

Air cooled high power laser systems for material processing

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Abstract

Cooling is one essential basis for high power diode and fiber laser systems in material processing. Nowadays water cooling is mostly used, but problems like water quality and chiller lifetime cause maintenance efforts that can be reduced to a minimum with an alternative air cooling system. The engineers of Leister Technologies AG managed to set up an air cooled diode laser system with an optical output power up to 300 W. The laser temperature is stabilized at ± 1 K of the set cooling temperature. The cooling device is able to keep the laser temperature at 10 K below the ambient temperature. An intelligent controlling software manages cooling power, temperatures and noise level for optimal laser performance, lifetime and convenient working conditions. Maintenance of the cooling device is simple and can be performed by anyone.

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Keywords: air cooling; laser system; temperature controlling

Nomenclature

TEC:	thermo electric cooler: an electrical semiconductor based device working with the Peltier effect. It uses electrical energy to create a heat flow. There are no moving parts in the device and the direction of the heat flow can be reversed with the electrical polarity.
COP:	coefficient of performance: characterizes the efficiency of the working point of a TEC. It is the ratio of the heat flow through the TEC and the electrical power used for that.
PWM:	pulse-width modulation: a method to encode information into a pulsing signal e.g. for power control of electrical motors or brightness of LEDs
RU:	rack unit: is a unit of measure defined as 44.5 Millimeters; often used for 19-inch rack frames
Laser diode	an electrically pumped semiconductor laser, which is typically soldered to a heat sink
Laser diode module	a device including one or many laser diode(s), a more or less sealed package, electrical contacts, beam shaping and/or fiber coupling, heat handling and optionally sensors and a visible pointer laser

1. Main text

Laser welding for plastics is one of the emerging technologies of our time. For reasons of cost, the laser sources used originate from industries in which they are mass manufactured and are price-optimized. This includes fiber-coupled diode lasers with wavelengths between 900 nm and 1,000 nm, which are otherwise interconnected with fiber couplers to build extremely powerful direct material processing lasers. Those fiber-coupled diode lasers can be used as both, either as a direct material processing laser source or as pump light source for highest beam quality lasers such as fiber lasers. Typical applications are in photovoltaics and metal working. These fiber-coupled diode laser modules are electrically pumped and achieve an electro-optical efficiency of more than 50%. The remaining power is converted to heat.

This heat must be conducted away so that the diode lasers can operate within a comfortable temperature range and are therefore efficient and durable. Heat transport is realized via conduction (heat flow in solids) and convection (heat is transported in flowing media).

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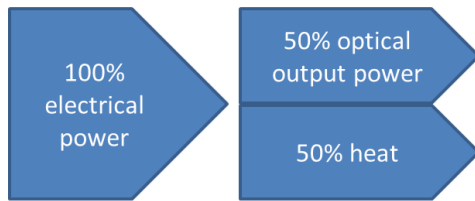


Fig. 1. Energy flow in laser diode modules

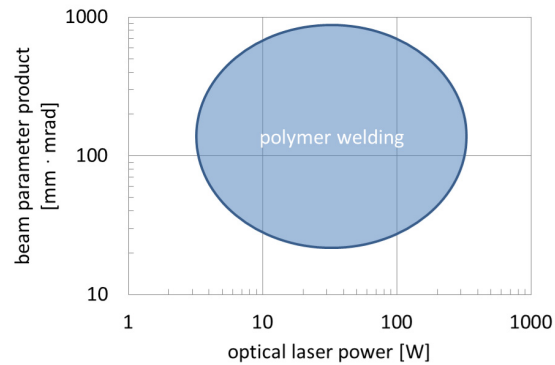


Fig. 2. Laser power and beam quality requirements in laser plastic welding

An optical power output of up to 300 W is nowadays standard in laser welding of plastics (except for processes involving laser lines and masks). Various technical configurations have been established in order to cool diode lasers with an optical output of several hundred Watts. Most technical solutions are based on water or other liquids as coolant. Solutions without liquids are also used, but less frequently, such as air-cooled systems.

1.1. Water cooling

Water has the highest specific heat capacity of all liquids. It is also non-toxic, only slightly corrosive and exists in a liquid state in a standard environment. These properties make it ideal for use in a cooling system. In general the cooling system of a laser is configured with:

- a closed water circuit where water flows as closely as possible to the heat source (laser diode)
- an electrical pump for the water flow
- a heat sink to cool down the water again

The heat sink can be a heat exchanger which works directly with either the ambient air or with a large water reservoir. Another solution is a compressor circuit which controls the cooling capacity and has its own cooler to radiate heat.

