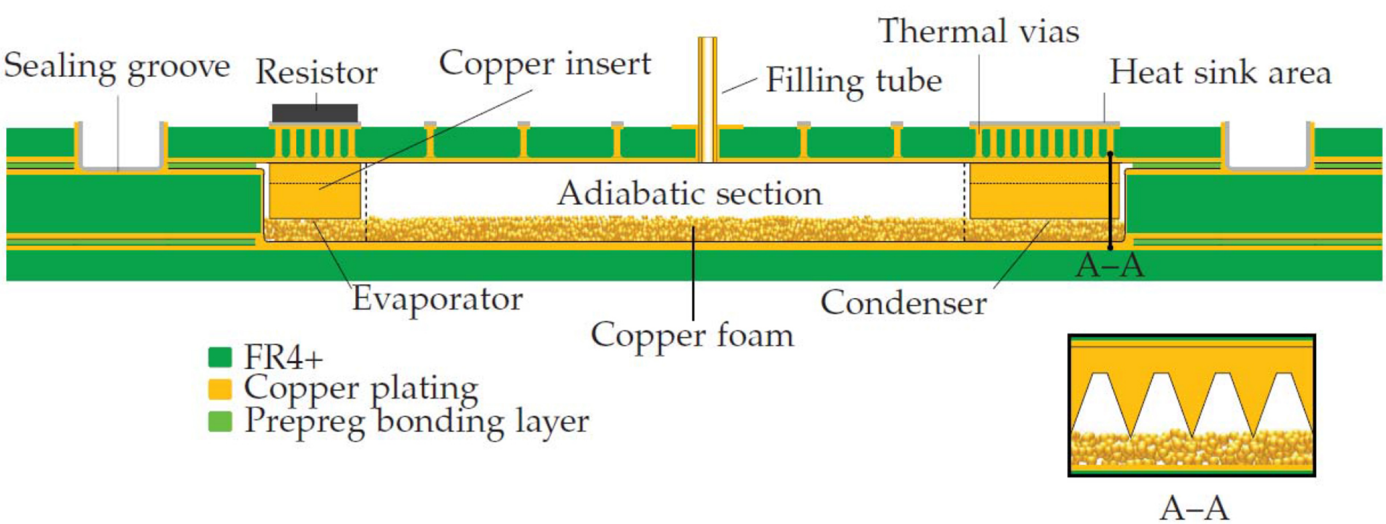


Figure 6. Prototype Heat Pipe Design [1]

The prototype is constructed from three layers of double plated polymeric material (FR 4+). The top layer has two machined openings for the pressure sensor and filling tube. Also, multiple small thermal vias are provided. The vias are plated and filled with a thermally enhanced epoxy (k = 3.5 W/m·K).

The middle layer features a rectangular slot that forms the heat pipe cavity. The third (bottom) layer is a regular flat laminate. The second and third layer will be laminated together and subsequently metalized. Before assembling

Figure 6 with a sintered wick structure, is 11 W, according to Equation (2). This value was obtained assuming an operational temperature of 80°C. Also, this value is for the worst case scenario, with the heat pipe working fluid ascending against gravity.

Conclusions

In conclusion, two existing concepts for integrating heat pipes into PCBs have been presented. Several challenges have been identified and a new prototype for a PCB-integrated heat pipe design has been proposed.

The heat pipe is integrated within the laminated structure of the PCB. The wick structure of the heat pipe is positioned with the help of two copper inserts that also minimize the top-bottom thermal resistance. Additional plating steps were introduced in the manufacturing process with the result of considerably reducing the dead volume. The new prototype should transport 11 W of power independent of orientation.

This is the first step towards further integration, with the designers of the future PCBs also designing the thermal management solution. Obviously, validation of the concept needs to be done, with short and long term tests for reliability as a part of it. For volume production, reliability testing (including shock and vibration) is absolutely necessary.

Even though it looks like a very promising new integrative approach, the end user should always be cautious when deciding to use it in a real application. First of all, an analysis of the risks versus rewards of this technology should be performed. Why should one use such a method versus the traditional heat pipe, what are the benefits and at what risks? Last but not least, what is the cost of a PCB integrating a heat pipe and is it justifiable?

