

# Cooling Techniques for High-Power Electronics – Laser Application

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## **Abstract**

With significant increases in power dissipation and power density expected in electronic parts to meet future space mission applications, advances in thermal control hardware and techniques will be needed to maintain the mission temperature and reliability. One such application is cooling the electronics associated with space-based lasers. Laser cooling requirements can be satisfied with single- or two-phase heat transport to space-facing radiators with the possible inclusion of phase change materials. Future laser cooling requirements will need more advanced hardware, such as microchannels, spray cooling, and jet impingement. This report describes the thermal control hardware associated with current and future laser cooling needs and provides recommendations for meeting future laser cooling objectives.

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# 1. Introduction

Rapid increases in the power dissipation needs of modern electronics have driven ever-increasing sophistication in the techniques for cooling piece parts in electronic units. Furthermore, as power levels increase and part sizes decrease, power densities ( $\text{W}/\text{cm}^2$ ) of these electronics have increased sharply. In modern applications, the heat flux generated by an electronic chip can be up to  $100 \text{ W}/\text{cm}^2$ . Future near-term applications will see next-generation power densities exceeding  $1,000 \text{ W}/\text{cm}^2$ , with localized hot spots within the chip being even higher. [1] The critical performance challenge of many electronics is dissipating the power they generate in an efficient manner. If not fully dissipated, these high-power densities can cause excessively hot part temperatures and high thermal gradients, thereby reducing part reliability, decreasing useful life, or causing failure.

While this applies to many types of high-power electronic units, one unit with a need for high-power cooling requirements is the space-based laser. In high-power lasers, substantial heat is generated in laser chips and the laser gain medium due to incomplete conversion of pump power into optical output power. For diode-pumped lasers, laser diodes are the source of heating.

Laser technology has progressed in the past decades with more optical power in smaller packaging. This has created challenges for laser design engineers. Optical wavelength and power are sensitive to temperature variations, so careful temperature control is often necessary for lasers used in industry. [2] In terrestrial applications, air cooling to remove waste heat is usually adequate for low-powered lasers ( $50 \text{ W}$  and below), and continuous flow of ambient-cooled water to a cold plate will usually suffice for medium-powered lasers ( $50\text{--}100 \text{ W}$ ). For higher-powered lasers ( $100 \text{ W}$  and greater), a recirculating chiller using active refrigeration is the common choice, providing consistent temperature, flow rate, and quality. These types of chillers have cooling capacities from  $600 \text{ W}$  to several kilowatts. [2]

Figure 1 shows typical regimes for different heat transfer mechanisms seen in modern electronic part cooling applications. Cooling requirements for relatively low power dissipation levels use forced and natural convection in air and liquid in terrestrial applications, whereas in space, cooling requires conduction of heat in high-thermal-conductivity materials. For higher power requirements, active two-phase thermal control techniques include pool boiling, microchannels, jet impingement, and spray cooling.

