A Novel Package-Integrated Ceramic Cyclone Cooler for the Thermal Management of High-Energy Lasers

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INDUSTRIAL LASER BACKGROUND

High-power industrial lasers (such as those used in heavy industry and construction) present a brutally difficult thermal management challenge for a variety of reasons. The high-power diodes required for their function combine high heat fluxes (> 1 kW cm^{-2}), with a very high isothermality (± 2 ℃ is the generally accepted value), at a relatively low temperature (23 ℃ is used as a standard value) [1-5]. The heat generated by the system must ultimately be rejected to environments across a broad temperature range depending on where the laser is operated and employed. In addition to all this, thermal interfaces must be thermal-expansion matched to avoid deforming the laser diodes, which limits the available materials for construction. Traditionally, lasers have been developed and tested in laboratories, i.e., in a temperature-controlled environment, with access to large quantities of facility coolant. However, if one wanted to create a more integrated solution that could be transported and used in the field, the size, weight, power, and cooling constraints of this laboratory/facility would be unacceptable. The location in which the laser is used may not have tight temperature regulation, nor large coolant reservoirs available, nor the space needed for the necessary pumps, pipes, and control valves.

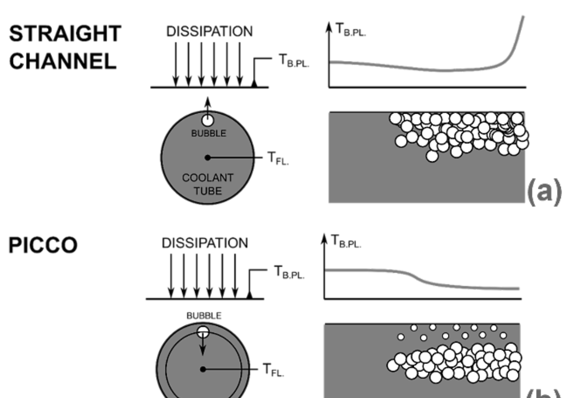

Figure 1 Concept of vapor accumulation in a straight channel versus swirled boiling flow and associated qualitative trends of wall temperature

This naturally leads one to the use of two-phase cooling, to both maintain a narrow temperature band as well as greatly decrease the required coolant flow rate. Current fiber amplifiers use a coldplate to which the pump diodes and other system components are mounted, with a two-phase fluid flowing through the plate. Such diodes constitute the majority of the heat load and their efficiency is ~ 55% electrical-to-optical versus the 80% optical-to-optical efficiency of the rest of the system. While vastly superior in performance to single-phase coolant loops, there remain multiple areas in which the performance and packaging of these two-phase coolant systems can be improved. Improvements can be made by: (i) increasing the vapor fraction at the exit section of the cold plate, (ii) processing the cold plate channels' surface roughness to increase the Critical Heat Flux (CHF) and improve boiling heat transfer, and (iii) using wavelength-stabilized diodes to allow for a larger thermal gradient across them. Operating the laser diodes at the maximum temperature allowed by their reliability leads to less thermal lift required to dissipate heat to the air in hot climate, and more efficient rejection if environmental temperatures are lower. The concept presented in this paper is an alternative packaging concept to traditional cold plate design that shows the potential for improved performance at much lower pumping power and coolant flow rates.

CYCLONE COOLER CONCEPT

Convective cooling by means of a fluid in phase transition from liquid to vapor is orders of magnitude more effective than single phase for the same fluid and the same Reynolds number [6,7]. In the case of subcooled boiling, as utilized to cool electronics, the