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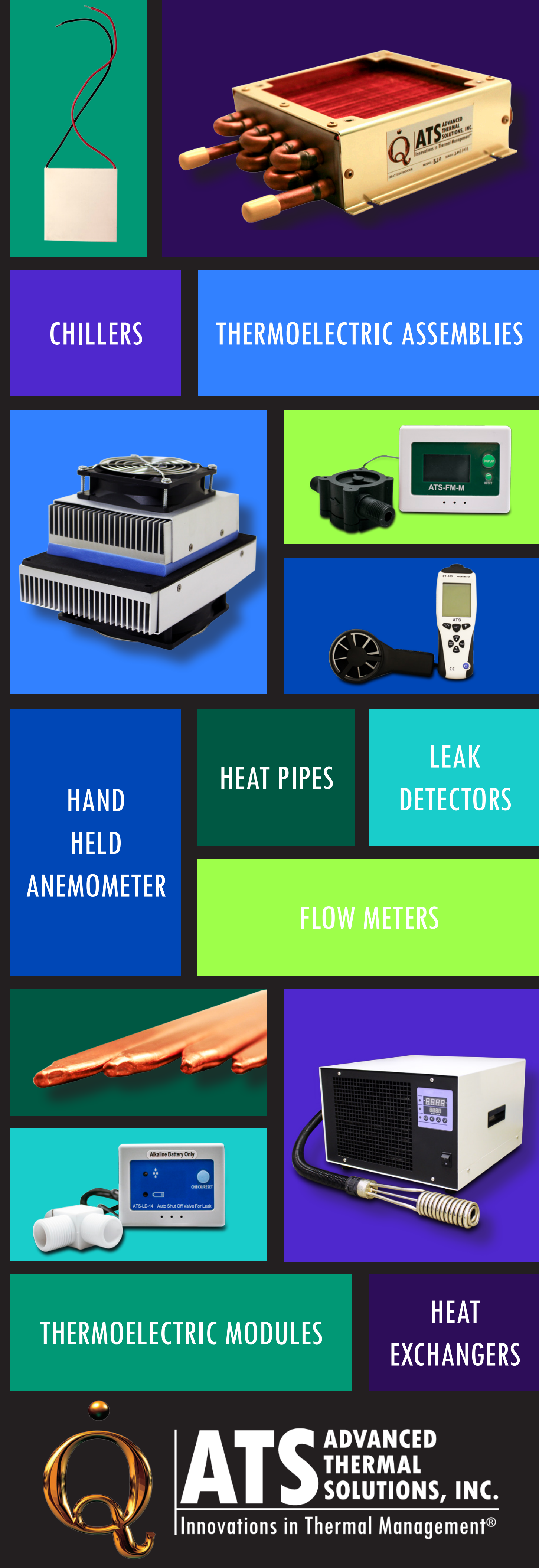

Nanofluids in Heat Pipes

Introduction

Heat pipes are simple heat transfer devices that are ubiquitous in electronics cooling applications. They transfer heat with a very low thermal resistance but are limited in the maximum load by various factors. The performance of the heat pipe is defined by both the maximum heat load and the thermal resistance when operating within that limit.

Figure 1 shows the schematic of a heat pipe and the different component thermal resistances. One of the variables that determine the performance of a heat pipe is the thermophysical properties of the working fluid. Because of the temperature range of electronics, the most cost effective working fluid is water. Although water is the best heat transfer fluid, its properties can be enhanced by introduction nano-particles.