The advantages and disadvantages can be summarized as follows:

Table 1. Advantages and disadvantages of water based laser chillers

Advantages	Disadvantages
The temperature of heat sources with a high power density can be easily controlled	The cooling unit for approx. 0.5 kW of heat is extremely large (19" slot with 3–4 RU)
Very compact design on the side of the heat source	Prone to leaks and biological contamination
Heat source and cooling unit can be spatially separated	Many moving parts that are declined as wearing parts (pump, fan, bypass valve)
Highly energy efficient	Special water properties that need maintenance (particle filter, ion exchanger cartridge)

1.2. Air cooling with forced convection

When a laser system is operated under standard conditions (room temperature of 20 to 22 °C) the ambient air can be used to store the waste heat. To optimize the transfer of heat to the ambient air both are used, coolers with increased surface areas and fans for the air flow.

The simplest configuration is to have the diode laser module mounted directly onto a cooler. The thermal resistance of cooler and fan must be adapted to the laser module and the amount of waste heat it produces. The objective is to keep the laser module at a baseplate temperature of 25–30 °C. Higher temperatures shorten the lifetime of the laser.

$$R_{th\ cooling} \leq \frac{T_{target\ Laser} - T_{ambient}}{P_{heat\ Laser}} = \frac{30\text{ °C} - 20\text{ °C}}{300\text{ W}} = 0.033\ \frac{\text{K}}{\text{W}} \quad (1)$$

A thermally conductive paste or foil is used to optimize heat transfer from the diode laser module to the cooler. Each millimeter of material and each interface boundary surface poses a resistance to the heat flow and therefore needs to be optimized accordingly. Nevertheless, the laser temperature in this configuration depends directly on ambient temperature, laser power and fan speed. The cooler and fan for a 300 W laser are very large in volume. Additionally heat spreading is required to ensure that the entire top surface of the cooler is used. The configuration is therefore large (165 × 165 × 562 mm³ W × H × D with a cooler length of 400 mm in the example) and heavy. It is restricted to use in air-conditioned production facilities from 20–22 °C. The electro-optical efficiency of the laser and cooling is 43% in this case.

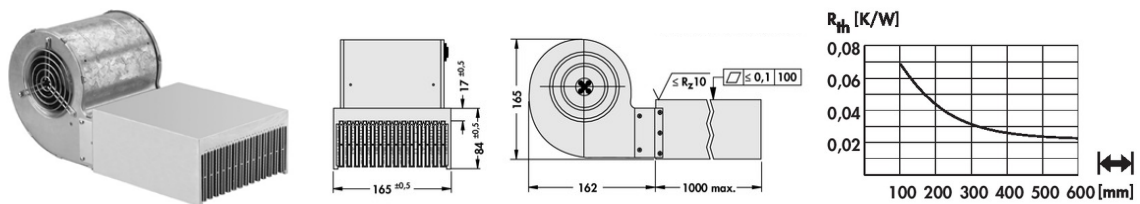


Fig. 3. Cooling unit LA 26 from Fischer Elektronik GmbH & CO KG

1.3. Hybrid cooling

A hybrid and compact solution can be achieved, if the diode laser module is cooled with water, but the water temperature is controlled by using TECs, a cooler, fans and ambient air.

