Innovative Solutions to Meet Thermal Performance of High-Power Laser Systems

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Introduction

Although there have been significant strides made in the last few years to increase the efficiency of laser systems, thermal management remains a critical design area. There is more demand than ever on designers to provide more capable systems, which, despite improved efficiency, leads to higher power densities and increases the overall waste heat of these systems. Across various industries that rely on laser technology, such as medical, defense and industrial manufacturing, there is a shared need for compact thermal management systems. This combination of high power and compact packaging creates the need for highly efficient heat transport and dissipation techniques. Two-Phase (liquid to vapor) technology enables many designers to achieve higher heat flux, higher total power and volume & weight efficient designs. The two primary liquid to vapor two-phase technologies being applied to the Photonics industry are passive heat pipe technology and active pumped two-phase (P2P) technology.

Heat Pipes

Heat pipe technology is a closed loop system that takes advantage of the latent heat of vaporization of the fluid to provide extremely high heat transfer coefficients and extremely low thermal resistance across the length of the pipe. It's beneficial in many designs because of its high reliability and passive operation. In high heat flux systems, such as laser diodes, heat pipes are used to accomplish one of two purposes: (1) point to point heat transfer; moving heat from the source to a remote heat sink or (2) spreading heat along a surface to reduce conduction gradients. The operation is such that the fluid boils at the heat source, moves via an internal pressure gradient to colder areas along the length and gives up its latent heat to condense back to liquid. The liquid is then transported back to the heat source via an internal wick structure that is integrated along the ID (inner diameter) of the pipe. A side and axial cross section of a heat pipe is shown in Figure 1.

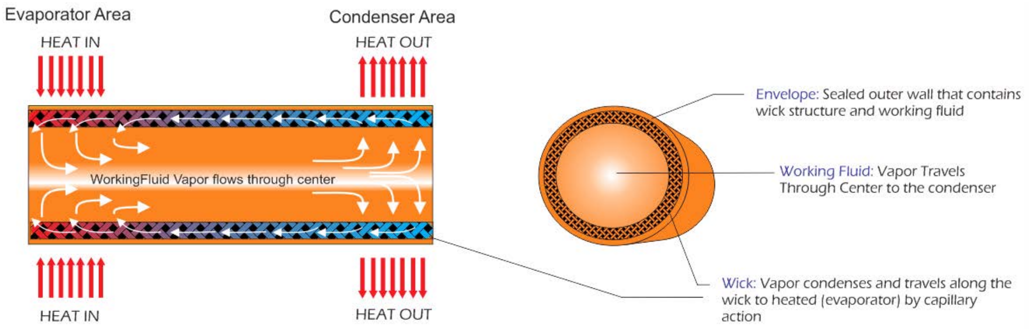

Figure 1. Heat Pipe Components and Operation Principles

To accomplish the boiling and condensing phenomenon, while maintaining a low thermal resistance, the fluid must be processed under a vacuum. This allows the fluid to be two-phase across a wide temperature range. In a well evacuated and sealed heat pipe, the operating pressure will follow the saturation curve of the fluid. The envelope and wick material are determined by fluid compatibility and pressure containment requirements. The saturation curve for water is shown in Figure 2. Using a copper envelope, which is fully compatible with water, operation can exceed 180 C, well above the failure point of most diodes and electronics.