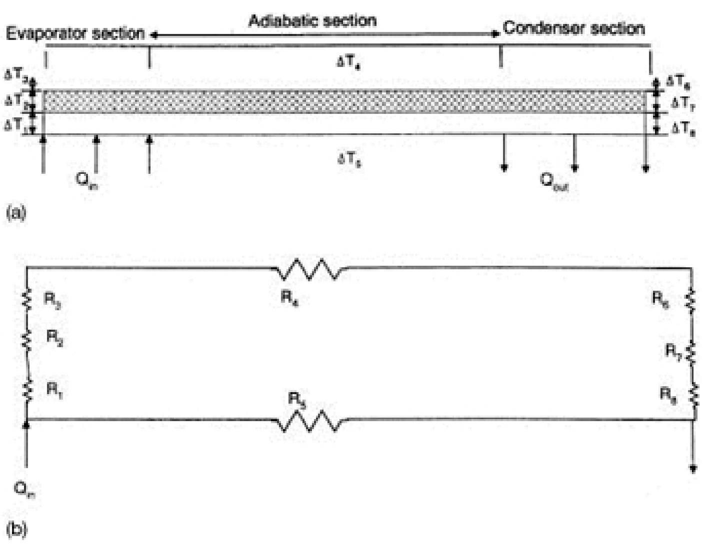

Figure 1. A Heat Pipe and its Thermal Resistance Network [1]

Nanofluids

The mixture of nanoparticles and a base fluid is known as a nanofluid. Nanofluids have been studied extensively over the past few decades because of their use in a wide Figure 2. CuO Nanoparticles in an 80:20 Water-Glycerin Base Fluid at Concentrations of 0.1, 0.3, 0.5, 0.8 and 1% by Weight [3] range of applications [2]. The techniques for creating such colloidal suspensions vary depending on the base fluid and the nanoparticle itself. The most common method is to disperse the nanoparticle powder in water through the use of an ultrasonic bath. Harikrishnan et al. [3] studied CuO nanoparticles in an 80:20 water-glycerin base fluid at different concentrations as seen in Figure 2.

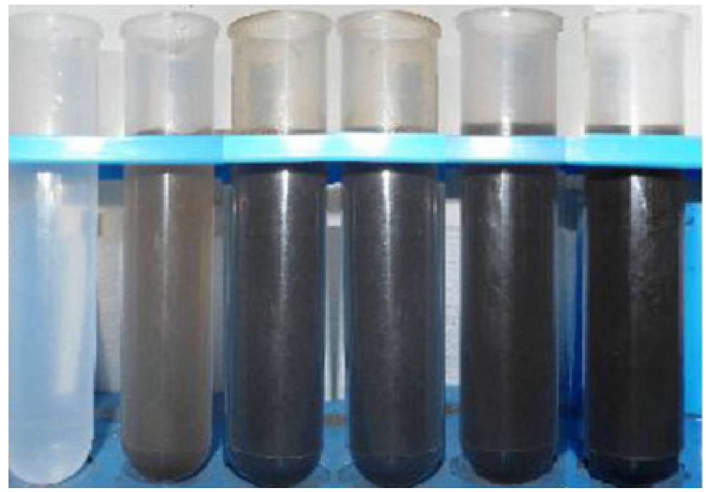

Figure 2. CuO Nanoparticles in an 80:20 Water-Glycerin Base Fluid at Concentrations of 0.1, 0.3, 0.5, 0.8 and 1% by Weight [3]

Heat Pipe Performance

Sureshkumar et al. [4] conducted an extensive review of the considerable research on nanofluids and heat pipes over the past two decades. As an aggregate, the results showed a positive change in the performance of heat pipes by decreasing the thermal resistance and sometimes through maximum allowable heat load.

Shafahi et al. [5] used experimental and theoretical analysis and found CuO to be the most effective nanofluid for use within heat pipes. As Figure 3 shows, the maximum heat transfer from a heat pipe increases 15-20% with a CuO concentration of 0.15. The nanofluid made from Alumina (Al2O3) and Titanium Oxide (TiO2) have little overall effect on the maximum heat transfer rate. However, all three nanofluids reduced the overall thermal resistance of the heat pipe. Figure 4 shows the relative decrease in thermal resistance for the three nanofluids at a 4% concentration.

In addition to the common nanofluids listed above, other researchers have explored more exotic nanofluids. Tsai et al. [6] used gold nanoparticles and found that the thermal resistance of the heat pipe dropped from 0.215 to 0.17°C/W with a specific cocktail of $HAuCl_4$, Na_3 Citrate and Tannic Acid. This is almost the same fluid as Alumina as used in [5] but with added complexity and more expensive gold. Kang et al. [7] found success with 35 nano-meter silver particles at a concentration level of 10 parts-permillion in pure water. The thermal resistance reduced from a range of 0.004-0.005°C/W to 0.001-0.002°C/W for different power loads.

