Additive Manufactured Titanium-Ammonia Heat Pipes for Thermal Management of Space Electronic Devices

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In the frame of the ESA project AO-6896, novel 'gravity friendly' additive manufactured heat pipes were developed and tested. The technology utilizes laser powered bed fusion (LPBF) additive manufacturing (AM) technique to construct titanium-ammonia heat pipes with integrated micro-scale lattice capillary wick structures. Laser parameter optimisation trials and capillary lift height experimentation enabled miniaturisation of the lattice structure cell size to below the current state-of-the art processes. This enabled a level of capillary pumping against gravity, whilst achieving the specified 30 W direct thermal management of a simulated microprocessor. The AM heat pipe technology is the first of its kind and has been granted European Patent No. 2715265. This paper presents an overview of the technology and gives a comparison against a stainless steel, ammonia heat pipe, with a screen mesh capillary wick structure, that was developed in parallel to the AM heat pipe.

Nomenclature & Acronyms

AM	=	*Additive Manufacture*
LPBF	=	*Laser Powder Bed Fusion*
Q	=	Power
ΔT	=	Temperature Difference
T	=	Temperature
TMS	=	*Thermal Management System*

Sub-Scripts:

max	=	*Maximum*
min	=	*Minimum*

I. Introduction

IN the frame of the ESA project AO-6896 '370-400 K Gravity-Friendly Heat Pipe with Low Freezing Temperature', novel additive manufactured (AM) titanium-ammonia heat pipe technology for thermal management of future space electronics payloads has been developed and compared against novel conventionally manufactured stainless steel heat pipes with screen mesh capillary wick. AM heat pipe technology offers an increased level of integration of the two-phase thermal management system (TMS) into the chassis elements and enables direct thermal management of the electronics components. In addition, the technology enables an increased level of functionality against gravity, easing ground testing. Both AM and screen mesh heat pipe capillary wick structures offer enhanced evaporator heat flux versus aluminium-ammonia, grooved wick heat pipes, enabling direct thermal management of electronics component (Figure 1 & Figure 2). The project has produced a first generation, additive manufactured titanium-ammonia heat pipe technology, with patented AM wick structure [1].

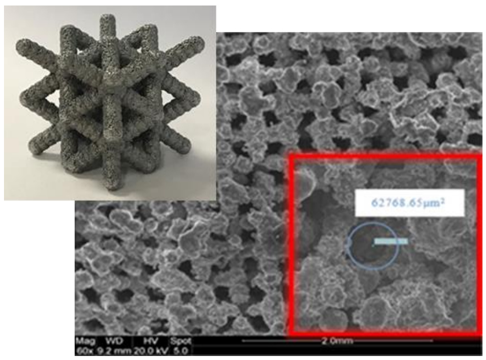

Figure 1: Additive Manufacture Lattice Cell Representation an SEM Image of Microscale AM Heat Pipe Wick Structure

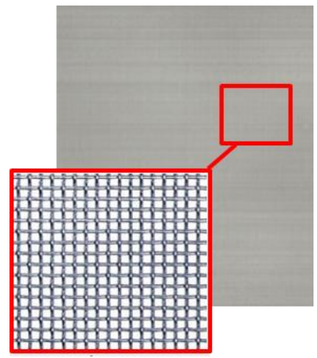

Figure 2: Stainless Steel Fine Woven Wire Mesh Wick Material

II. Overall Project Overview

Future telecommunications satellite payloads are expected to realise a step-increase in power dissipation, requiring novel thermal management techniques. Ammonia heat pipes are heavily deployed at platform level within radiator panels, as surface mounted heat pipes and as thermal links, however they are prohibited from integration into electronics chassis and direct thermal management of micro-electronics, due to low evaporator heat flux limit of the extruded axially grooved capillary wick, low maximum operating temperature (suggested T_{max} = 90 °C) and inability to function against gravity on ground test. Novel gravity friendly heat pipes offer a means of direct thermal management of future payloads. In this study, the first additive manufactured heat pipes were created, therefore the heat pipe vessels were maintained as circular, tubular components, that were assembled with 40 mm x 40 mm aluminium saddles that provide direct thermal management of a simulated microelectronic components (heater block) (30 W at $T_{adiabatic}$ = 80 °C),. Similarly the condenser region of the three heat pipes (length = 200 mm) were assembled onto a second saddle, that could potentially interface with a region of an electronics chassis or directly onto a secondary thermal management system. Future applications of the technology will deoploy more complex heat pipe designs such as vapour chamber heat pipes, that can be integrated into the electronics chassis and potentially could integrate secondary features, such as mass reduction, by replacing solid CNC machined walls, with lattice style walls.