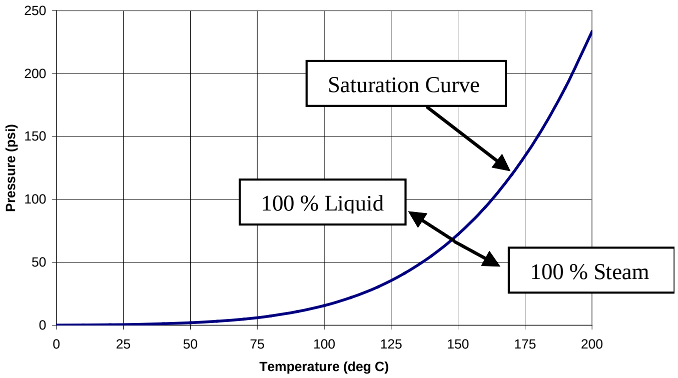

Figure 2. Saturation Curve of Water

Overall, a well manufactured copper-water heat pipe operating within its limitations will have a temperature gradient of less than 5 C across its length. This temperature gradient is caused by thermal resistance stack up within the heat pipe, the largest delta T is caused by the heat entering and exiting the envelope (conduction through the wall and wick). The evaporation, condensation and vapor space temperature drops are all relatively low meaning that the length of the heat pipe does not affect the temperature gradient to a large degree. Therefore, the aforementioned < 5 C delta T is valid for water heat pipes of various lengths, assuming no heat pipe limit has been exceeded. The major limits for consideration in most copper-water heat pipes for laser diode cooling are: (1) capillary limit, (2) entrainment limit, (3) boiling limit, as described below:

Capillary Limit: In systems operating in adverse orientation (condenser below the evaporator, see Figure 1.), the capillary limit is the most common limiting factor. It determines the amount of power a heat pipe can transport, which is limited by the amount of liquid that can be returned to the evaporator. The wick structure, through its porosity and permeability, creates a capillary pressure drop that must overcome or balance the other pressure drops in the system (liquid (l), vapor (v) and gravitational (g)). Equation 1 shows the capillary limit equation, where r1 and r2 are the radius of curvature depending on the pore size of the wick structure.

$$\Delta P_c \geq \Delta P_g + \Delta P_l + \Delta P_v$$

$$P_c = \sigma \cdot \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

Equation 1. Capillary Limit

Entrainment Limit: occurs when the vapor velocity in the heat pipe is high enough to shear liquid from the wick. Essentially, this limit reduces the liquid flow returning to the evaporator. It is most common at low temperatures (when fluid density and vapor velocities are high). Equation 2 describes the entrainment limit.

$$q_{Entrain} = A_{Vapor} \cdot \left[\lambda_{fg} \cdot \left(\frac{\sigma \cdot \rho_V}{2 \cdot r_c} \right)^{\frac{1}{2}} \right]$$

Equation 2. Entrainment Limit

Where:

$q_{Entrain}$	Entrainment limit, W
A_{Vapor}	Heat pipe vapor space area, measured perpendicular to the flow, m^2
λ_{fg}	Latent heat, liquid to vapor, J/kg
σ	Surface tension, N/m
ρ_V	Vapor density, kg/m^3
r_c	Wick pore radius, m

Boiling Limit: In normal operation, the wick remains saturated with liquid; heat is conducted through the wick and vaporizes at the wick ID. At high heat flux, temperature drop across the wick increases to the point that vapor bubble nucleate occurs, disrupting liquid flow. As a general guideline, in order to avoid the boiling limit for copper-water pipes using screen or sintered powder, operate with heat flux < 75 W/cm^2.

Each of the above limits is dynamic with the operating temperature of the heat pipe. The Figure below shows the performance of a screen wicked heat pipe. The left Figure shows each limitation in a different color and the right Figure shows the heat pipe performance by selecting the lowest operational point at a given temperature. Note: Sonic limit occurs when the exit velocity of the vapor is too high. This is only a concern at very low temperatures.

