Loop Heat Pipe with 3D Printed Evaporator Designed for the NASA VIPER Engineering Demonstration Unit

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Introduction

- A Loop Heat Pipe (LHP) featuring a 3D printed evaporator was designed, fabricated, and tested by Advanced Cooling Technologies, Inc. (ACT) with the purpose of serving as a heat transfer device in an Engineering Demonstration Unit (EDU) for NASA VIPER
- This effort served to project 3D printed evaporators as low-cost and low-lead-time alternatives to standard evaporators for LHP and to help establish confidence in this piece of technology for future use on flight hardware

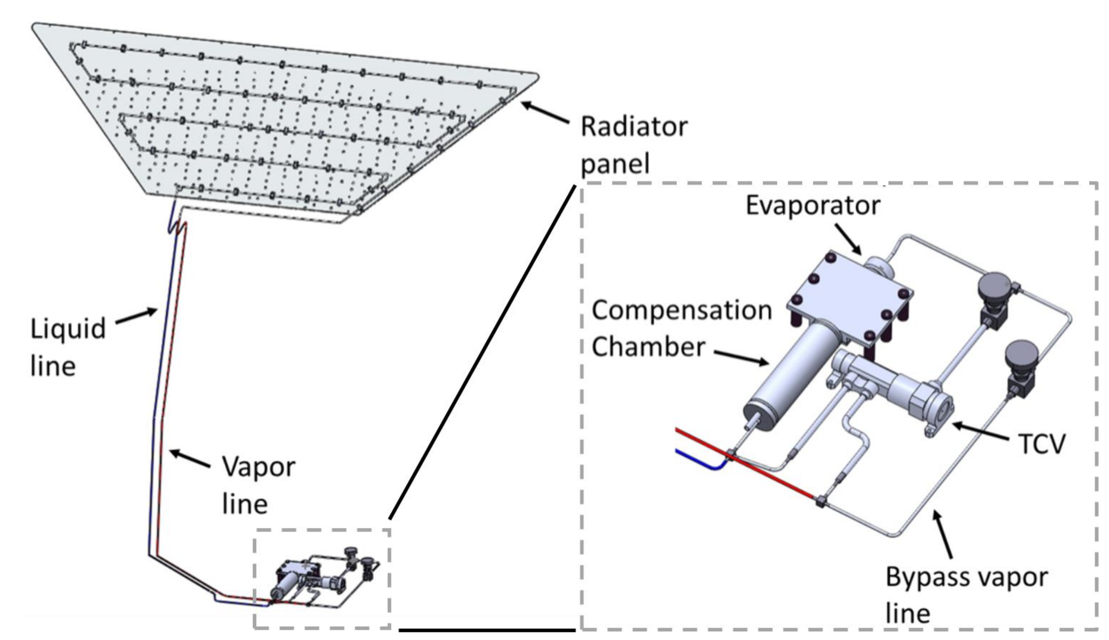

Figure 1. CAD rendering of the ACT 3D Printed LHP for NASA VIPER EDU

System Specifications

- Evaporator wick:
  - Material: 316L SS
  - Equivalent pore radius = 7.6 μm
  - Porosity = 29%
  - Permeability = 1.16 × 10^{-13} m^2
- Propylene was used as the working fluid
- A -10°C to 10°C PDT TCV valve was installed on the vapor line to bypass the radiator at low temperatures
- Expected mission thermal load of 50 W

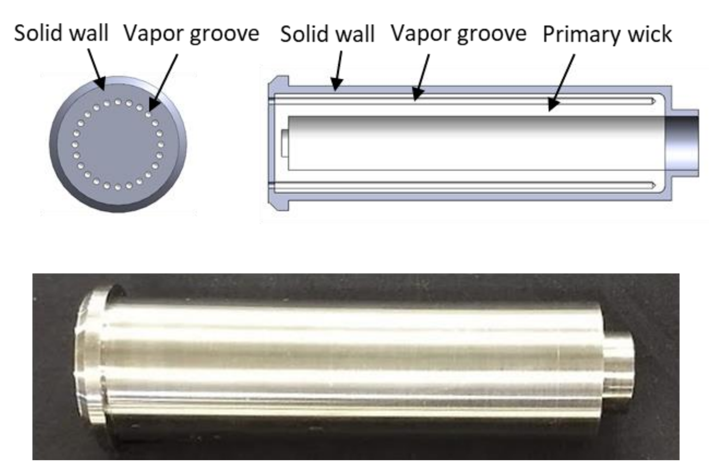

Figure 2. *(above)* CAD renderings with the front face and sectional view of the 3D printed evaporator; *(below)* A photo of the actual evaporator taken prior to installation