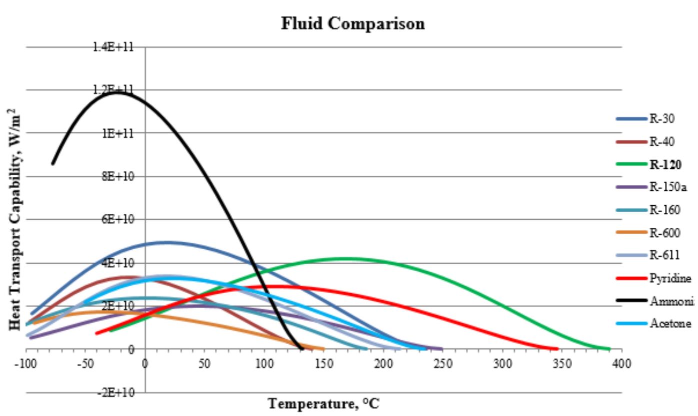

Figure 3: Heat Transport Capacity Curves for Various Considered Working Fluids (Aavid UK)

The ESA project's main objective were to identify, develop and complete qualifiation testing on new heat pipe technologies, with gravity friendly wick structures that are capable of extending the functional temperature range above that of ammonia and overcoming the ground test challenges faced by non-gravity friendly heat pipes, by expanding the functionality limits when operating at adverse tilt. The main focus of this paper is the development of gravity friendly additive manufactured heat pipes, with integrated AM lattice wick structures. However, although not discussed in detail in this paper, novel materials and fluids combinations (Figure 3) were investigate to increase the operating temperature range to greater than 120 °, whilst maintaining as freezing point < 0 °C (e.g. -40 °). In addition, enhanced screen-mesh wicked, stainless steel-ammoia heat pipes were investigated and compared against the AM heat pipes. A secondary aim was to enable heat pipe integration into the electronics chassis to enable direct thermal management of microprocessors. Regarding the working fluid selection, the maximum transport capacity of ammonia occurs between 80 °C and 90 °C, therefore limits the appications of the technology, however ammonia was utilised as it has extensive space flight heritage. In a second study, the authours have extended the functional temperature range above the maximum operating temperature of most microprocessors (T_{max} > 120 °C) by deploying water as the working fluid. Water also gives a step-increase in thermal transport capacity, but is non-functional below 0 °C, so was out of the scope of this study. It should be noted that freeze-thaw testing of copper-water heat pipes have been extensively tested by the Aavid and are qualified for space flight.

The major innovations of was the development of lattice structure additive manufacturing techniques to enable microscale pore sizes that are able to function as a heat pipe capillary wick structure. Characterisation of the capillary wick structures was completed enabling the lattice capillary structures to be deployed in first generation space heat pipe assemblies, that successfully completed qualification testing to the ESA project specifications. The investigation was conducted in two phases; phase 1 investigated a range novel heat pipe wick & fluid options and phase 2 developed and qualification tested additive manufactured titanium-ammonia heat pipes and stainless steel, screen mesh ammonia heat pipes.

III. Gravity Friendly Heat Pipe development

A. Additive Manufactured Heat Pipe Development

The laser powder bed fusion (LPBF) additive manufacturing process functions by laser melting 2D solid patterns into sequential layers of metal powder to form complex 3D geometry. The development of additive manufactured heat pipes utilizes the 3D design flexibility of the LPBF process, to enable complex mechanical designs. An introduction to the LPBF process and preliminary AM heat pipe feasibility investigations was presented by the authors of this paper in 2013 [2].

The major challenge in realizing AM heat pipes is the production of sufficiently small wick pore sizes, that enable capillary pumping against gravity. The capillary wick development focused on miniaturisation of lattice cell structures and laboratory characterisation of the capillary structures. At the onset of the project, the minimum lattice cell size produced by additive manufacturing was too large to enable capillary pumping against gravity. Cell size reduction was achieved by conducting laser parameter developments, utilising custom software to programme and complete multiple lattice build trials, with customised laser parameters, defined to each build sample. A series of AM wick test pieces were constructed with lattice cell sizes ranging from 700 µm to 200 µm in 50 µm steps. The associated cell size at 700 µm is too large to enable capillary pumping against gravity and at 200 µm, the lattice becomes a closed cell structure. The optimum lattice size to balance capillary lift height against mass flow rate was determined experimentally.