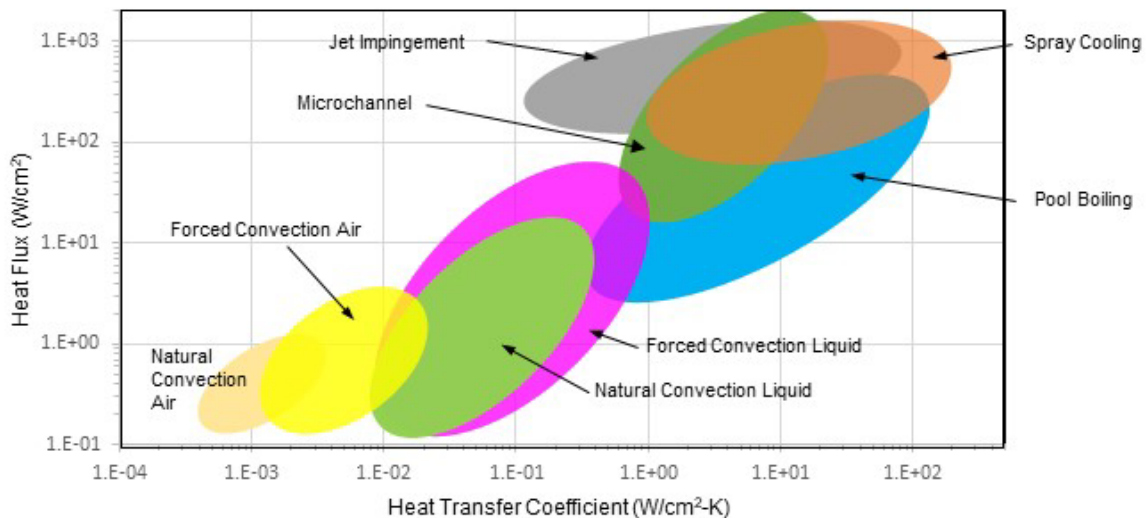


Figure 1. Comparison of heat transfer methods. [3]

## **1.1 Military and Space Laser Applications**

The U.S. Navy deployed the first high-energy laser weapon, known as the Laser Weapon System (LaWS), on the USS Ponce in 2014, with a reported 30 kW output. It was a solid-state laser tested against swarming boats and swarming unmanned aerial vehicles. Most military lasers tend to be in the 30–100 kW range and used for shooting down small drones. At the time of this writing, the U.S. Army was planning to demonstrate a 300 kW laser. General Atomics and Boeing are building the device, which is the size of a shipping container and mounted on a heavy truck.

In space applications, without convection cooling, laser cooling must rely on high-conductivity materials to conductively transport heat from its source to liquid transport or phase change systems that ultimately will dissipate this energy onto a vehicle radiator surface for rejection to the cold space temperature sink. The conduction transport lengths (between the power source and the liquid, and between the liquid and the radiator) are kept as short as possible. The liquid transport may include pumped fluid loops, heat pipes, microchannel loops, and phase change materials (PCMs), and the appropriate choice will depend upon the power level, operational profile, and geometry.

## **1.2 Objective**

Thermal control techniques for removing heat from laser power sources are discussed, although the discussion is applicable to any high-power electronic piece part. In Section 2, current thermal control techniques for cooling space-based lasers are described. Section 3 discusses the next evolution of cooling techniques for projected 2030 (and beyond) laser applications.

## 2. Thermal Control for Modern Space-based Laser Applications

Cooling techniques for modern space laser applications are based on moving the heat from its source to single- or two-phase liquid systems. This involves conduction cooling from the part to a heat pipe or liquid cooling loop. The liquid or vapor will transport the heat to a space-facing radiator or to a PCM unit, where its heat will be dissipated to the radiator over a longer period. Inclusion of a PCM unit will depend upon the pulse of the laser heating and whether the thermal design can transfer the heat to the radiator before the laser exceeds operational or performance temperature limits.

The basic heat flow mechanisms are shown in Figure 2 for relatively low power requirements using conventional heat pipes (top figure) and for loop heat pipes or a pumped fluid loop (bottom figure). In both cases, heat from the source must be conducted efficiently into the pipes for transport. This is accomplished with a high-conductivity metal, such as aluminum or copper, and minimizing the thermal resistances at the interfaces by using conductive filler materials. A PCM is shown with integrated pipes if needed. Ultimately, the heat will be radiated to space. If a pumped fluid loop is utilized, a pump (not shown) is added along the return line.

