

PERFORMANCE EVALUATION OF A 3D-PRINTED VAPOR CHAMBER

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ABSTRACT

Increasing power densities of electronic components poses new challenges to thermal management of high heat-flux devices. Advanced Cooling Technologies Inc. (ACT) and the University of Alabama in Huntsville (UAH) have developed a 3D-printed copper vapor chamber to dissipate heat produced by high power ultraviolet LED's. This vapor chamber consists of an evaporator, condenser, working fluid, and wick structure. All copper components of which were fully additively manufactured in a single selective laser melting (SLM) process. In this study, the performance of a 3D printed vapor chamber was compared to a conventional aluminum cold plate. The preliminary data shows that the vapor chamber reduced PCB temperatures by up to 40% at 360 W. Additionally, temperature uniformity across the PCB was maintained within 1 °C over the entire power range, while aluminum cold plate exceeded 5 °C. The significantly improved thermal performance of new cooling solution shows significant promise for future 3D printed vapor chamber solutions.

Keywords: Vapor Chamber, thermal management, additive manufacturing,

NOMENCLATURE

Q	Power Input (W)
T	Temperature (°C)
dT	Temperature Difference (°C)

1. INTRODUCTION

The increase in power densities of electronic components, such as power electronics or high-power LEDs, creates new challenges for electronics packaging in the form of strongly localized high heat generation and need for effective heat dispersion. As electronic components continue to deliver higher power in increasingly compact designs, the challenge of developing cooling systems that can meet these demands effectively has grown [1]. To accommodate these higher heat fluxes, many high-power devices utilize a vapor chamber, or “heat spreader”, to decrease heat flux while increasing heat sink area. The vapor chamber is one of the most efficient passive

two-phase cooling systems for heat spreading because of its compact design, structure, and performance which have shown improvements in the ability to maintain the electronic device temperature below a design limit while meeting space requirements [2]. Additionally, the advancements of metal additive manufacturing allow for the potential of complex heat exchanger geometries, wick designs, and reduced weight. In this study, a planar vapor chamber is manufactured with an integrated cold plate using additive manufacturing.

A vapor chamber is a sealed device that uses phase change and capillary action to efficiently move heat. Vapor chambers are typically made up of three major components: the evaporator wall, the wick structure, and the condenser wall, as shown in **Fig. 1**. The vapor absorbs the heat and travels to the condenser wall, where it releases heat and condenses back into a liquid. This liquid is then returned to the evaporator wall through the wick structure by capillary action. [1,3] The continuous cycle of evaporation, mass transfer and condensation at new location results in very highly effective thermal conductivity. Additional pillars can be employed inside to reduce the deformation of the vapor chamber [4].

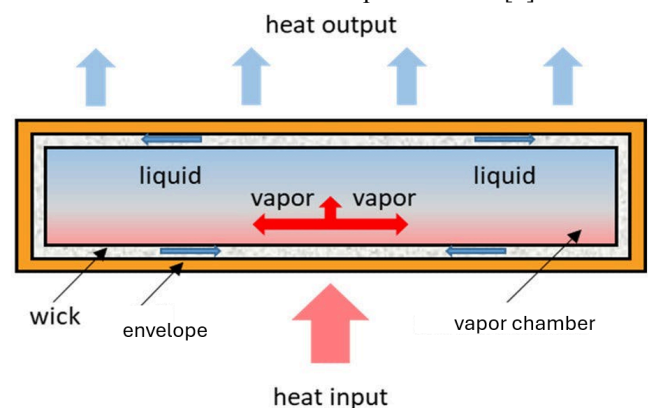


Figure 1: Vapor chamber structure and operation.

The wick structure, which is located on the evaporator and condenser wall, as illustrated in **Fig.1**, is critical to the operation of the vapor chamber. The capillary pressure of the wick drives the working fluid back to the heat source. Conventionally, the manufacturing of the wick inside a sealed

chamber typically involves power sintering or using mesh-based wicks for reduced performance. These conventional approaches also require complicated steps such as brazing to assemble parts of the vapor chamber and has thus intrinsic manufacturing defections.

Along another line, Additive Manufacturing (AM), or 3D printing, enables the fabrication of complex structures that are difficult to produce with conventional machining processes. Freeform capabilities allow components to be designed in complex shape for improved performance, reduced weight, and unconventional geometries that can fit within constrained spaces. Therefore, AM methods can be used to fabricate a vapor chamber that is fully sealed and internally structured to match the specific requirements of the electronic device. Furthermore, the internal wick structure can also be produced with the 3D printing technique, having a control of its geometry and properties to achieve more effective fluid circulation and thermal performance [5].

