Design and Manufacturing Processes for High-Volume Production of Two-Phase Loops

Katherine Piper[1,*]

Background. Two-Phase Loops are a highly efficient method for heat transfer across long distances. In the context of this disclosure, Two-Phase Loops refer to any multiphase thermal control device which uses an evaporator containing a porous wick to separate liquid and vapor phases, improve the rate of evaporation, or otherwise alter the performance characteristics of the system. Some example devices which fall into this category include Two-Phase Mechanically Pumped Loops, Capillary Pumped Loops, and Loop Heat Pipes. The documented technology focuses on an improvement to the state of the art manufacturing process for two-phase loops. Historically, the design and manufacturing of two-phase loops was limited by the metal sintering process. Advances in additive manufacturing have reduced the manufacturing costs of Two-Phase Loops in several ways, including preventing the need for assembly. Additive manufacturing, however, is slow, limiting manufacturing throughput and preventing application of two-phase loops in large scale systems such as data centers. This technology disclosure focuses on a design, manufacturing, and assembly process intended to maintain the strengths of additive manufacturing, while increasing the manufacturing throughput, reducing the time-to-market for large scale implementation of Two-Phase Loops.

Design and Manufacturing Process. In the production of evaporators for two-phase loops, the additive manufacturing process remains a primary bottleneck. We aim to reduce the quantity and size of additively manufactured components, while also reducing the cost of assembly between traditionally manufactured and additively manufactured components. The core innovation relies on manufacturing evaporator wicks with built-in mating surfaces. While the assembly of wicks is traditionally expensive, additively manufacturing a built-in mating surface enables low cost assembly, while maintaining the advantages of an additively manufactured wick. The difference in manufacturing capacity between single-component Two-Phase Loop Evaporators and the proposed technology is shown in Figure 1. This demonstrates the difference in capacity for the state-of-the-art in additively manufactured Two-Phase Evaporators and the proposed technology, for evaporators with 2"x2" dimensions, on a 9.8"x9.8" build plate, corresponding to a common industrial printer used for additively manufacturing Two-Phase Evaporators.

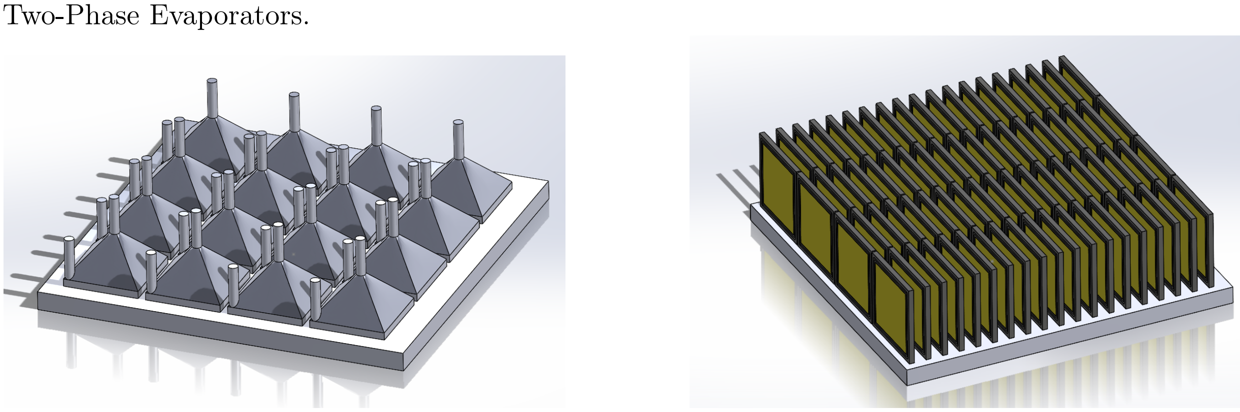

Figure 1: A Figure Demonstrating the Difference in Manufacturing Volume between traditional methods and through the proposed technology, which includes Additively Manufactured Wicks with Dedicated Mating Surfaces

*Corresponding author
Email address: kbpiper@andrew.cmu.edu (Katherine Piper)

Design Considerations Several critical design considerations must be made for the benefits from the higher manufacturing volume to be realized. Several of these considerations are detailed in this section.