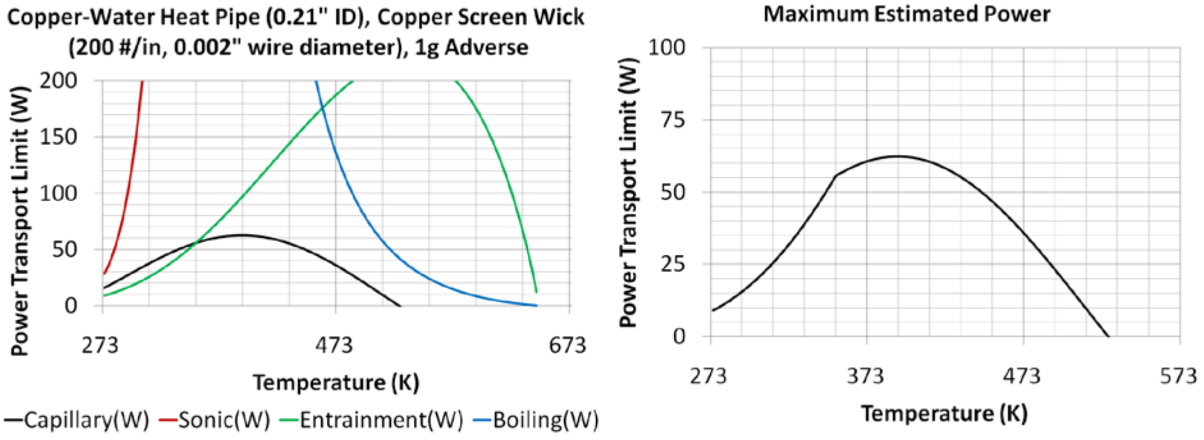

Figure 3. (Left) Limit Curves (Right) Maximum Operating Power of the Same Design

Determining the power capacity of a heat pipe is one major hurdle in heat pipe design. The next area to understand is the practical integration of heat pipes within your system. The design flexibility of copper-water heat pipes is a major benefit to the engineer; the thin-walled design allows heat pipes to be bent and flattened into countless configurations. Practical considerations include maintaining a centerline bend radius greater than 3xOD (outer diameter) for each bend, and flattening no more than 2/3 the OD of the pipe. [Note: Flattening of a heat pipe will affect the vapor space geometry and transport power calculations.]

The final practical consideration for heat pipe integration is the attachment method. Using a copper-water design allows for several options, most common are epoxy or solder. Epoxy has a lower thermal conductivity and is a weaker bond, however it can be applied to most materials. While solder has thermal and mechanical advantages, it does require a plating operation when attaching to non-wetting materials such as aluminum. In most ruggedized or harsh environment applications, customers prefer fully embedded heat pipes, as shown in the right image of Figure 4. These high thermal conductivity plates or HiK™ plates, provide the same structural integrity and weight as an aluminum heat sink, with the effective thermal conductivities ranging from 500 to 1,200 W/m-K depending on geometry (reference: Al6061: k~167W/m-K)

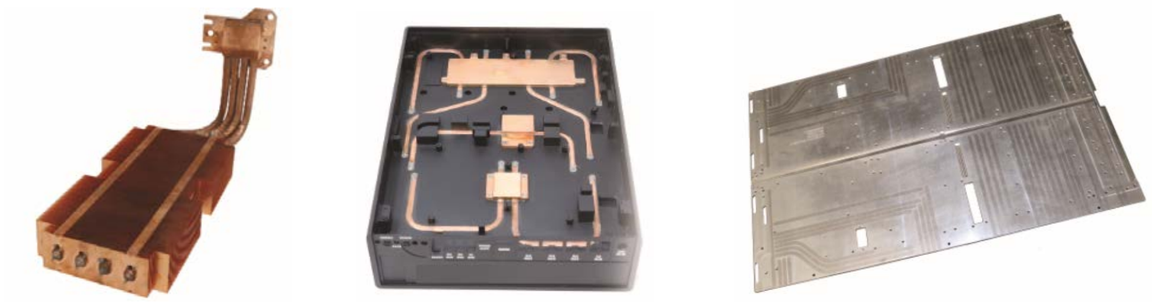

Figure 4. Heat Pipe (Left), Partially Embedded Assembly (Middle) and Fully Embedded Design (Right)

The final component to understand is how to model the system level thermal performance when integrating heat pipes into your design. In most photonics applications, the system complexities demand computational software to achieve an accurate model. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are often leveraged to predict system level thermal performance, and to verify safe operating temperatures can be maintained at the diodes. When analyzing a heat pipe using computational software, it’s imperative to simplify the physics; running models with two-phase flow or internal film coefficients is often too time consuming. One way to accomplish this is to model the heat pipe as a solid conduction element with an effective conductivity that simulates the overall temperature gradient of 3-5 C. For a six (6) inch heat pipe, that k value is approximately 10,000 W/m-K. Longer heat pipes will have a higher k value. This estimation can save significant computational time and still provide reasonably accurate results.