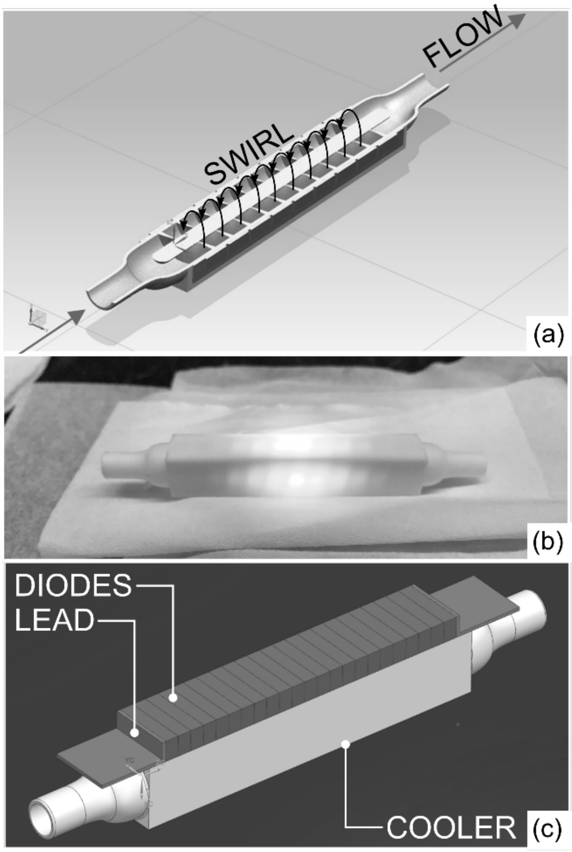

Figure 2 (a) Rendering of a meridional section of the cyclone cooler, (b) a picture of the actual alumina part, and (c) a suggested diode laser package including the cyclone cooler

fluid engulfs [8], is impinged on, or is circulated nearby the junction to absorb the heat and sustain the phase transition process [5], [7], [9], [10-13]. The advantage of two-phase with respect to single-phase cooling is two-fold. First, although the coolant removes heat under the electronics, it does not increase its temperature and therefore: (i) it mitigates the in-plane thermal gradients that lead to laser polarization shift and beam section distortion (*smile*), (ii) it can help spread heat by transporting energy from hot spots to other locations with negligible heat load [4]. Secondly, the heat transfer coefficient at the fluid-wall interface is augmented by the local agitation of the liquid phase, where bubbles destroy its viscous sublayer. As shown by Galloway and Mudawar [14], the heat flux causing thermal runaway, i.e., the CHF, can be significantly enhanced by increasing the fluid body force, thereby promoting the vapor removal from the surface and increasing fluid subcooling. For example, Costello and Tuthill [15] demonstrated that the CHF can be increased with augmented fluid rotational speed and correlated their results to increased bubble departure frequency and reduced bubble diameter. Indeed, both mechanisms would result in reduced vapor confinement at the surface and improved CHF.

Figure 1 shows the Package Integrated Cyclone Cooler (PICCO) basic concept. A conventional, straight-channel cold plate, Figure 1a, flows coolant that absorbs heat flux from the electronics in the form of sensible and latent heat. As heat is accumulated by the coolant, its temperature increases. When brought at its saturation temperature, the gas phase segregates and migrates along the hot wall. As the gas fraction increases due to heat intake, pockets form at the wall and eventually across the passage area causing abrupt decrease in heat transfer and thermal runaway. Conversely, the swirled coolant in PICCO, Figure 1b, promptly pulls bubbles away from the wall and collects them at the core of a vortex thus ensuring that fresh coolant is always in contact with the hot wall. The driving force pulling the bubbles away from the wall is the buoyancy (body force) induced by the density ratio of vapor/liquid and by the tremendous centrifugal acceleration field created by the swirled flow.

Predicting the heat transfer coefficient in the presence of nucleation is challenging due to: (i) the physics-based models being still in progress and (ii) limited capability when modeling surface roughness, which is known to decrease the free-energy threshold that is needed to trigger nucleation after the metastable state (liquid-phase tension). Therefore, the most effective approach is mechanistic, i.e., the heat flux is re-calculated at every step of a solver that includes the surrogates of: (i) the heat removal via phase-change (the actual boiling phenomenon), (ii) the quenching process due to the liquid quickly occupying the void left by a departed bubble, and (iii) the enhanced single-phase heat transfer due to the liquid being agitated by the nucleating bubbles. The latter is modeled assuming that bubble nuclei can be treated as roughness elements laying on the hot wall. Modeling the phenomenon of swirling two-phase flow for electronics cooling and thermal storage means defining transfer functions to predict the heat conductance per unit area from the fluid to the junction, and the CHF the cooler can absorb before losing control of the gas phase and undergoing thermal runaway. To predict the conductance, a model including vaporization, quenching and convection through the liquid layer has been implemented and experimentally validated by Miorini et al. [16]. The model was adapted from the seminal work of Amidu and Addad [17] and of Galloway and Mudawar [14].