An example of a AM laser parameter trial plates, building porosity & permeability test pieces, is shown in

Figure **4**. It can be seen in the left image that towards the bottom left of the plate, the laser power and time are too high, resulting in solid blocks, where in the top right of the image, laser power and time, is too low resulting in failure of the components. Characterisation testing and examination of the successful builds, allows the optimized parameters to be defined, allowing a full, successful build plate to be created (right side image).

Figure 5 shows an example of an AM build plate, of two AM heat pipe versions with and without fill tubes. The internal structure incorporates a lattice wick around the vessel wall and stress reduction features to accommodate the ammonia saturation pressure. Achieving a hermetically sealed vessel, mass reduction and LBPF minimum feature size, led to the selection of titanium as the preferred AM powder material. To enable the main focus to be on the capillary wick development, a simple circular tube design was selected for the heat pipe. A CNC machining allowance was added to enable a tolerance fit with aluminium evaporator and condenser saddles in the final test piece assembly.

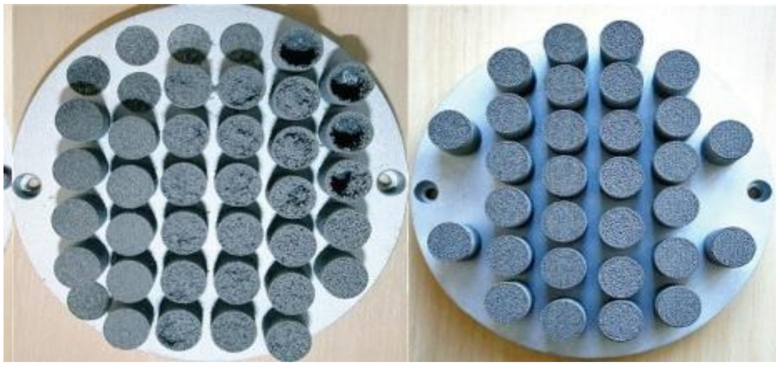

Figure 4: Preliminary Laser Parameter Build Plate and Optimised Laser Parameter Build Plate Examples

Figure 5: Example AM Heat Pipe Build plate

B. Screen Mesh Wicked Heat Pipe Development

To provide a benchmark comparison against the AM heat pipes an evaluation and trade-off study was completed that identified manufactured and tested a range of promising heat pipe technologies. The trade—off study was reviewed with ESA and and the lowest risk / highest chance of adoptation technology was selected for development and benchmarking against the AM heat pipe technology. Various technologies that may be progressed in the future included a high temperature copper-methanol heat pipes and a new working fluid that potentially enables very high operating temperatures, with low freezing point and equivalent thermal performance to ammonia. Copper-methanol heat pipes were deselected as at the time of the work, laser powder bed fusion of copper to create the required pore sizes was not possible, as titanium is higher strength than copper, the ultimate mass would be lower for titanium. Also, the heat transport capacity for methanol is significantly lower than that of ammonia at 90 °C, although methanol can function with low risk of failure at temperature up to 110 °C. The potential high performance working fluid was de-selected as the required materials & fluid compatibility and qualification programme was out of the scope of the study.

Various screen mesh wicked heat pipe configurations were examined including copper, aluminium and stainless steel vessels, that would enable an increase in evaporator heat flux over aluminium grooved wick heat pipes. Typically the pore size of screen mesh wicks is large, providing a large mass flow rate of condensate, enabling high power transport, but limits functionality against gravity due to low capillary pressure.

Ultimately, the final benchmark heat pipe selection was to develop a novel heat pipe with fine pore size stainless steel screen mesh wick. To avoid galvanic corrosion, stainless steel was also used as the vessel material and to allow comparison against the additive manufactured heat pipes, ammonia was selected as the working fluid.