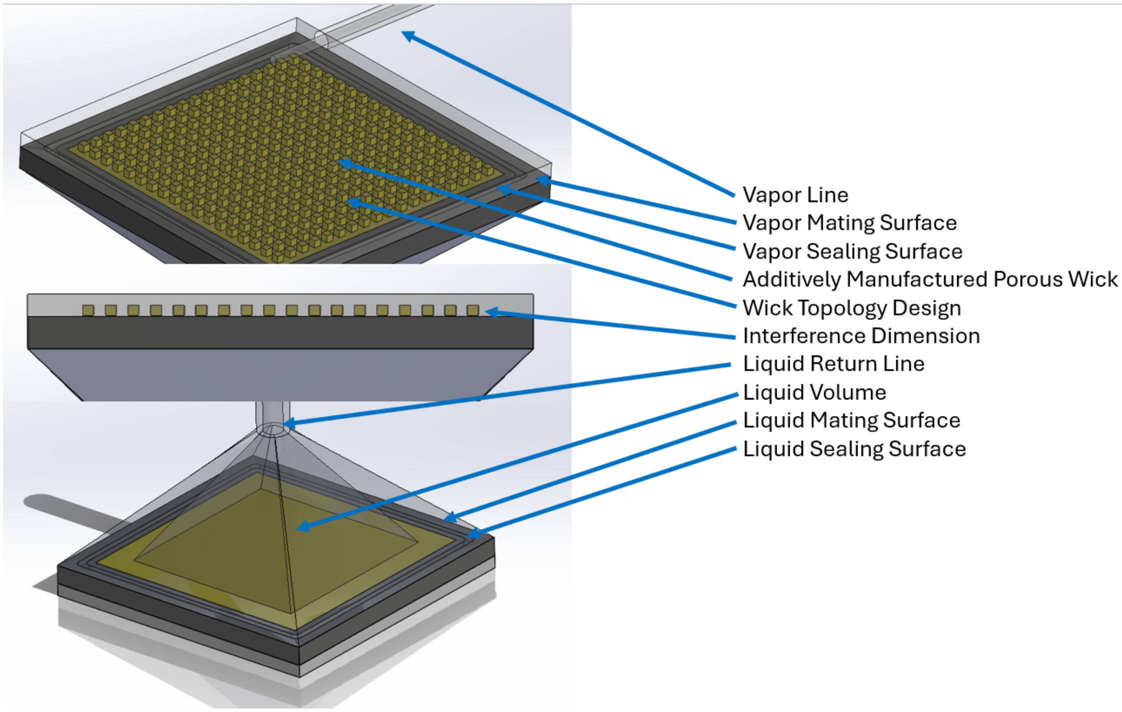

Figure 2: A Figure Demonstrating Several Key Design Considerations for the large scale implementation of assembled additively manufactured Two-Phase Loop type Evaporators

- Vapor Line: The Vapor Line must be located as to not interfere with the vapor mating surface or vapor sealing surface
- Vapor Mating Surface: The vapor mating surface must be designed to seal against internal or external pressure
- Vapor Sealing Surface: A seal must be selected to provide sufficient sealing pressure. Additional considerations include material compatibility, temperature range, expected lifespan, dimensional tolerance, and cost, among other standard design metrics for sealing surfaces
- Additively Manufactured Porous Wick: The manufacturing settings for the wick must be optimized to maximize the rate of evaporation, as specified in NPO 53642 Novel Geometric Considerations for Solid and Porous Design in Loop Heat Pipe Evaporators
- Wick Topology Design: The macro-scale wick topology must be designed to meet structural requirements of the mating surface. New considerations to this work include modulus of elasticity, poisons ration, and other mechanical properties of the porous structure.
- Interference Dimension: The wick structure must include an optimized interference dimension to provide maximum evaporation and heat transfer, while avoiding damage to the wick during assembly. Considerations include modulus of elasticity, poisons ration, and other mechanical properties of the porous structure.