Table 1. Dimensions of the various LHP components

Parameter		Value
Evaporator	Material	316 L SS
	Diameter	0.025 m (outer)
	Length	0.1 m
Reservoir	Material	316L SS
	Diameter	0.038 m (outer), 0.002 m (thickness)
	Length	0.13 m
Fluid Lines	Material	316L SS
	Diameter	0.003 m (outer), 5 × 10^{-4} m (thickness)
	Vapor line length	3 m
	Condenser line length	6 m
	Liquid line length	2 m
Radiator	Material	Al 6061
	Area	0.525 m^2

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3D Printed Evaporator Development

- ACT has been conducting an R&D campaign to develop 3D printed evaporators with the motivation to minimize manufacturing costs and time by eliminating manual labor-intensive processes, such as wick fabrication, wick insertion, etc.
- Using Laser Powder Bed Fusion (LPBF), the evaporator is directly printed as one continuous part, complete will all the required features, such as the wick, vapor grooves, and the outer solid wall

Figure 3. A wick sample that was 3D printed as part of an ongoing evaporator development campaign conducted by ACT

- Initially, a dedicated wick advancement study was conducted to improve the wick capillary performance through iterative optimization of the LPBF parameters that modulate the laser energy deposition
- Several wick samples were printed in this effort spanning a wide range of porosities between 14% and 49% and equivalent pore radii between 4.9 μm and 27 μm, measured at bubble point
- Sample 3 wick was chosen for the current evaporator due to favorable porosity and capillary limit combination

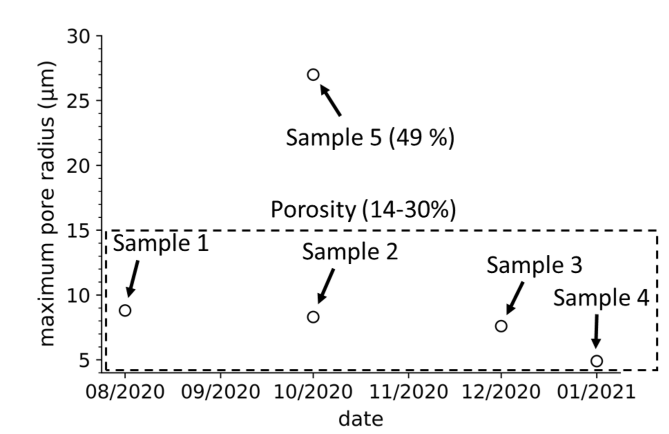

Figure 4. ACT wick development timeline showing significant capillary improvement

System Testing

- Figure on the right shows the fully-fabricated LHP installed on the shipping rack and ready to be shipped to NASA for thermal-vacuum testing
- Prior to shipping, however, the system was tested at ACT under the following test conditions:
  - Radiator panel cooled using a cold plate attachment to near 0°C
  - Step increase in thermal load starting from 20 W
  - Operation in the expected reflux orientation through bypass

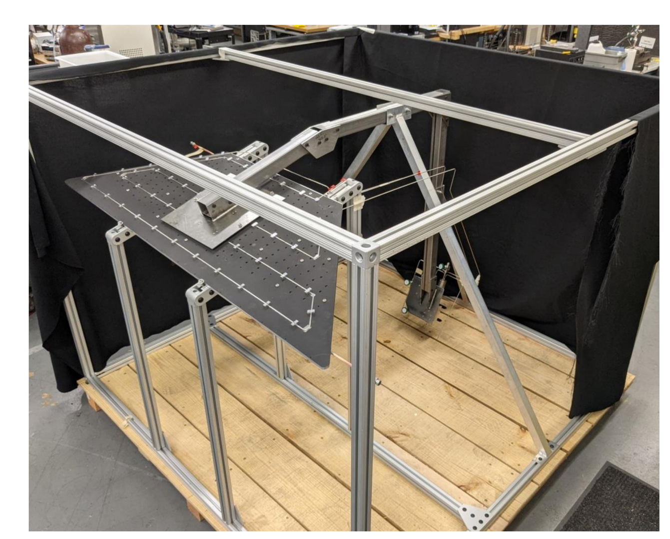

Figure 5. Fully-fabricated LHP installed in the shipping rack prior to delivery to NASA