C. AM Lattice Wick Structure

To identify an appropriate specification for the AM wick structure, existing heat pipe capillary wick technology was evaluated. Aluminium-ammonia constant conduction heat pipes (CCHP's), with extruded smooth axially grooved heat pipes have extensive heritage in space applications such as large telecom satellites (150 to 300 per satellite). Evaluating the groove wick structure, the minimum characteristic dimension is too large to enable functionality against gravity and the material surface is smooth, limiting the maximum evaporator heat flux to ≤10 W/cm^2 for ammonia (Figure 7). Screen mesh wick structures as shown earlier in Figure 1, offer an increase in surface heat flux to 15 W/cm^2 (water) due to increased surface area, with limited functionality against gravity. The mesh fibre surfaces are smooth, limiting nucleation heat transfer. Sintered powder capillary wicks enable high heat fluxes (50 W/cm^2; water)

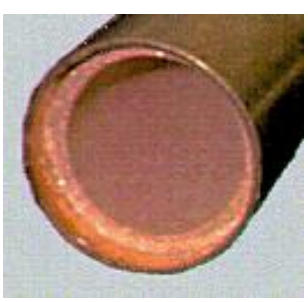

Figure 6: Sintered Powder HP (Aavid)

Figure 7: Axially Grooved HP Wick (Aavid)

and excellent functionality against gravity, due to fine pore size / high capillary pressure and a large rough surface area that enhances nucleation (Figure 6). However typically sintered heat pipes are manufactured from copper therefore mass and incompatibility with ammonia as a working fluid are challenges.

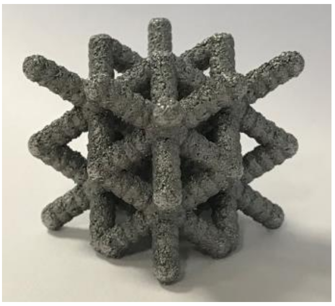

Figure 8: Lattice Demonstrator (≈ 25 mm)

Although sintered heat pipe wick structures are able to evaporate high surface heat fluxes, the small capillary pore size limits the mass flow rate of the returning condensate, therefore AM lattice wick miniaturisation is seen as a strong candidate to balance pore size and mass flow rate, increase nucleation heat transfer and create a 3D tailored wick, that would allow the required ESA 30 W power transport specification to be met, whilst enabling a level of enhanced functionality against gravity over screen mesh wicks.

The construction of lattice wicks is visualized in Figure 8**Error! Reference source not found.**. It can be seen that the lattice is formed by eight interconnecting wires, which effectively create an eight faced lattice structure, with both a large internal cell size and smaller pores through the face cavity. Miniaturisation of the lattice cell size is illustrated in figures Figure 9 & Figure 10. The porosity & permeability test pieces were utilized to characterise the lattice structures, manufactured with different laser parameters. A solid 0.3 mm wall is included to prevent bypass flow during the tests. The final heat pipe is effectively similar, but with a hollow bore to enable vapour flow, as illustrated in Figure 11.

In addition to porosity, permeability and pore size measurement, transport of the working fluid is a major parameter that enables the functionality of the heat pipe. Based on the 'half-pipe' technique, multiple test pieces with different cell size and laser parameter lattice wicks were manufactured and tested using a novel test technique that enabled visualization of the capillary pumping of the working fluid through the wick structure and measurement of the mass flow rate of fluid being capillary pumped. An example of a capillary wick lift height test piece is shown in Figure 12. The wick parameters are graded between each test channel. A coarse lattice is shown that may be more suitable for high power applications and a dense sample is highlighted, where the material has a closed cell structure, preventing the wick from capillary pumping the working fluid. The optimized cell size, to maximize lift height was selected (tailored to the application) and balanced against the 10 W transport power specification per heat pipe. An example of IR Imaging, showing the progression of the water flowing vertically against gravity through the test pieces to a lift height of 80 mm can be seen in Figure 13.

Figure 9: Lattice Cube with 1.5 mm Cell Size & Ø12.7mm Miniaturised Lattice Test Piece with 0.3 mm Solid Wall