Overall, if heat pipes can transport the power (operating power is below any heat pipe limit), and meet system level thermal considerations (maintain diode temperatures below max operating temperature) they are an ideal solution to improve performance and make more effective use of available volume. The passive operation of heat pipes ensures a highly reliable and energy efficient design. Understanding the limitations, integration and modeling techniques as described above can allow designers to quickly develop a solution using heat pipe technology. Heat pipes can ultimately expand the limitations of conduction or air-cooled systems.

Pumped Two Phase (P2P)

Similar to how heat pipes can expand conduction limitations, Pumped Two-Phase (P2P) is a technique that can expand the heat flux and total power capabilities of liquid cooled solutions. In many applications, laser diode stacks utilize multiple high-power boards, with high heat flux cooling requirements. For example, some vertical-cavity surface emitting lasers (VCSELs) can output heat flux greater than 500 W/cm^2. P2P can handle such high heat flux due to the latent heat of vaporization, while single phase will have large temperature spikes due to the increased pressure drop it experiences, and the thermal resistance getting heat into the fluid flow. Another requirement that limits the suitability of single-phase liquid cooling for laser-based applications is the need for temperature uniformity across arrays of laser diodes. In a single-phase system, the heat input will raise the temperature of the fluid across the system, while in a P2P system, the latent heat of vaporization can be leveraged to provide uniformity; the quality (mass fraction of the fluid that is vapor) is increased while temperature of the cold plate remains relatively stable.

Finally, from a system level perspective, P2P will offer packaging advantages over single-phase pumped liquid cooling. A single-phase system relies on flow rate to increase the heat transfer coefficient, which drives pump size. Comparatively, P2P relies on boiling heat transfer and therefore can operate efficiently with much smaller pumps. Similarly, many single-phase laser diode coolers are utilizing extremely small channels (microchannels), which leads to high pressure drop and shorter pump lifetimes. P2P systems, due to the boiling heat transfer, can be designed with larger channels to avoid high localized pressure. A depiction of a basic P2P system is shown in Figure 5. A P2P cooling loop is comprised of (at minimum) a cold plate/ evaporator which contacts the heat generating components, a condenser to dissipate heat and condense the two-phase fluid back to liquid, an accumulator for fluid storage and inventory, and the pump.

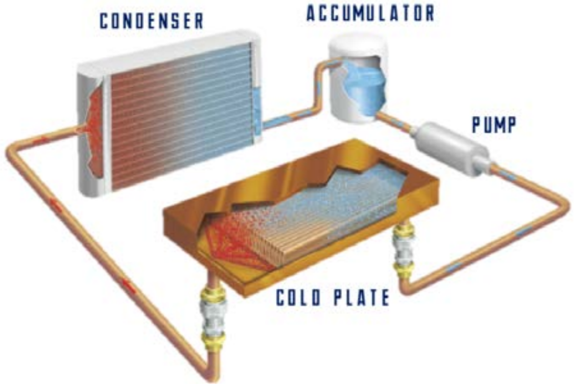

Figure 5. P2P System Components

When designing a P2P system, the fluid choice is fairly straightforward. While two-phase mechanisms are well-suited for high heat flux cooling, they are susceptible to flow and thermal instabilities. Stability is usually lower for working fluids with smaller ratios of liquid to vapor density. Figure 6 shows a plot of liquid to vapor density ratio vs boiling coefficient[1]. In most fielded systems, dielectric fluids such as R134a are chosen due to their operating temperature and reliability.