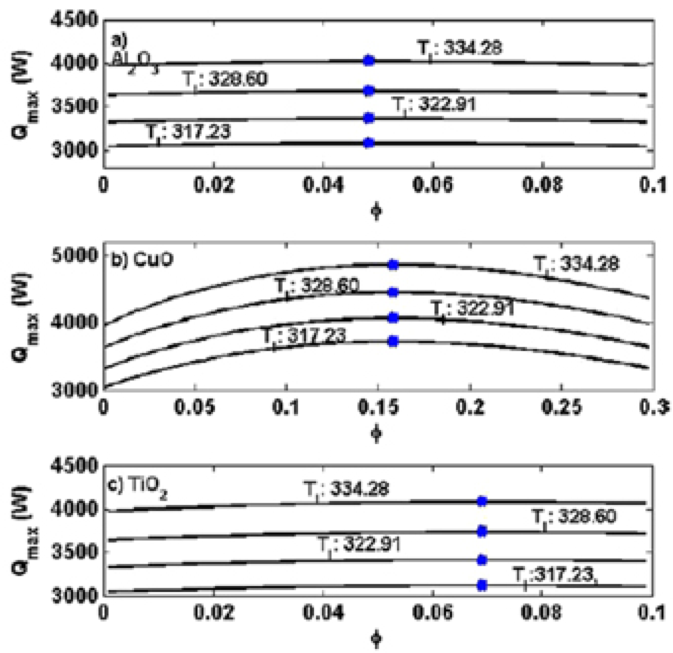

Figure 3. Maximum Heat Transfer Limit of Heat Pipes with Various Nanofluids [5]

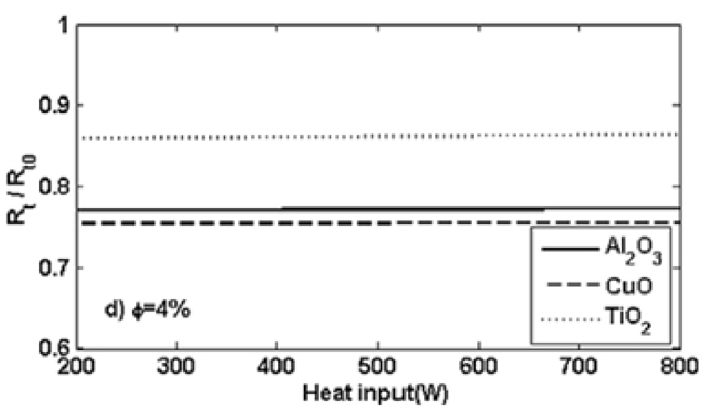

Figure 4. Thermal Resistance of Various Nanofluids Shown as a Ratio of the Thermal Resistance with Pure Water [5]

Explanation For The Effect Of Nanofluids

Most of the researchers in this field have concluded that the largest effect of nanofluid on the performance of heat pipe is due to an increase in thermal conductivity over the base fluid [4]. As an example, Figure 5 shows an increase in thermal conductivity by using Copper Oxide (CuO) nanoparticles in an 80:20 water-glycerin base fluid, measured by using differential scanning calorimetry [3]. Curiously, although attempts have been made in understanding the mechanism for the increase in thermal conductivity, there is no clear explanation. Wang et. al summarized the plethora of research work that has gone into understanding the heat transfer characteristics of the nanofluids [7].