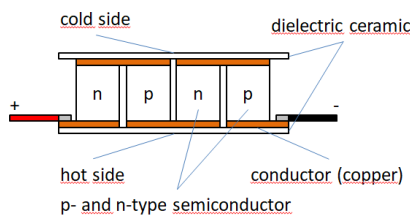


Fig. 4. TEC device in detail

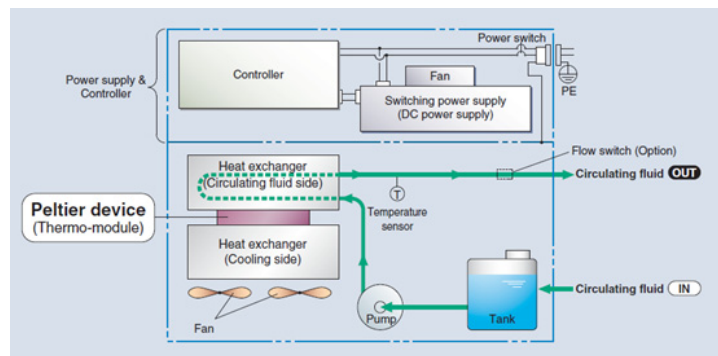


Fig. 5. Scheme of a TEC based laser chiller; HECR series from SMC Corp. Japan

This helps to resolve most of the mechanical problems of conventional water cooling systems (bypass valve, compressor). This solution is a little more compact than a comparable compressor cooler, as the compressor and heat exchanger are no longer needed. Nevertheless, an extra current source and a device to control the TECs are now additionally required. Using TECs has the advantage that both heating and cooling is possible as the polarity of the current is reversed at the TECs. The electro-optical efficiency of the laser and cooling is approximately 25% in this case.

1.4. Controlled air cooling

The next logical step is to create a sandwich out of the laser diode module, Peltier elements and the cooler with fan. The individual components must be carefully designed, selected, and joined. This ensures a cost-effective air cooled laser system for industrial use.

The advantages are obvious:

Table 2: Advantages of TEC based cooling units

Compact design	No moving parts except of the fan
Less sensor technology in the device	Very stable temperature of the diode laser module
Minimized noise level	No leaks, corrosion, algae infestation
Very simple to service	An extremely low risk of failure

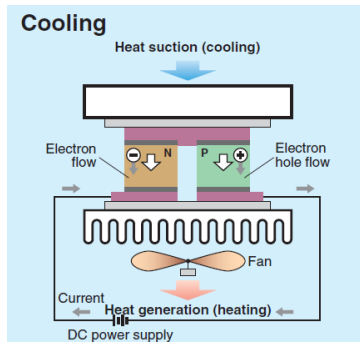


Fig. 6. Diagram of Peltier cooling device, SMC Corp. Japan

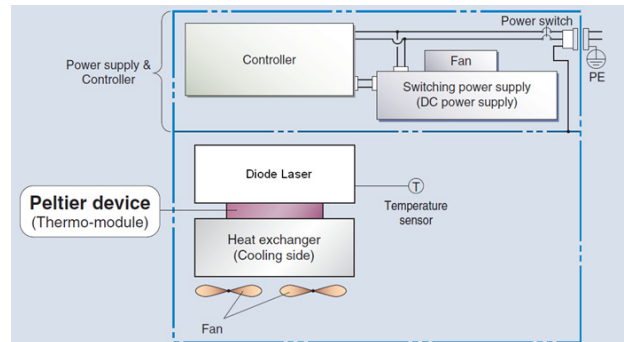


Fig. 7. Diagram of a TEC-based laser cooling device; adapted from SMC Corp. Japan

The components are designed in several steps: Firstly, the maximum thermal output of the diode laser module is estimated using the specifications provided by the manufacturer for voltage, current, and optical output. Alternatively these values are determined in experiments. It is important that the laser is operated at the highest defined operating temperature for a worst-case scenario estimation.

Next, an estimation is made of which and how many TECs are required. The target temperature of the laser (25 °C) and the permitted maximum ambient temperature of the system (35 °C) are important parameters. The amount by which the heat sink is permitted to heat up is another important influencer. A temperature that is too high reduces the performance of the TECs. A temperature that is too low results in a very large cooler and requires a higher quantity of TECs.

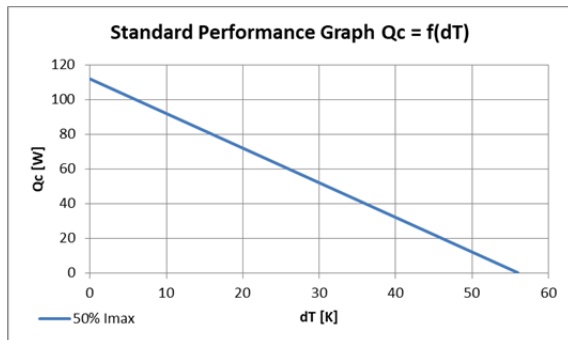


Fig. 8. Diagram of an example Peltier cooling device showing the heat transfer performance from one side to the other depending on the temperature difference of the two sides