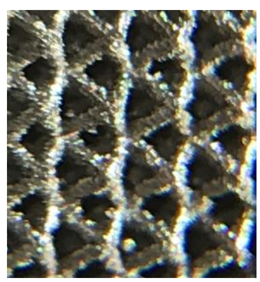

Figure 10: Detailed View of Miniaturised Lattice Cells

Figure 11: AM Heat Pipe Half Pipe, Lift Height Test Piece

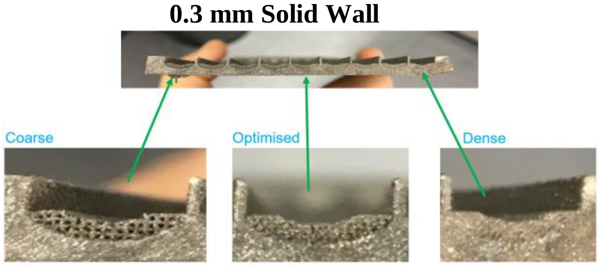

Figure 12: Coarse, Optimised and Dense Lift Height Test Pieces

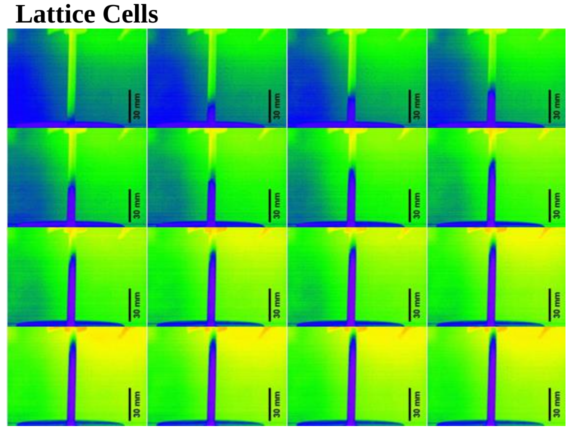

Figure 13: Example of IR Imaging of Capillary Pumping Progression of Water Vertically Against Gravity, Through an AM Capillary Wick Structure.

D. Breadboard Heat Pipe Test Pieces & Assemblies

Qualification testing was completed on both the individual heat pipes and on a representative qualificaiton heat pipe assembly consisting of three heat pipes (Ø8 mm x 200 mm long), bonded using a space qualified thermal epoxy to mass optimized aluminium evaporator and condenser saddles (40 mm x 40 mm), that interfaced with the heat source and liquid cold plate within the test rig's test section (Figure 14). The heat pipe assemblies were designed to meet the ESA project specification, to transport a 30 W heat load a distance of 200 mm. The saddles designs were optimised to reduce mass and include fixing lugs that in allowed the heat pipe assembly to be to apply the required compression load to a thermal interface material. To allow comparison between the screen-mesh and the AM wicked test pieces, the mechanical designs were similar. In an actual application, the heat pipe assembly potentially would be replaced with a single piece AM vapour chamber, to maximise the thermal performance of the component and eliminate the epoxy bonds. A series of AM heat pipe test pieces is shown in Figure 15 and an AM heat pipe undergoing ammonia charging process is shown in Figure 16.

Figure 14: AM Heat Pipe Assembly Breadboard Test Piece (Titanium-Ammonia)

Figure 15: AM Heat Pipe Test Pieces

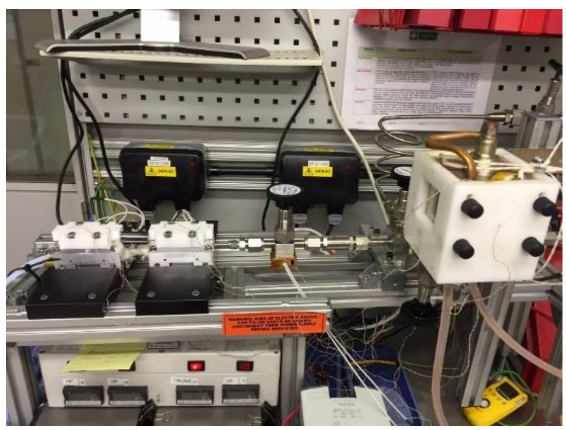

Figure 16: AM Heat Pipe Ammonia Charging

IV. Qualification Testing

Extensive qualificaiton testing of the wick structures and heat pipe test pieces was completed as per the ESA project (AO-6896) requirements. Qualificaiton testing was in align with ESA ECSS Standard ECSS-E-ST-31-02C requirements [3]. Manufacturing acceptance tests included proof pressure test (76 Bar), burst pressure test, helium leak detection, X-ray inspection, charge mass optimisation & liquid slug test, heat pipe sealing development, non-condensable gas test + ageing and burn-in tests. Tests on the completed heat pipes and breadboard heat pipe assemblies included proof pressure at temperature test, lifetime at temperature test, thermal characterisation, mechanical tests such as thermal cycle testing and vibration testing. At the end of the test campaign, an ammonia leak test and final thermal tests were completed to identify any variations in performance created by the induced mechanical stresses.