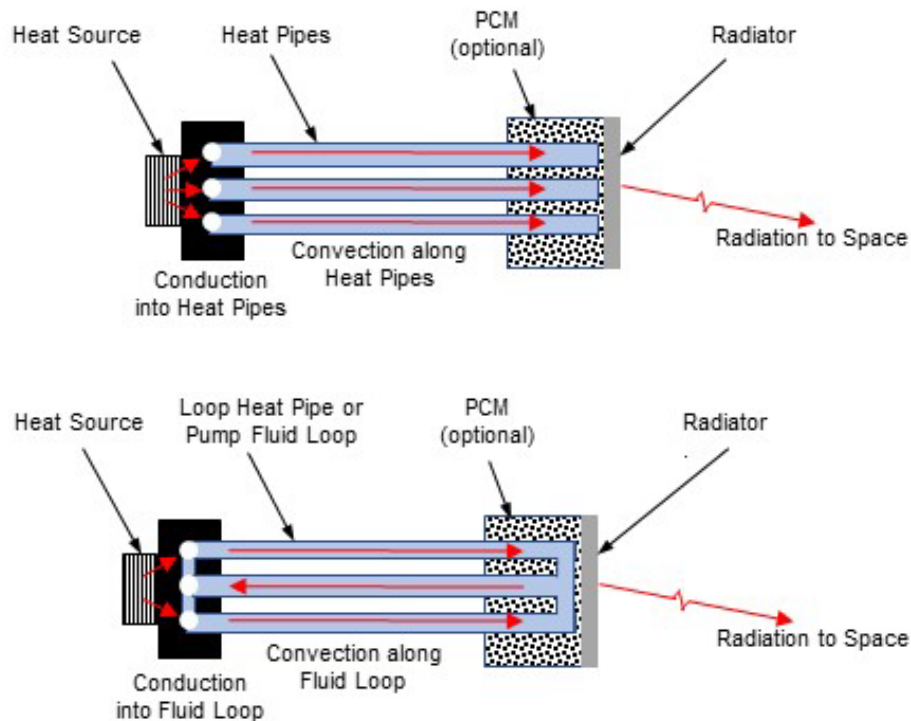


Figure 2. Heat flow mechanism using conventional heat pipes (top) or fluid loops (bottom).

### 2.1 Phase Change Material

In Figure 2, use of PCM is shown as optional. Phase change materials are added to a thermal control subsystem when other passive means of removing heat from a source prove inadequate. A PCM may be a viable design option in the following cases:

- When solid heat sinks or thermal doublers of high-thermal-conductivity materials or high specific heat cannot fully absorb and transfer a unit's power dissipation before thermal limits are

exceeded. An efficiently packaged PCM may show a mass advantage over a solid heat sink, but the cost and complexity of the PCM may make it unattractive.

- When radiators cannot be enlarged to handle the unit's power dissipation before thermal limits are exceeded. A PCM may result in a radiator size reduction, but this will come at the expense of the additional mass and complexity of the PCM.

The most common space applications for PCMs are for extremely high-power heat sources with pulsed operation. When the source is operational, the PCM absorbs large quantities of energy via the PCM's high latent heat of fusion while undergoing a phase change (typically solid to liquid) at essentially a constant temperature. As shown in Figure 3, the energy profile is essentially dampened, resulting in lower peak unit temperatures.

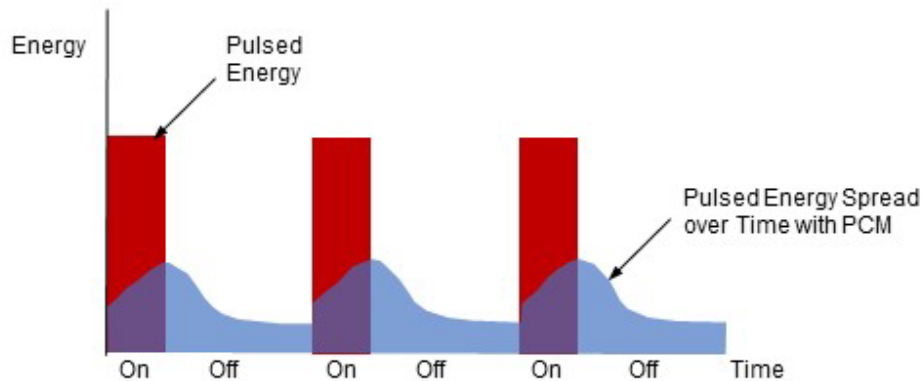


Figure 3. Notional system energy profile with and without PCM.

During operation, the heat source increases in temperature as governed by its sensible heat (specific heat) until the melting temperature of the PCM is reached. At that point, the PCM begins to melt and the system temperature no longer increases, but remains steady at the PCM melting temperature. If operation continues after the PCM is completely melted, system temperatures will begin to increase again and do so until the heat source is turned off.