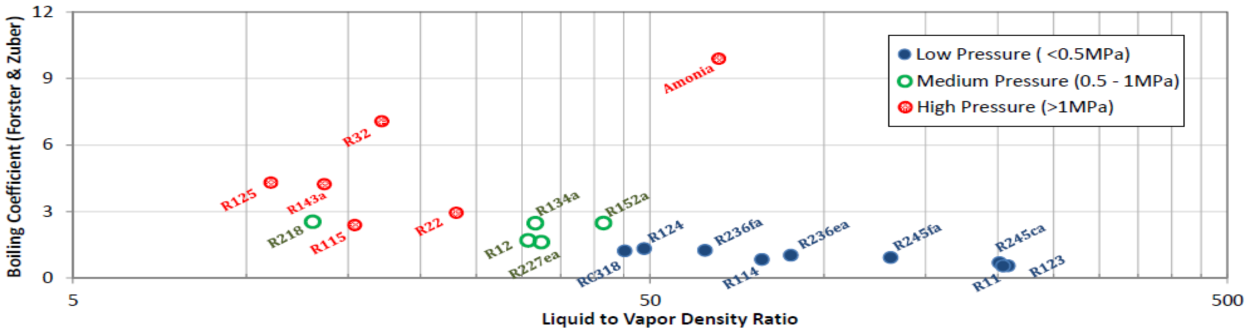

Figure 6. Plot comparing different fluids in terms of Saturation Pressure, Liquid to Vapor Density Ratio and Pool Boiling Coefficient (Fixed saturation temperature of 30 C and wall superheat = 15 C.

Another important design consideration is the Critical Heat Flux (CHF). With flow boiling, vapor quality plays an important role to characterize the flow inside channels. Saturated flow boiling in channels is governed by two mechanisms: nucleate boiling and forced convection boiling. Flow regimes and the heat transfer coefficient along a uniformly heated channel for these conditions is shown in Figure 7. An increase in the vapor quality corresponds to the formation of more bubbles inside a channel and in turn increases the risk of covering the heated surface by a blanket of vapor, leading to the point of CHF. CHF will lead to a sharp decrease in the heat transfer coefficient and a corresponding increase in device temperature. To avoid this, the general recommendation is to maintain a vapor quality at the outlet of the channel around 0.3.

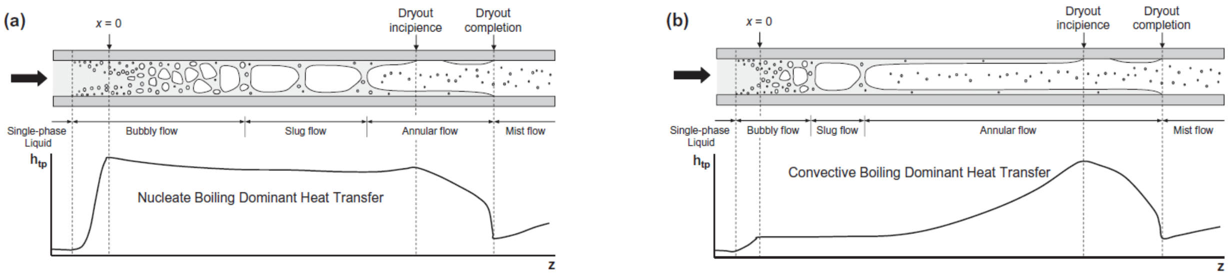

Figure 7. Flow Regimes and Heat Transfer for Nucleate Boiling Dominant (a) and Convective Boiling Dominant (b) Flow.

In order to determine heat transfer coefficient (HTC) and ΔP, correlations are used. Due to complexities of physics in two-phase systems, there is no universal correlation to predict these values.