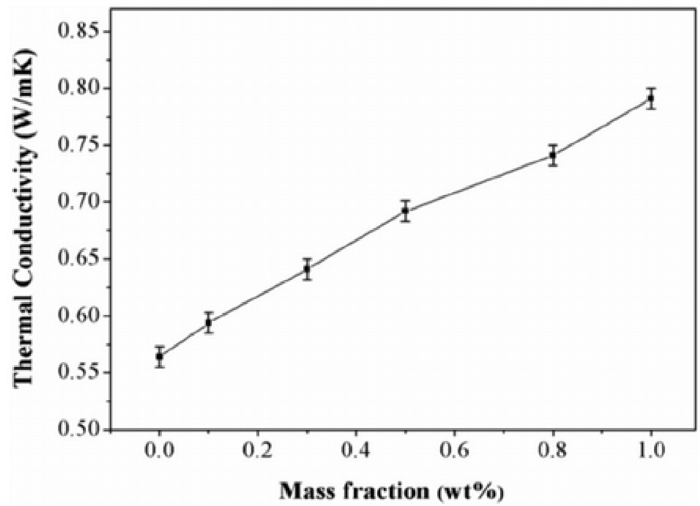

Figure 5. Thermal Conductivity vs Concentration of CuO Nanoparticles in an 80:20 Water-Glycerin Base Fluid [3]

In addition to an increase in thermal conductivity, nanofluids also change the density and viscosity of the fluid. The increase in density allows for a more efficient mass transfer per volume but the increased viscosity leads to a higher pressure drop [5]. The reason for the optimal performance at the middle of the concentration range in Figure 3 can be partially explained due to an increase in pressure loss that is much higher than the increase in mass transfer per volume. In other words, after a certain increase in nanoparticle concentration, the resulting fluid becomes so viscous that it negates any other gains. In practice, higher concentration of nanoparticles also leads to sedimentation and blocking of the wicking material.

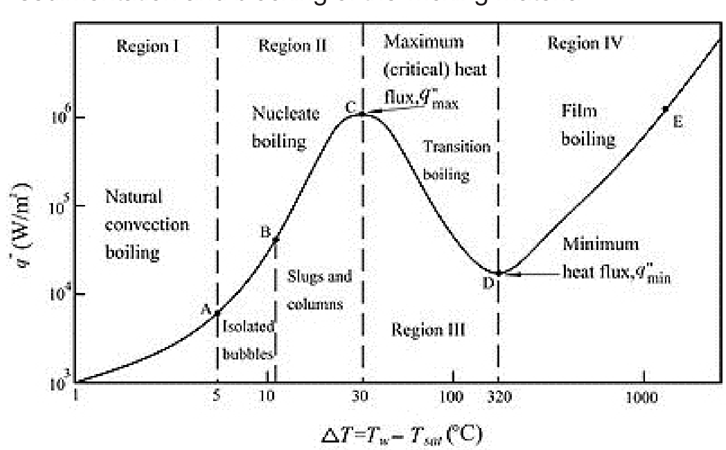

Figure 6. The Pool Boiling Curve. Heat Pipe Evaporators Should Stay in Regions I and II [7]

The increase in maximum allowable heat and the thermal conductance can also be attributed to the shift in the boiling curve. Figure 6 shows the pool boiling curve and its associated regimes [7]. Beyond the critical heat flux (CHF), the heat pipe evaporator requires a higher wall temperature for the same amount of heat flux. Additionally, the larger nucleation bubbles close to and beyond the CHF can also block the liquid flow in the wicking and disrupt the capillary pumping. The general consensus in the operation of heat pipes and thermosyphons (a wickless heat pipe) is to remain to the left, regions I and II in Figure 6, of the CHF [8].

The addition of nanofluids increases the CHF [4]. This phenomenon raises the overall boiling limit of the heat pipe. As an example, Yang and Liu [10] found a 14% increase in allowable maximum heat flux for a looped thermosyphon by using a 1.5% concentration of Al_2O_3 by weight. The researchers attributed that performance increase to an increase in CHF.

Conclusions

The addition of nanoparticles to a base working fluid can increase the thermal performance of a heat pipe. The performance increase comes as a decrease in thermal resistance and an increase in total allowable heat load.

The two most common nanofluids with water are Alumina (Al_2O_3) and Copper Oxide (CuO); although positive effects have also been seen with Titanium Oxide (TiO), Gold and Silver. While many of these nano-particles come in commercially available powder form, manufacturers should evaluate the increased complexity of creating such a heat pipe vs the benefits outlined in this article.

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