In space applications, the mass (size) of the PCM should be estimated such that it is not fully melted (margin) when unit operation ceases, and to ensure that peak hot temperatures are below allowable thermal limits. Spreading the heat within the PCM is important for uniform melting and refreezing, so the PCM enclosure is typically embedded with stacks of fins or heat pipes. Paraffins are the most common PCM with advantages of having a high heat of fusion (ability to absorb large amounts of energy), being very stable in different environments, and being relatively inexpensive. For other space applications, hydrated salts or metallics can be used.

As the PCM resolidifies, it gives up the heat it absorbed. The optimal location of a PCM on a space vehicle would have at least one of its surfaces as a dedicated radiator with a clear view to space. A sufficiently sized and located radiator ensures that the temperature of the heat source will be brought back to its initial value prior to the next operational cycle. Knowledge of the operational period (maximum on time and minimum off time) is important in sizing the PCM to ensure the unit does not reach hotter temperatures with each operational cycle.

The most important parameter when selecting a PCM is the operating temperature range of the unit being protected. A PCM's melting temperature must be well within this range to ensure that unintentional

undercooling or overheating will not damage the unit. Design characteristics of a PCM are summarized in Table 1, and a listing of the melting temperature and heat of fusion for common PCMs are given in the appendix. Additional guidance in the design and integration of PCMs can be found in Reference [4].

Table 1. Design Characteristics of the PCM [4]

<b>Property or Characteristic</b>	<b>Desirable Value or Tendency</b>
Melting temperature	Consistent with unit's operating range with margin
Heat of fusion	High
Thermal conductivity	High
Specific heat	High
Density	High
Volume change during melting	Low
Vapor pressure	Low
Melting and freezing behavior	Dependable and reversible
Availability	Readily available
Cost	Low
Compatibility	Compatible with container and filler materials
Toxicity	Nontoxic
Hazardous behavior	Not exhibited
Property data	Readily available, well documented, and nonproprietary
Surface tension	Low

## 2.2 Assessment of Modern Thermal Control Applications

Thermal control requirements of modern laser applications are adequately satisfied with simple passive hardware, as discussed in this section. The thermal design will use a highly conductive material to move heat from its source to a two-phase heat transport unit, such as heat pipes, where it will then move this energy at a nearly constant temperature to a space-facing radiator. The inclusion of a PCM will depend upon the laser power, duration of operation, and how quickly it will be needed for its next service. The design of a thermal control subsystem for modern laser applications is well within the skills of thermal engineers in industry.

### 3. Thermal Control for Future Space-based Laser Applications

Recent improvements in space-based laser applications have resulted in significantly more power and smaller overall size. This makes the thermal control of these future payloads challenging to achieve heat transport requirements, minimize thermal gradients, and avoid localized hot spots. Figure 1 provides options for future thermal control subsystems with capabilities greater than natural and free convection. Spray cooling, jet impingement, and microchannels provide the best options for meeting thermal requirements of lasers developed in the next decade. While pool boiling has its upper reaches into these technologies, it has disadvantages in space applications (namely gravity) that makes the other three options more appealing. The following sections will discuss these three thermal control techniques.

#### 3.1 Spray Cooling

In spray cooling systems, a spray or stream of liquid droplets impinges on a heated surface, efficiently cooling the surface through phase change of the liquid. The evaporated liquid moves away from the heated surface toward dedicated cooled radiator surfaces resulting in the condensing of the gas back into a liquid. The condensed liquid is transported back to the spray nozzle by various means such as a passive capillary grooves or active pump systems. The system is pressurized to take advantage of convective cooling from the heated surface. The effectiveness of the cooling depends on many features of the systems with the most important being the spray momentum (bubble size and speed), working fluid (commonly ammonia or water), and the heated surface finish. These factors have been investigated. [4]

As shown in Figure 4, at the heated surface, the spray can develop into a uniform thin liquid film that evaporates efficiently at the heated surface due to low thermal resistance through the liquid. Furthermore, bubbles that form on the heated surface can enhance heat transfer from nucleate boiling heat transfer. The two mechanisms combine to form a very effective means of removing the electronics power dissipated at the heated surface.