MODEL PREDICTIONS

The thermo-fluid dynamics model implemented and validated by Miorini et al. [16] can be utilized to predict the performance of any PICCO geometry with

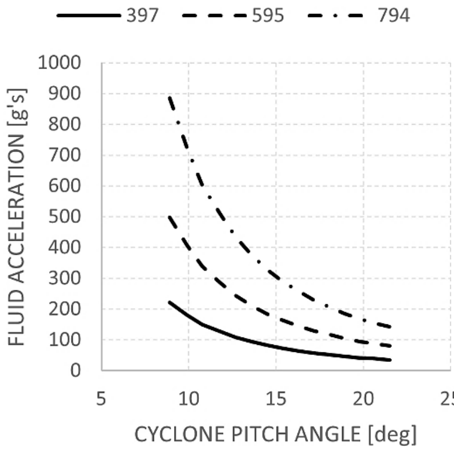

Figure 3 Radial acceleration imposed by the cyclone cooler to the fluid as a function of the cyclone pitch angle, the legend indicates the coolant mass flux in kg m^{-2} s^{-1}

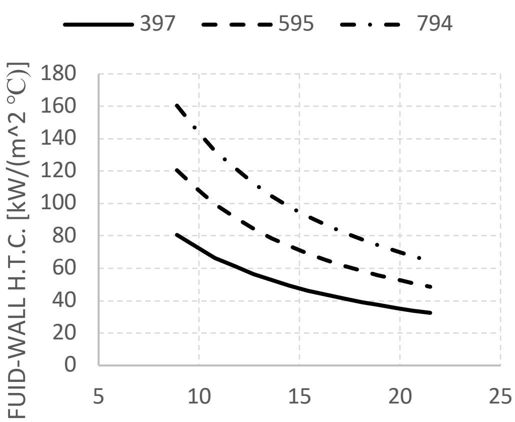

Figure 4 Heat transfer coefficient (HTC) at the cyclone wall as a function of the cyclone pitch angle, the legend indicates the coolant mass flux in kg m^{-2} s^{-1}

any coolant flow. In regards to the results shown in this article, the fluid of choice for our model is perfluoro-n-hexane (C_6F_{14}) - also known as tetradecafluoro-n-hexane. This fluid is clear, colorless, dielectric, and commonly used for research in two-phase heat transfer. Moreover, this fluid was selected because it would allow for direct comparison with the work from Galloway and Mudawar [14].

The fluid is delivered to the cyclone inlet port as saturated liquid at 101.3 kPa (47.6 °C). The cyclone has an inlet port, seen in Figure 2a, and an outlet port. Figure 2b shows an actual cyclone cooler, additively manufactured using alumina, which is dielectric and allows direct deposition of electronics, as shown in Miorini et al. [16]. Right downstream of the inlet port, the flow is swirled by a single, triangular fin that is grown from the internal diameter and merges with a central, solid rod, which strengthens the structure, seen in Figure 2a. The inner diameter of the cyclone, at the fin base, is 6.35 mm. The finned section is 50.8 mm long. In the numerical model, a 250 W heat load is imposed uniformly at the top surface of the cooler where, for instance, an array of laser diodes could be soldered, seen in Figure 2c. The heat flux at the top of the cyclne cooler is therefore 78 W cm^{-2}.

Figure 3 shows the radial acceleration to which the fluid is subjected as it is turned by the cooler geometry into a 6.35-mm-diameter vortex. The swirl pitch is controlled by the geometry of the fin and the mass flux of the coolant. For instance, at 794 kg m^{-2} s^{-1}, corresponding to 2.0 liter per minute, the radial acceleration reaches 900 times gravity. Figure 4 shows the heat transfer coefficient increase with both the pitch angle of the fin and the mass flux of the coolant. Note that a 10° pitch cyclone flowing 595 kg m^{-2} s^{-1} (1.5 liter/minute) can deliver ~100 kW m^{-2} °C^{-1} by swirling the coolant at ~300 g's and requiring ~10 W of pumping power.