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[1] Forster & Zuber

Understanding your heat flux, mass flow rate, channel dimensions, etc. are imperative to selecting the most accurate correlation. Some famous correlations for predicting these values are listed below:

Heat Transfer Coefficient

- Chen's correlations (*I&EC Process Design and Development 5 (1966) 322-329*)
- Shah's correlations (*ASHRAE Trans. 82 (1976) 66-86*)
- Kandlikar's correlations (*J. Heat Transfer 112 (1990) 219-228*)
- Lee and Mudawar's correlations (Int. J. Heat Mass Transfer 48 (2005) 941-955)

Pressure Drop

- Lockhart and Martinelli, *(Chem. Eng. Prog. 45 (1949) 39-48)*
- Lee and Mudawar, (Int. J. Heat Mass Transfer 48 (2005) 928-940)
- Zhang. et al., (Int. J. Heat Mass Transfer 53 (2010) 453-465)
- Li and Wu, (Int. J. Heat Mass Transfer 53 (2010) 2732-2739)

In practice, P2P fluid loops have been used for numerous laser diode cooling applications to achieve high heat flux and temperature uniformity requirements. In many practical applications it is required or desirable to have the evaporators configured in parallel. This often raises the question of transient response and temperature stability during component on/off periods. In the example shown in Figure 8, an experiment was designed using parallel flow channels to demonstrate thermal response to high heat flux sources being intermittently turned on/off. The resultant temperature and flow rate response is shown below the test setup. At t=0s, power was applied to all evaporators. At t~200s, power to the yellow and blue evaporator was turned off. At t~400s, power to the blue evaporator was restored and at t~550, power to the yellow evaporator was restored. The test demonstrated very low temperature fluctuations across the other two continuously powered evaporators (red and orange), and once power was restored the effected evaporator balanced to original performance without overshooting temperature limits or causing system level instabilities.

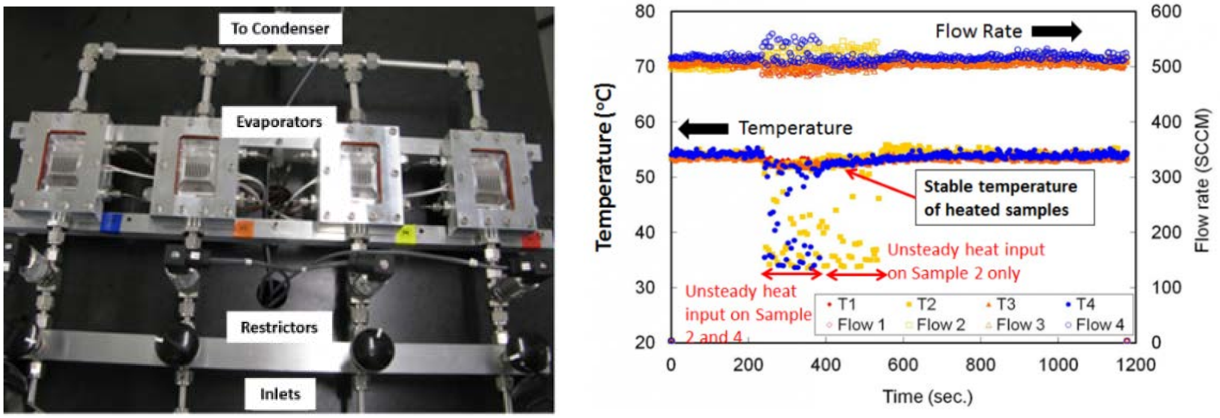

Figure 8. Parallel Evaporator Test Set (Left) and Results (Right)[2]

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[2] https://www.1-act.com/resources/pumped-two-phase-cooling/

In summary, two-phase solutions provide system level thermal benefits by taking advantage of a fluids latent heat of vaporization to efficiently absorb and transport waste heat to the system's ultimate heat sink. In a low to medium power cooling application, the high effective conductivity (k_{eff}) achieved by the heat pipe can efficiently spread heat from the source components, taking full advantage of all heat dissipation surfaces. This can allow for higher power, reduce operating temperature or shrink the heat sink footprint in your system. For high power systems, P2P can expand the limits of single-phase cooling by introducing boiling effects instead of relying on fluid velocity to improve heat transfer. This provides higher heat flux and more uniform temperature profiles along a fluid cold plate, providing thermal and packaging advantages for designers.

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