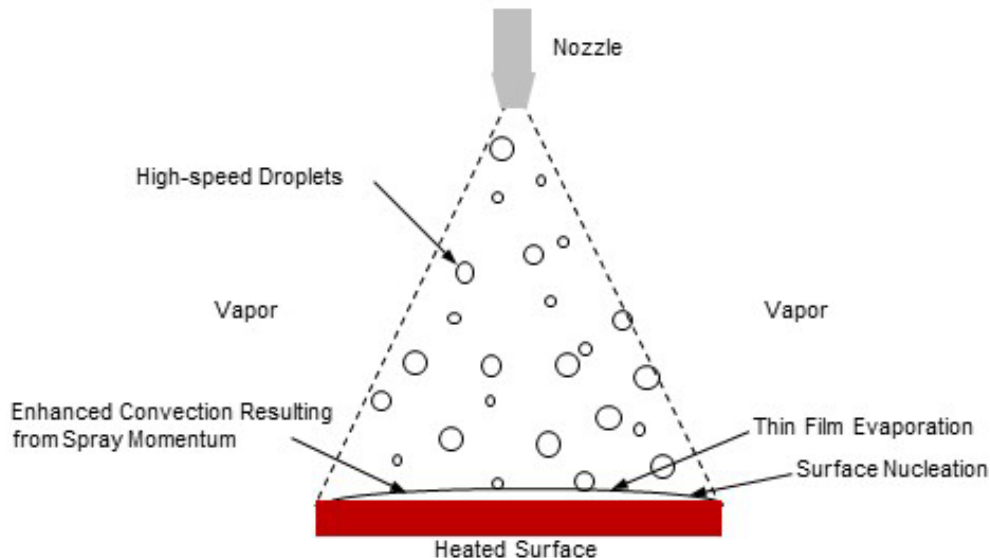


Figure 4. Heat transfer mechanisms associated with spray cooling.

While there are attractive heat transfer abilities of spray cooling, there are technological and reliability challenges to successful implementation. The nozzle orifice size is small creating concerns with clogging and significant pumping power is needed to overcome the large pressure drop produced in the system.

The nozzle also has design and fabrication inconsistencies. Nozzle manufacturing variations make predicting and correlating spray characterization and performance difficult. [5] Even with these challenges, there has been successful demonstration of the technology in microgravity applications. [6]

### 3.1.1 Flash Cooling

Flash cooling, or flash evaporation cooling, is an advanced spray cooling technique in evaporation mode in which the environmental pressure is lower than the saturation pressure of the liquid working fluid. At the surface of the liquid and the droplets, evaporation occurs quickly, absorbing large amounts of heat. Cooling occurs primarily with the flash evaporation of the liquid film covering the heated surface and, to a lesser degree, with the flash evaporation of the droplets before reaching the heated surface. Compared to spray cooling, flash cooling occurs more rapidly (10–100 ms) and with higher heat removal by both convection and flash evaporation. [7] Experiments have shown cooling of about 100 W/cm<sup>2</sup> while maintaining a stable system temperature of ±5°C. [7]

While flash evaporation cooling has seen industrial applications in food dehydration and laser surgery [8], it is especially applicable in space vehicles because the external environment is at vacuum conditions. While open systems (using space vacuum as the environment) have been proposed for some space systems, most space vehicle applications, including laser cooling, will need to be closed low-pressure systems. Compared to other cooling techniques, flash cooling has many of the same benefits and challenges associated with spray cooling.

### 3.2 Jet Impingement Cooling

Jet impingement cooling is similar to spray cooling in that it forces a fluid stream (liquid or gas) onto a heated surface with the same basic heat transfer mechanisms at work. Jet impingement differs from spray cooling in that the stream and its associated heat transfer are more focused on a small area on the heated surface, typically from a single orifice nozzle. This cooling option is particularly applicable to localized hot spots on heated surfaces. Nozzles may also be designed with an array of orifices. As depicted in Figure 5, it takes three forms:

- Free impingement forces a liquid against the heated surface where it changes to a gas and is convected away.
- Submerged impingement forces a liquid against a heated surface where it may change to a gas or stay a liquid and is convected away in the same liquid.
- Confined impingement forces submerged impingement with the convected liquid (fluid or gas) convected away in the same liquid within a confined space.