This study investigates the thermal performance of a single piece 3D printed vapor chamber heat dissipation unit for high power LED assembly. It is compared to a classic solid aluminum cold plate to evaluate the potential of new manufacturing technology in improving thermal dissipation.

2. MATERIALS AND METHODS

2.1 Vapor Chamber Design and Manufacturing

The test vapor chamber design, which included an integrated cold plate is shown in **Fig. 2**. Specifically, the test vapor chamber has comparable dimensions, particularly the total thickness, of a commercial off-the-shelf cooling block (PTF-B-1000) to be compatible with the existing form factor of the UV system. The test vapor chamber has a vapor chamber designed with a cold plate to be 3D-printed as one part. The vapor chamber has a ~ 7 mm spacing between the evaporator and the condenser panel. The part was 3D printed in a single piece from AMCu-100 using the Selective Laser Melting (SLM) method by a professional AM provider. The particle size used was 100 micron, with a goal of 60% copper density. It is worth noticing that the vapor chamber orientation is vertical, comparing to the horizontal orientation they are commonly used. To facilitate the adequate fluid return, pillars with wicks were designed between the evaporator and condenser side (as shown in **Fig. 2a**). Additionally, the distance between the evaporator and condenser surface is only $\sim 0.5''$, further minimizing the liquid return distance.

SLM being a powder-bed AM method required a removal of loose powder upon the print. Cleaning of the 3D printed vapor chamber was completed using several methanol rinsing cycles. These cycles were performed until no further copper particles were visible in the discharged methanol. A subsequent bake out was performed in a reducing furnace. The unique processing method allowed to achieve the wick structure as partially sintered powder with an effective porosity of 40%.

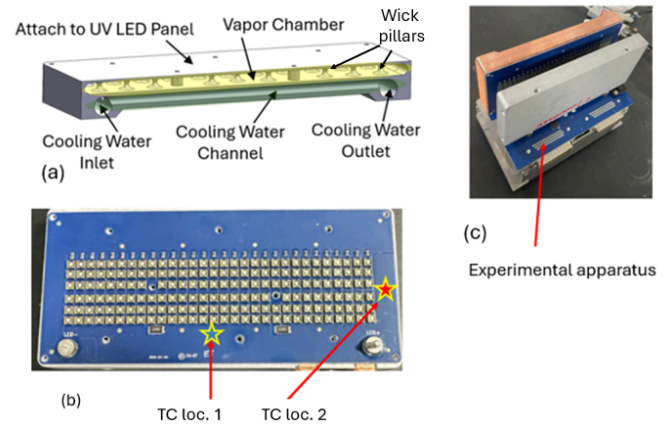


Figure 2: Experimental setup showing (a) illustration of the cross-section of the additively manufactured vapor chamber with internal wick structure, (b) UV LED PCB heat source with thermocouple locations marked with stars (★), and (c) assembled test apparatus in vertical orientation with integrated liquid cooling.

After the AM of the vapor chamber, we initially overfilled the vapor chamber with deionized (DI) water with a filling ratio of $\sim 40\%$, which is more than the volume that wets all the porous wick structure. We then heated the vapor chamber to 100°C in an upright orientation and performed the burping process to purge the non-condensable gases (NCGs) and excessive water while monitoring the temperature difference between the center and the edge of the vapor chamber. The burping process is completed when the temperature difference reaches a minimum (typically ~ 1 K), and the final effective filling ratio is 25% by measuring the weight difference of the vapor chamber, and the vapor chamber is subsequently sealed.

2.2 Experimental Apparatus

The AM Vapor Chamber (copper finish), and the solid aluminum reference cold plate (gray finish) were mounted on the supplied frame in a vertical orientation as shown in **Fig. 2c**. Two UV LED panels, one shown in **Fig. 2b**, are screwed on the evaporator side of vapor chamber and aluminum cold plate respectively. UV units were able to achieve a uniform maximum power input of 360 W at the surface of the vapor chamber. Solid aluminum cold plate was tested under the same conditions. The temperature uniformity across the surface of the UV PCB panels was measured by two T-type thermocouples with ± 0.5 K tolerance located at key places on the LED panel, as seen in the stars in **Fig. 2b**.

2.3 Experiment and Calculation

The AM vapor chamber and the baseline aluminum cold plate were tested over an increased total power range from 10 W to 360 W via variable DC source. Both the cold plate and vapor chamber were independently cooled with filtered water supplied from the chiller at 2.5 LPM and 10°C . The baseline

cold plate and the vapor chamber were tested simultaneously using the same power input, water supply, and coolant flowrate. The temperature data for each panel was purposely gathered with the adjacent unit also powered on, to simulate the end-user's operational configuration. In this way, the total heat removed by the vapor chamber or cold plate is a combination of heat produced by the LED's and absorbed UV radiation from the opposite LED panel. The experiments were conducted in a continuous manner by varying the UV LED from 10 W to 360 W. The LED power output was achieved using the widely-adopted pulse width modulation (PWM) approach by adjusting the duty cycle of the power signal. Same tests were repeated twice with the same room temperature and no significant differences were found.