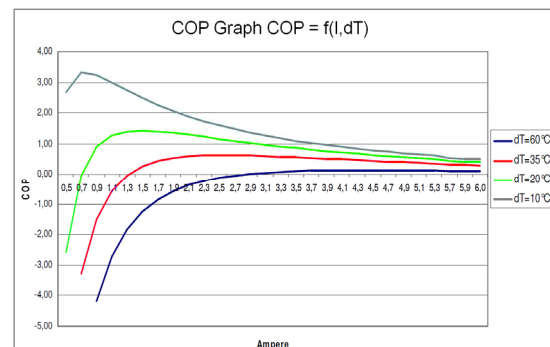


Fig. 9. Diagram of an example Peltier cooling device showing the COP depending on current and on the temperature difference of the two sides

A good value for the temperature difference is 20 Kelvin, which is equivalent to 45 °C at the cooler. Powerful TECs operate highly efficient under these conditions (COP of approximately 1.2) and at around 33% of their maximum cooling capacity. In general focusing on efficiency of the TECs is more important than focusing on maximum cooling capacity when optimizing heat conduction. For these operating conditions the number of TECs can be calculated.

Table 3. COP of different TEC types at similar ambient conditions

TECs (16x)	$Q_{\text{heat Laser}}$ [W]	V_{air} [m/s]	V_{air} [m ³ /s]	$R_{\text{th,cooler}}$ [K/W]	$T_{\text{air,in}}$ [°C]	$T_{\text{air,out}}$ [°C]	$T_{\text{TEC,hot}}$ [°C]	$T_{\text{TEC,cold}}$ [°C]	$P_{\text{el,TEC}}$ [W]	Q_{hotside} [W]	COP [-]
Typ A						42.9	54.1		407	707	0.737
Typ B	300	5	0.04	0.045	35	41.3	50.3	22	265	565	1.133
Typ C						41.0	49.6		238	538	1.261

The additional TEC heat input to the heat sink can be calculated from the amount of TECs and the electrical specifications. A COP of 1.2 and laser heat output of 300 W results in an additional 250 W of heat. The thermal resistance of the configuration may therefore be a maximum of 0.018 K/W according to formula 2.

$$R_{th} \leq \frac{T_{\text{max,cooler}} - T_{\text{max,ambient}}}{P_{\text{heat Laser}} + P_{\text{el,TECs}}} = \frac{10 \text{ K}}{550 \text{ W}} = 0.018 \frac{\text{K}}{\text{W}} \quad (2)$$

Using this information, models with reasonable air flow can be selected from the standardized cooler geometries.

Manufacturers provide characteristic curves with their coolers, which show the thermal resistance and flow resistance depending on the air flow rate. This is helpful when selecting the fan. Fans with speed sensor and PWM input can be controlled and monitored easily. Nevertheless, the cooler should be designed so large that the air velocity inside does not exceed 40 km/h, so that the noise level remains below the required 70 dB(A).

For a safe and precise operation the entire setup requires only sensors for the temperatures of the ambient air, laser diode module and cooler, a humidity sensor for the ambient air and a fan speed sensor. Using the available sensor data, the cooling power of the TECs can be controlled, the fan speed can be dynamically maintained at the required level, the cooling function can be monitored, a warning of any risk of condensation can be issued and a recommendation can be made to check or replace the air filter element. Furthermore, the laser can also be programmed to only operate within a certain temperature range. This ensures that the laser has a long lifetime.

Comparing the price for the cooling device either with water and compressor or with TECs a clear picture can be drawn. The market price for a controlled TEC based air cooling device for 300W heat load with the described sensors and controller would be nearly twice the price for a complete water chiller for the same heat load, with tap water quality and safety sensors and controller. That is much more, but with a look at the whole laser system it makes sense: The new cooling device allows Leister to choose other laser module vendors while still offering an air cooled and water free system. Looking on the market price for integration ready Leister laser systems of 300W optical output power the advantage becomes obvious. The new air cooled device from Leister can be sold with a 25% lower price than the common uncontrolled air cooled systems. The customer pays a lower price for even a better performance of the system and has much lower maintenance cost.

The work carried out at Leister has created a compact (19", 6 RU, 480 mm deep), inexpensive and maintenance-friendly laser system, with standard-compliant safety features for laser welding of plastics. The optical output power of 300 W is more than sufficient for most welding processes. A stable laser temperature at a sufficient level guarantees high quality welding and a long lifetime of the laser source. The operational ambient temperature range extends up to 35 °C with constant 25 °C at the laser. Further development is conceivable in order to extend the climatic operational range.