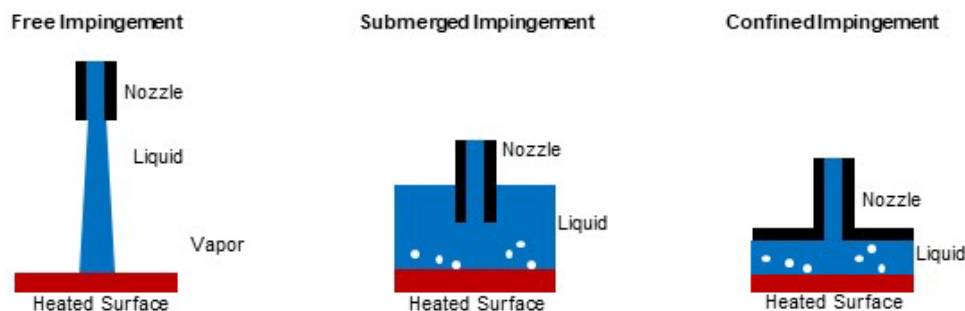


Figure 5. Heat transfer mechanisms associated with jet impingement.

The three forms depicted in Figure 5 show the energy transfer resulting in a phase change (liquid to gas), but for lower power applications, the transfer may remain single phase (staying in a liquid state). For future laser cooling applications, the energy levels will likely be sufficiently high to expect phase change.

The nozzle design is vital to achieving the high heat transfer from jet impingent. The effectiveness can be improved through changing the number or pattern of the orifices, orifice contouring, mass flow rate, and nozzle distance/angle of impingement. [9] Like spray cooling, there is a pressure drop associated with the nozzle design, but it will typically be less, requiring a smaller pump. Clogging is still a concern, but may be less of an issue since the orifice size is larger than what is commonly implemented for spray cooling.

### 3.3 Microchannel Cooling

Microchannels have significant applications in terrestrial applications with reported heat transport greater than  $1,000 \text{ W/cm}^2$  in agreement with the values reported in Figure 1. In concept, they are similar to liquid cooling loops used in current heat transport systems, but they differ in that they have significantly smaller diameters and are machined into dedicated transport materials nearer to the source of the heat generation. The proximity to the source is an important parameter because every material interface between the source and the microchannel, even if filled with a thermally conductive material, becomes a thermal resistor in the heat path. Each interface results in the laser running at hotter temperatures, so minimizing the number of interfaces is important to managing the heat flow.

Microchannel systems can utilize either single- or two-phase fluids. Small flow rates in single-phase systems result in laminar flow and heat transfer coefficients inversely proportional to the hydraulic diameter. Decreasing the hydraulic diameter with single-phase fluids can result in very high heat transfer coefficients, but with very large pressure drops and large increases in the coolant temperature and the temperature of the electronic part. [10] In contrast, two-phase microchannel cooling systems entail partial or complete liquid evaporation, requiring lower flow rates and maintaining greater temperature uniformity. While two-phase systems are more complex, the advantages are typically preferred for high-power heat sources in space applications. Additional information on these concepts can be found in Chapter 12 of [4].

An experiment conducted by Faulkner [1] employed subcooled and saturated forced convection boiling in microchannels using water and several ceramic-based nanoparticle suspensions (nanofluids). Results showed the ability to dissipate  $275 \text{ W/cm}^2$  with the subcooled liquid ( $125 \text{ W/cm}^2$  with the saturated liquid) while maintaining the substrate at or below  $125^\circ\text{C}$ . Use of nanofluids was found to provide limited improvement in overall performance. It was conjectured that optimization of the microchannel fin geometry would result in greater than  $500 \text{ W/cm}^2$  of cooling. A roadmap of challenges and opportunities for microchannel use in high heat flux applications expects microchannel cooling to achieve  $1,000 \text{ W/cm}^2$  with junction to air temperature of  $50^\circ\text{C}$  [10]. With 3-D stacking of silicon packages, microchannel designs have shown promising performance results through direct cooling of the dies. Figure 6 shows a proposed design. [12]