- Liquid Return Line: The liquid return line is not modified in this design versus other two-phase loops
- Liquid Volume: The liquid volume is not modified in this design versus other two-phase loops
- Liquid Mating Surface: The liquid mating surface must be designed to seal against internal or external pressure
- Liquid Sealing Surface: A seal must be selected to provide sufficient sealing pressure. Additional considerations include material compatibility, temperature range, expected lifespan, dimensional tolerance, and cost, among other standard design metrics for sealing surfaces

In addition to these design considerations, several critical considerations are required for the design of the additively manufactured wick.

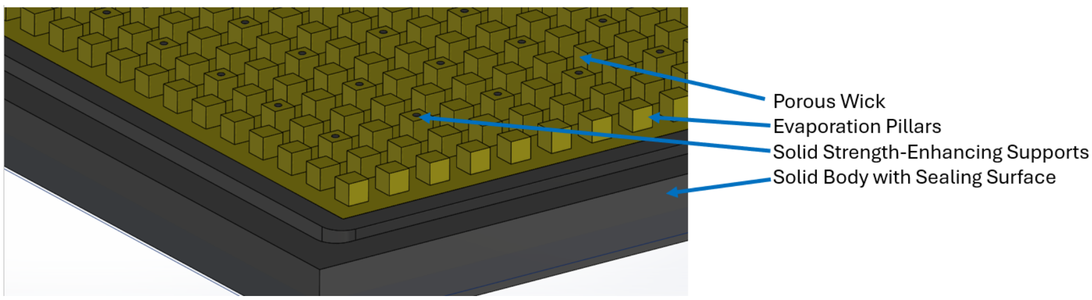

Figure 3: A Figure Demonstrating Several Key Design Considerations for additively manufactured wick, a key component in large scale manufacturing of two-phase loops

- Porous Wick: The design and manufacturing process for additively manufactured porous wicks is covered by several prior Caltech provisional patents and technology reports.
- Evaporation Pillars: The design of evaporation pillars within a porous wick is covered by a provisional patent and was discussed in NPO 53642: Novel Geometric Considerations for Solid and Porous Design in Loop Heat Pipe Evaporators
- Solid Strength-Enhancing Supports: The implementation of solid supports specifically to increase the material strength of the structure is novel. These are a critical component in the assembly process, which prevent cracking or damage to the porous wick during assembly.
- Solid Body With Sealing Surface: This is a novel design, wherein the wick is integrated into a solid body containing a sealing surface. Design factors include the depth, surface finish, and material of the mating surface, as well as the location. Additional sealing surfaces may be added internally to the wick to provide enhanced strength for high pressure applications, such as cooling applications involving ammonia or other high-pressure fluids, as well as to enable assembly of other novel geometries and additional applications where a heat source may be nonlocal.

Finally, several novel manufacturing constraints must be considered in the additive manufacturing process of the wicks. Some of these considerations are listed below.

- Total Part Quantity: A critical goal of this design and manufacturing process is to maximize the total part quantity. The process for manufacturing and positioning the integrated porous