3. RESULTS AND DISCUSSION

Fig. 3 shows the compiled temperature data of the PCB panels over the entire panel power range. The aluminum cold plate allowed for up to 16 °C increase at maximum power with the maximum spatial temperature difference of ~6.5 °C the two thermocouples. Meanwhile, the UV LED panel with the new AM vapor chamber showed a much-reduced temperature increase of 8 °C from 10 W to 360 W, and the temperature difference was within 1 °C.

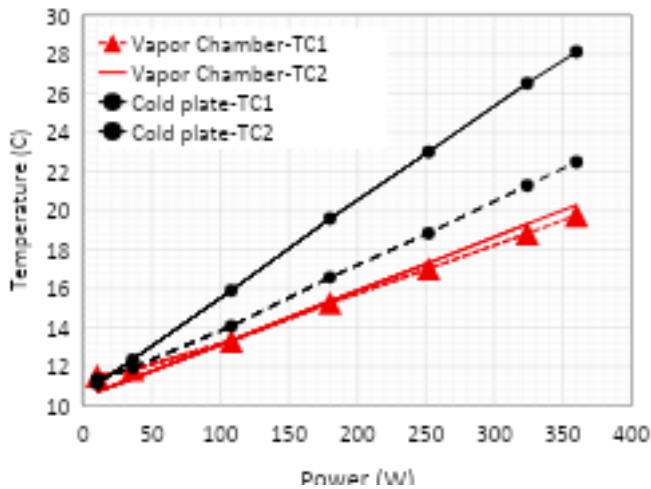


Figure 3: Measured PCB temperatures at thermocouple locations TC1 and TC2 as a function of UV LED input power (10–360 W) for the aluminum cold plate and additively manufactured vapor chamber.

The plot of temperature difference between points (1) and (2) over all power input range, Fig. 4, we see that the PCB mounted to the vapor chamber has significantly improved temperature uniformity along its length. The aluminum cold plate shows increased dT as power increased due to lower thermal conductivity making the longitudinal heat transfer a limiting factor.

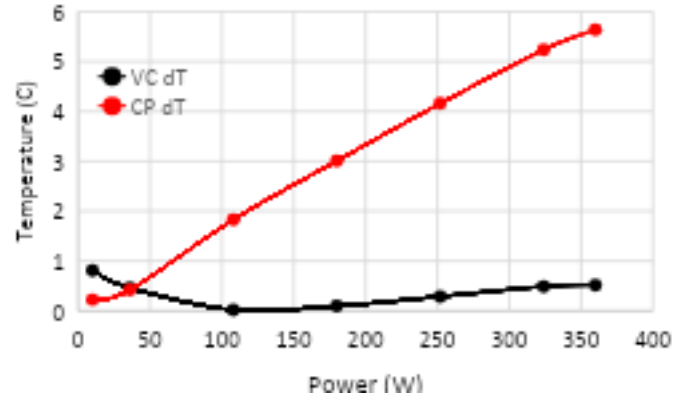


Figure 4: Temperature difference between PCB thermocouple locations TC1 and TC2 as a function of the UV LED input power, illustrating spatial temperature uniformity for the vapor chamber and aluminum cold plate under identical cooling conditions.

The very small temperature difference between the two thermocouples in case of Vapor Chamber test comes from the significantly higher effective thermal conductivity. Meanwhile the much lower overall temperature, not exceeding 21 °C, shows that the vapor chamber design improved heat dissipation by reducing overall thermal resistance.

4. CONCLUSION

Vapor chambers are preferred solutions for situation when a large area needs to be maintained at a uniform temperature. In this study, an experimental copper vapor chamber was manufactured using selective laser melting and tested with UV LED panel capable of 360 W of powered operation. Additionally, the integrated design that combines the vapor chamber and the cold plate further eliminates the contact thermal resistance between the two components. Further, the vapor chamber is designed with the AM manufacturability in mind, and adopted unique designs such as pillars with the wick to achieve a significant performance improvement over the conventional aluminum cold plate design and show the feasibility of 3D printed heat transfer devices. Through the advanced manufacturing and design techniques, the vapor chamber was shown to provide a 40% reduction in PCB temperature as well as maintaining the surface temperatures within 1 °C across the PCB length.

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