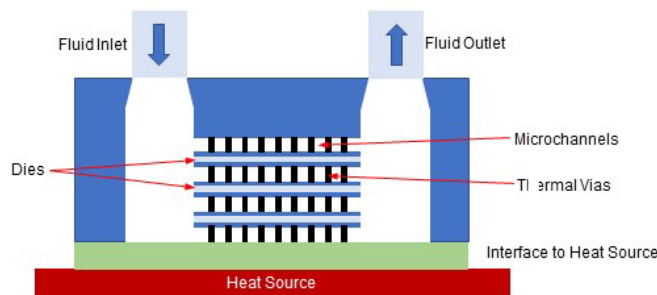


Figure 6. Microchannel cooling design for 3-D silicon package. [12]

Microchannels have been machined in various shapes with common ones being circular and rectangular. The rectangular groove design extends material fins in the same direction as heat flow for high surface area and good heat transport. Of the three high-power technologies, microchannels have the simplest design, the most heritage, and the most analysis heritage in accurately predicting performance. For an in-depth review of both single- and two-phase microchannel state of the art, see Reference [13].

### **3.4 Note: Application of Supercritical Fluids**

There is continuing research on cooling capabilities of supercritical fluids. Specifically, supercritical CO<sub>2</sub> (sCO<sub>2</sub>) is of high interest to the thermal management community. This fluid has a unique property that there is approximately a 600 percent increase in specific heat at its pseudocritical region, so with a minimal temperature increase of the fluid in the laser system, the required radiator size can be smaller. With the fluid being supercritical, there is no phase change, which mitigates wall dry-out and flow instabilities due to phase change, and cooling systems will require less pumping power than a typical single- or two-phase fluid. Current models predict that sCO<sub>2</sub> can outperform traditional fluids up to 850 W/cm<sup>2</sup>. [14] With increased research, sCO<sub>2</sub> combined with microchannels could meet the future demands for laser cooling applications. Potential roadblocks may be the required high pressure to maintain the CO<sub>2</sub> in the supercritical regime. Tubing and components will require much higher pressure ratings compared to alternative cooling fluids, thus impacting mass and reliability and the design of the subsystem components (compressor/pump, heat exchanger, valves, tubing, etc.).

### **3.5 Assessment of Future Laser Cooling Thermal Control Applications**

Of the three future applications for laser thermal control, microchannel cooling is the most promising technique for high heat removal. In comparison to the other two methods:

- In concept, microchannels are the simplest with the fewest parts. Microchannels are the closest extension of current thermal control techniques.
- There is more experimental data and research currently conducted in industry and academia on microchannels. Data from experimental studies show promise of achieving the 1,000 W/cm<sup>2</sup> goal.
- Microchannels are least affected to vehicle accelerations or orientation changes.

#### **4. Conclusions and Recommendations**

While existing spacecraft thermal control hardware can meet the power dissipation needs of modern spaceborne lasers, the future trend of increased power over smaller dissipation areas poses significant challenges to the thermal subsystem. Given the complexity of spray cooling and jet impingement cooling, the next evolution of cooling technology applicable to space lasers should be microchannels with subcooled liquids. With its ability of absorb significant heat, supercritical fluid systems show promise for these applications and should be considered as their development matures. Although there has been considerable research done on the capabilities and enhancements associated with cooling using microchannels, more work is needed to demonstrate higher power dissipation level performance in flight-like environments.

Considerations also need to be given to a combination of the cooling techniques described in this paper. The cooling mechanisms from the different systems have many aspects in common and could be combined to take advantage of their benefits. In addition, other thermal control hardware can be added to these high-cooling techniques for specific benefits. For example, adding a PCM could enable longer operational modes and adding a thermoelectric cooler could enable more precise part temperature control during heat removal.

## 5. Acronyms

cm	centimeter (length)
K	Kelvin (temperature)
LaWS	Laser Weapon System
ms	milliseconds (time)
PCM	phase change material
sCO <sub>2</sub>	supercritical carbon dioxide
U.S.	United States
USS	United States Ship
W	watts (power)

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## Appendix A. Thermal Material Properties for Common PCMs

Table A-1. PCMs with Melting Temperatures  $-25^{\circ}\text{C}$  to  $+62^{\circ}\text{C}$  [4]