If the heat transfer coefficient at the channel wall is relatively high, the thermal resistance from the diode-to-fluid is low. Therefore, the cooler can remove more heat from the diodes at the same junction temperature, which sets the target beam's wavelength. In turn, and because the diode's efficiency is set, if the cooler can manage more dissipation, it can support diodes that utilize more electrical power and therefore produce a brighter beam. However, the higher the pitch angle, the higher the fluid velocity and the longer the flow path. Both increase the pressure drop across the cooler and therefore the pumping power required, as seen in Figure 5.

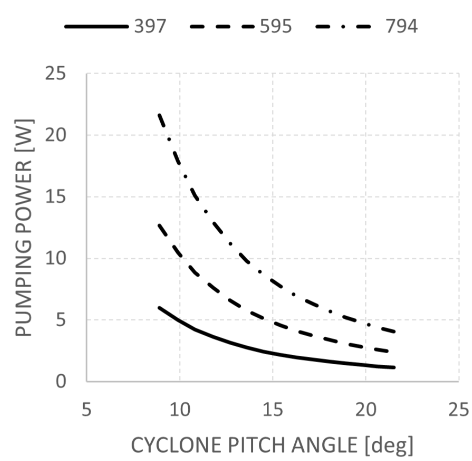

Figure 5 Power required to pump the coolant through the two parallel cyclones as a function of the cyclone pitch angle, the legend indicates the coolant mass flux in kg m^{-2} s^{-1}

The augmented pumping power associated with the swirled flow path has a negative impact on the size, weight, power consumption, and cost of the thermal system because a more powerful pump must be chosen. However, we have demonstrated that with respect to a straight channel and for the same Reynolds number, the cyclone cooler provides a 100% gain in heat transfer coefficient with a modest (13%) increase in pressure loss [16]. Note that high flow speed induced by the high fin pitch increases the erosion rate of the ceramic fin.

ADDITIVE MANUFACTURING

A number of PICCO prototypes were additively manufactured at GE Research using a Lithoz CeraFab 7500 furnace and alumina slurries supplied by Lithoz GmbH. The choice of ceramic slurry and nuances in the process are still at the pioneering stage. Our first efforts were not successful, but we learned through deeper investigations a method to produce rugged and crack-free prototypes. We identified six potential root causes for the early failures that were divided into design and process causes. A successful design must take into account that: (i) edges and corners cause stress concentration in the printed structure, (ii) if a part is hollow like PICCO, non-uniform wall thicknesses cause non-uniform shrinkage and therefore high stresses, and (iii) if the structure is too stiff, the thermal profile associated with de-binding and sintering the part may cause stresses. Process-related causes that were evaluated included: (i) a particularly unfortunate combination of printing direction and geometric features in that direction leading to weak regions, (ii) hot air trapped inside the part must be able to flow out of it through vents (to be sealed after cool-down) to avoid hot spots during the cool-down process, and (iii) constrained shrinkage due to friction between the part and its substrate during firing.

The most effective solution to reduce stresses and cracking during firing was switching alumina slurry grade from HP500 to 350D and tapering the inlet/outlet ports to provide more resistance to the bending moments that are inherent in handling the part. The 350D grade slurry particle size is larger compared to the HP500 grade. The larger particles in the 350D slurry provide a larger interparticle spacing for the binder decomposition by-products to diffuse and volatilize out of the green body. The larger spacing reduces capillary forces that form among the particles, which can put stress on the body.

ACKNOWLEDGMENTS

This research was sponsored by the U.S. Army Research Laboratory’s Sensors and Electron Devices Directorate (SEDD) and was accomplished under Cooperative Agreement Number W911NF1920276. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Army Research Laboratory’s Sensors and Electron Devices Directorate (SEDD) or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. The views expressed are those of the author and do not necessarily reflect the official policy or position of the Department of the Air Force, the Department of Defense, or the U.S. government.

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