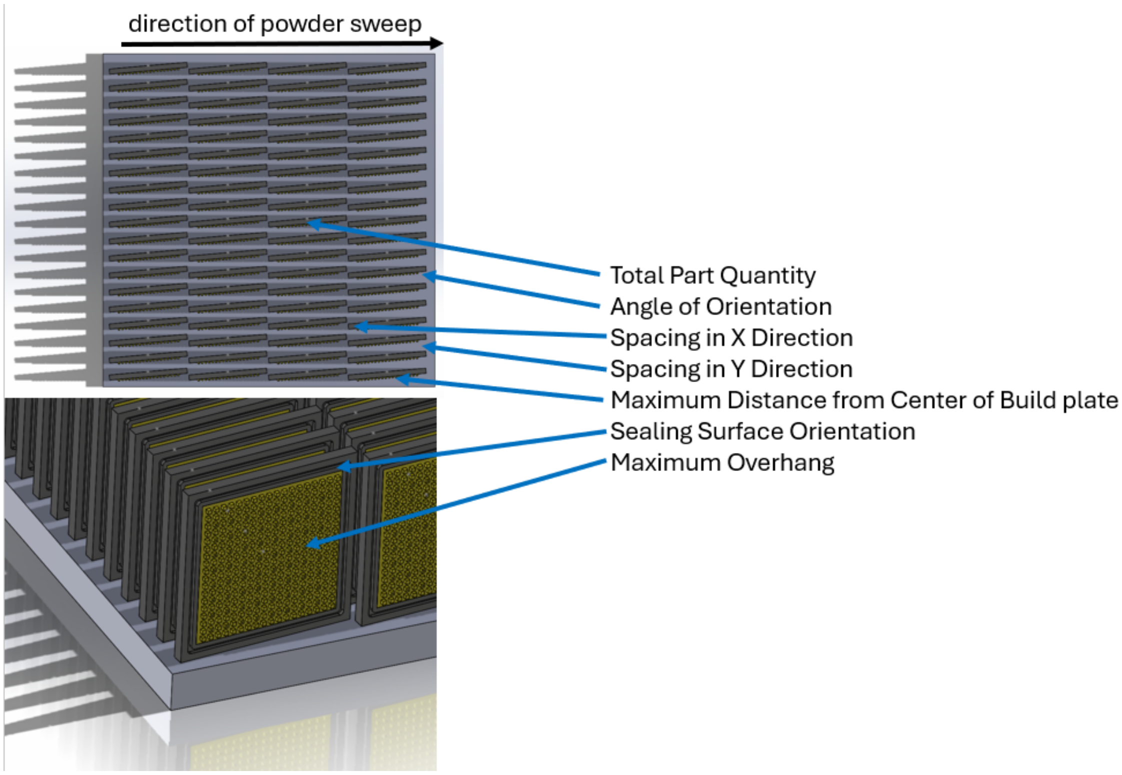

Figure 4: A Figure Demonstrating Several Key Design Considerations for additively manufactured wick, a key component in large scale manufacturing of two-phase loops

wick structures on the build plate is a critical consideration. This model is for 2"x2" parts on a 9.8"x9.8" build plate, matching a common model of industrial printers, but is applicable to all laser powderbed fusion printing technologies and printers, as well as some other additive manufacturing technologies, including all forms of laser sintering.

- Angle of Orientation: During laser powderbed fusion additive manufacturing, the powder is swept across the build plate between layers. The orientation of parts with respect to this direction is one design consideration in maximizing the total part quantity and throughput.
- Spacing in X direction: The spacing in the direction of powder sweep is critical to prevent part interference and ensure part quality, aiding in maximizing the total part quantity
- Spacing in Y direction: The spacing in the direction against the powder sweep is critical to prevent part interference and ensure quality, aiding in maximizing the total part quantity
- Maximum Distance from the Center of Build Plate: Research has demonstrated parts printed further from the center of the build plate are of lower quality. Ensuring parts near the edge of the build plate remain high quality is a critical consideration.
- Sealing surface orientation: The quality of surfaces printed in additive manufacturing has a substantial dependence on the orientation. Sealing surfaces should be oriented to maximize the surface quality to meet the specifications for the required seal, or, otherwise, be post-machined to meet required specifications. Sealing surfaces may be oversized during the initial printing process to accommodate for post-processing.

- Maximum Overhang: The shape and structure of the evaporation pillars must be such to minimize the risk of failure due to exceeding the maximum overhang available with the printing technology used. If used, support structures must be designed to not damage the porous wick, which may be extremely brittle and prone to cracking.

The invention report disclosed here explicitly refers to Two Phase Loops consisting of two or more components. While the most space-efficient method would be to exclusively manufacture the wick through additive manufacturing, other components may be additively manufactured as well. Following manufacturing, devices consisting of two or more components must be assembled. In addition to the critical evaporator components, additional items may be used during assembly, including compressible sealing surfaces such as O-rings, crush gaskets, vacuum gaskets, chemical sealants, or other mechanical sealing apparatuses, bolts, screws, rivets, or other mechanical fasteners, as well as tubing or other fluid-containment hardware.