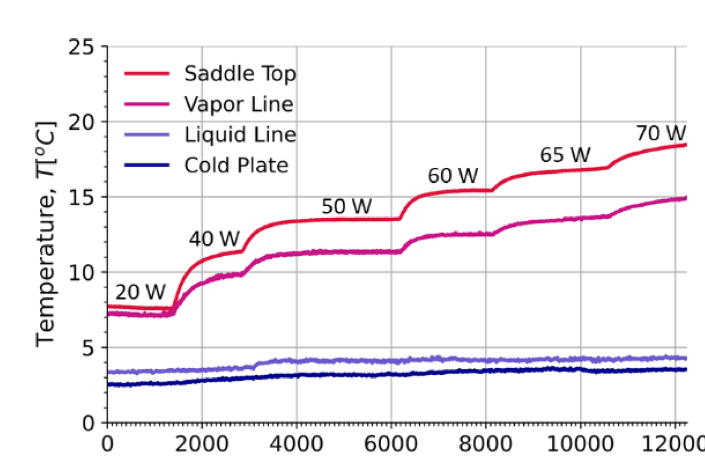

Figure 6. Select temperature profiles acquired during testing of the LHP at ACT

Results

- LHP tested successfully up to a thermal load of 70 W, which was the highest power setting used during testing
- Near flat system conductance of ~5.5 W/°C, based on the temperature difference between the evaporator and the cold plate
- System conductance largely affected by inadequate insulation on the liquid line leading to a significant jump in the temperature between the condenser exit and compensation chamber inlet

Startup Behavior

- During testing, it was observed that the LHP startup required a minimum threshold thermal load, which seemed to depend on the condenser temperature
- In order to further investigate this behavior, a series of dedicated startup tests were conducted on a "test" LHP system, which was configured to be similar to the LHP for NASA VIPER EDU
- The startup power was seen to increase monotonically with decreasing condenser temperature