Material	Melting Point ( $^{\circ}\text{C}$ )	Heat of Fusion (kJ/kg)
n-Eicosane ( $\text{C}_{20}\text{H}_{42}$ )	37	246
Polyethylene glycol 600 [ $\text{HO}(\text{CH}_2\text{CH}_2\text{O})_n\text{H}$ ]	20–25	146
Nitrogen pentoxide ( $\text{N}_2\text{O}_5$ )	30	320
Phosphonium chloride ( $\text{PH}_4\text{Cl}$ )	28	752
Dibasic sodium phosphate ( $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ )	37	279
Sodium sulfate ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ )	31	215
Glycerol [ $\text{C}_3\text{H}_5(\text{OH})_2$ ]	18	199
Calcium chloride ( $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ )	29	170
p-Xylene [ $\text{C}_6\text{H}_4(\text{CH}_3)_2$ ]	16	164
Sodium chromate ( $\text{Na}_2\text{CrO}_4 \cdot \text{H}_2\text{O}$ )	23	164
n-Undecane ( $\text{C}_{11}\text{H}_{24}$ )	$-25$	141
n-Dodecane ( $\text{C}_{12}\text{H}_{26}$ )	$-12$	211
n-Tridecane ( $\text{C}_{13}\text{H}_{28}$ )	$-6$	155
n-Tetradecane ( $\text{C}_{14}\text{H}_{30}$ )	6	228
n-Hexadecane ( $\text{C}_{16}\text{H}_{34}$ )	17	237
n-Heptadecane ( $\text{C}_{17}\text{H}_{36}$ )	22	213
n-Octadecane ( $\text{C}_{18}\text{H}_{38}$ )	28	244
n-Nonadecane ( $\text{C}_{19}\text{H}_{40}$ )	32	187
n-Octacosane ( $\text{C}_{28}\text{H}_{58}$ )	62	253
1-Tetradecanol [ $\text{CH}_3(\text{CH}_2)_{12} \cdot (\text{CH}_2)\text{OH}$ ]	38	230
Acetic acid ( $\text{CH}_3\text{COOH}$ )	17	187
Water	0	333

Table A-2. PCMs with Melting Temperatures of  $-78^{\circ}\text{C}$  and Lower [4]

Material	Melting Point ( $^{\circ}\text{C}$ )	Heat of Fusion (kJ/kg)
Methyl propyl ketone ( $\text{C}_5\text{H}_{10}\text{O}$ )	-78	104
Amyl alcohol ( $\text{C}_5\text{H}_{12}\text{O}$ )	-79	112
1-Methyl-1,2 ethylbenzene ( $\text{C}_9\text{H}_{12}$ )	-81	88
Ethyl acetate ( $\text{C}_4\text{H}_8\text{O}_2$ )	-82	118
Methyl ethyl Ketone ( $\text{C}_4\text{H}_8\text{O}$ )	-86	111
n-Butylbenzene ( $\text{C}_{10}\text{H}_{14}$ )	-89	82
Isopropyl alcohol ( $\text{C}_3\text{H}_8\text{O}$ )	-89	88
Butyl alcohol ( $\text{C}_4\text{H}_{10}\text{O}$ )	-89	125
n-Heptane ( $\text{C}_7\text{H}_{16}$ )	-91	140
Toluene ( $\text{C}_7\text{H}_8$ )	-94	72
Ethyl benzene ( $\text{C}_8\text{H}_{10}$ )	-95	86
n-Hexane ( $\text{C}_6\text{H}_{14}$ )	-95	151
Isopropylbenzene ( $\text{C}_9\text{H}_{12}$ )	-96	81
n-Propylcyclopentane ( $\text{C}_8\text{H}_{16}$ )	-117	88
1-Heptene ( $\text{C}_7\text{H}_{14}$ )	-119	126
2,4-Dimethyl pentane ( $\text{C}_7\text{H}_{16}$ )	-119	67
Chloropropane ( $\text{C}_3\text{H}_7\text{Cl}$ )	-123	84
Butane ( $\text{C}_4\text{H}_{10}$ )	-135	76
Ethane ( $\text{C}_2\text{H}_6$ )	-172	93
Methane ( $\text{CH}_4$ )	-183	59

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# Cooling Techniques for High Power Electronics - Laser Application

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