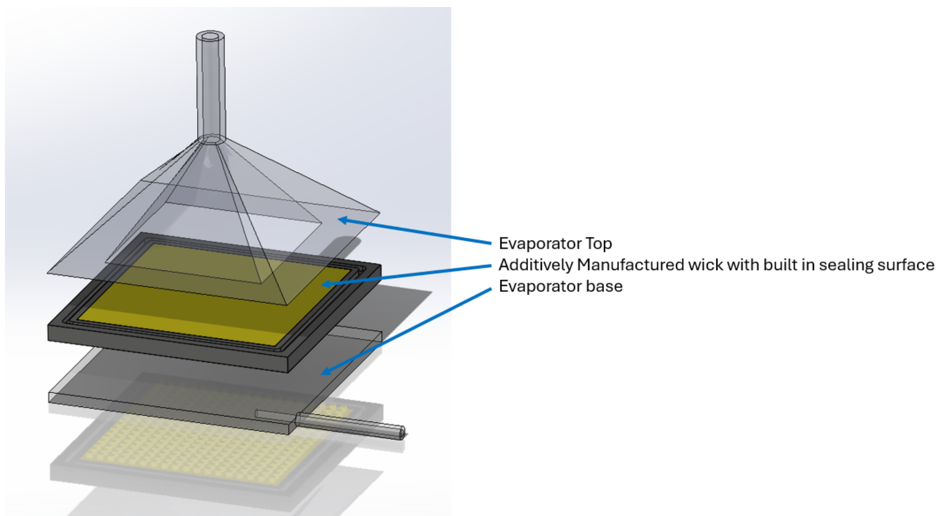

Figure 5: A diagram of a 3 component system

Additional alternative designs with benefit from this manufacturing method include the implementation of baseless evaporators, which may be mounted directly to computer chips or other heat sources to provdie direct two phase cooling if fluid compatibility allows, as well as two-component designs, which integrate the evaporator base through the additive manufacturing process, but retain a separate evaporator top, which is manufactured separately either though additive manufacturing or traditional processes.

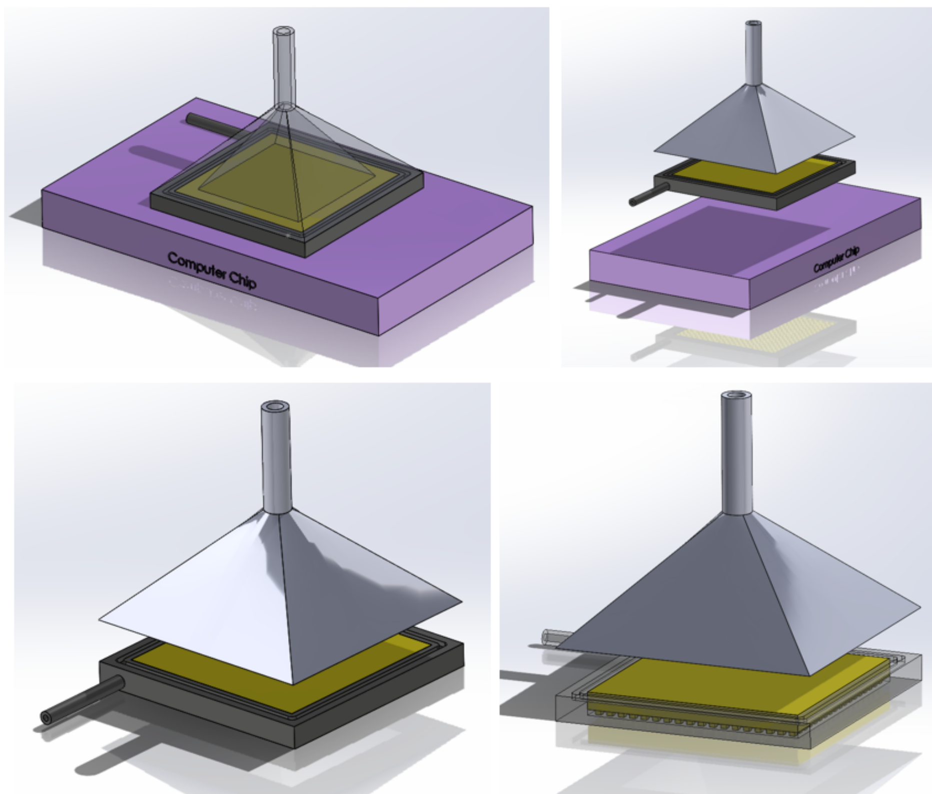

Figure 6: Example Alternative System Designs