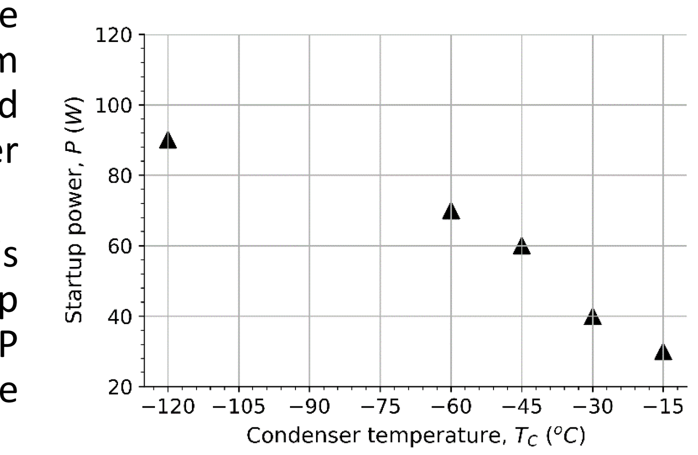

Figure 7. The variation in startup power with condenser temperature for test LHP

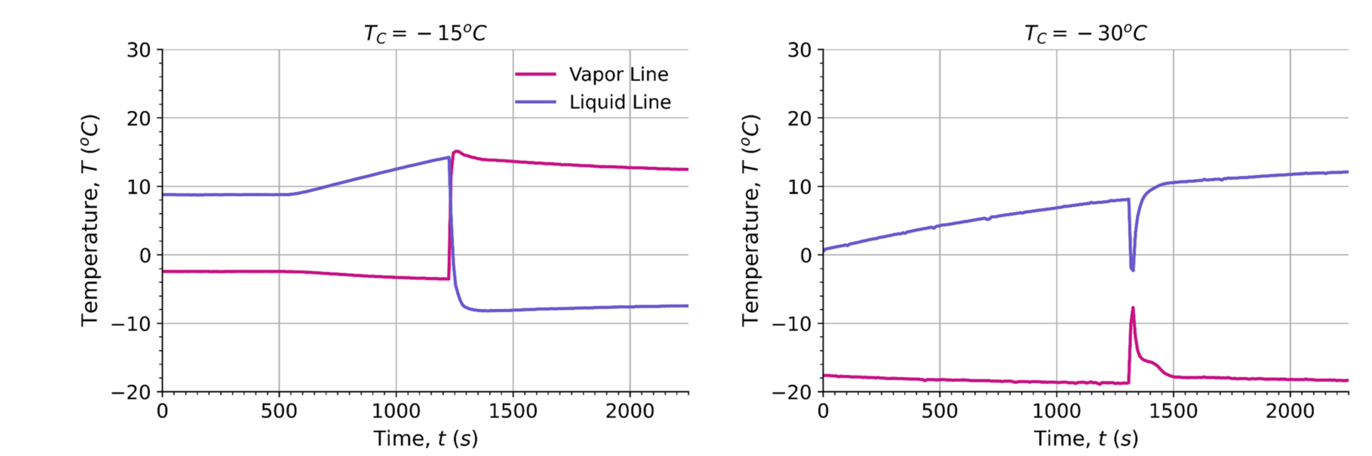

Figure 8. Temperature profiles corresponding to startup attempts of the test LHP with a thermal load of 30 W at two different condenser temperatures of (*left*) -15 °C and (*right*) -30 °C

- The startup power dependance stems from the current LHP configuration in which the evaporator is installed below the compensation chamber
- A two-phase interface appears in the compensation chamber with the evaporator completely flooded with sub-cooled liquid prior to startup
- With condenser cooling, the LHP begins to operate in reverse as a loop thermosyphon, as seen in the results
- For forward operation, the applied heat load must therefore, be sufficiently large to force vaporization in the primary wick and produce the required capillary locking

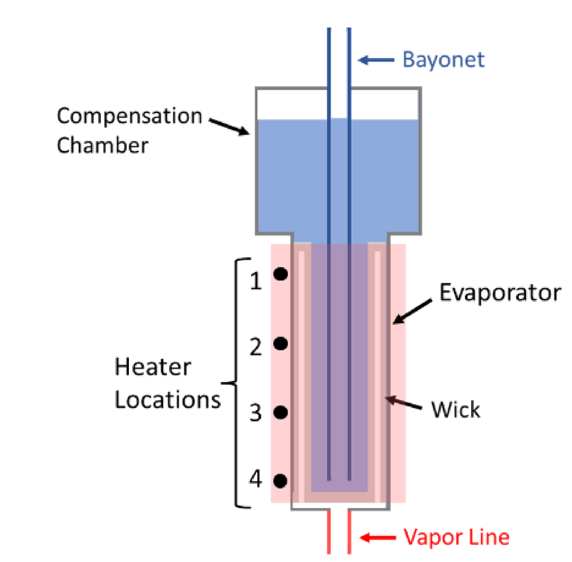

Figure 9. A schematic showing the configuration of the LHP evaporator and compensation chamber

On-going Development

- A significant effort is being directed towards the improvement of the thermal conductance of the evaporator through the use of bi-porous wicks and advanced vapor groove designs
- A combined primary and secondary wick part is being developed to further minimize LHP manufacturing costs
- The miniaturization of the 3D printed evaporator is also being pursued with the goal of developing cost-effective LHP systems for small satellites
- A final effort is being made towards finding a suitable flight opportunity

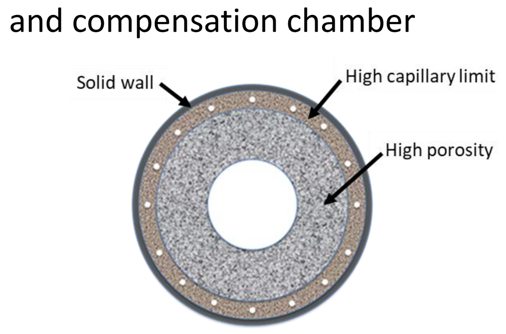

Figure 10. A schematic of a bi-porous wick design

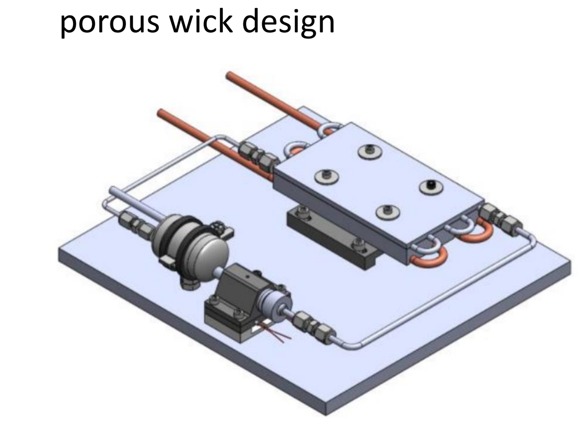

Figure 11. A CAD rendering of a mini LHP system design