Although no significant variation in thermal performance was observed after the mechanical tests, it was interesting to observe that a slignt improvement in performance could be seen in the 30 W test data after vibration testing (ref. Table 2). This potentially may be due to entrapped AM poweder being vibrated out of the wick, improving capillary flow. As the tests completed were extensive, the test data presented in the following section is limited to the final qualification tests including pre-and post mechanical test, thermal test data for the AM heat pipe.

Regarding functionality against gravity, the titanium-ammonia AM heat pipes, with lattice wick structure demonstrated functionality against gravity at angles of -15°, versus a maximum angle of -2° for the stainless steel, ammonia heat pipe with screen mesh wick structure. One AM heat pipe was observed to function at an angle of -20°, against gravity indicating there is scope to further improve over the first geration AM heat pipe technology. In addition, it was demonstrated that, due to higher surface tension, utilising water as the working fluid enables functionality vertically against gravity up to a minimum lift height of 80 mm (maximum height of the test piece examined as a functional heat pipe).

A. Vibration Testing

Both the stainless steel screen mesh and AM titanium heat pipes and heat pipe assemblies were exposed to vibration frequencies that simulated potential launch conditions as shown in Table 1. The individual heat pipe test pieces successfully passed all vibration tests in all orientations. The heat pipe assemblies passed the test without observing any resonant frequencies in the X and Y in-plane, directions. However in the Z-direction, high-Sinusoidal vibration induced small changes to the resonance frequency peaks within acceptable limits. Random vibration induced higher changes to the resonance peaks, potentially due to the formation of micro-cracks in the epoxy joints. As the thermal performance of the test piece was unaffected, the change in resonance is acceptable. The high sinusoidal (z-direction) and Resonance Trace are shown in Figure 17 and Figure 18..

It is noted that the ESA vibration specifications do not account for the mass of the electronics equipment or chassis, therefore are more severe than expected in an application. For this reason, the Z-direction resonance frequencies potentially won't be induced in the end application. A stiffener can be integrated into the heat pipe assembly design to eliminate the issue.

Table 1: Vibration Test Specification

Sinusoidal vibration qualification test levels:

Frequency (Hz)	Level	Sweep rate	First frequency > 100 MHz	First frequency ≤100 MHz
5 to 21	11 mm (0 to peak)	2 octaves / minute, 1 sweep up	No notching	With notching
21 to 60	20 g (0 to peak)		No notching	With notching
60-100	6 g (0 to peak)		No notching	With notching

Random vibration qualification test levels:

Location	Duration	Levels	
Equipment not located on external panel[a]	All axes 2,5 min/axis	(20 - 100) Hz	+3 dB/octave
		(100 - 300) Hz	PSD(M)[c] = 0,05 g2/Hz × (M+ 20 kg)/(M + 1 kg)
		(300 - 2 000) Hz	-5 dB/octave

[a] Panel directly excited by payload acoustic environment.
[b] Equipment vertical axis = perpendicular to fixation plane.
Equipment lateral axis = parallel to fixation plane.
[c] M = equipment mass in kg, PSD = Power Spectral Density in g2/Hz.

Vertical Axis			Lateral Axis		
Frequency (Hz)	Level	Composite	Frequency (Hz)	Level	Composite
20-100	+3 dB/oct	26.8 g rms	20-100	+3 dB/oct	17.34 g rms
100-300	1.26 g^2/Hz		100-300	0.525 g^2/Hz	
300-2000	-5 dB/oct		300-2000	-5 dB/oct	

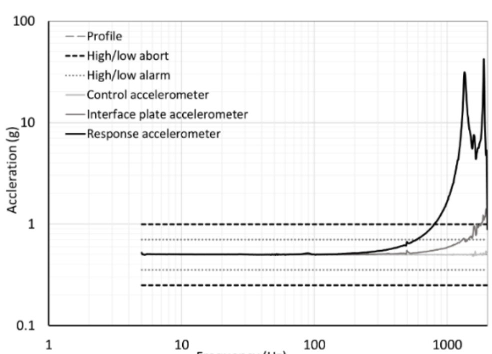

Figure 17: Resonance Trace (z-direction)

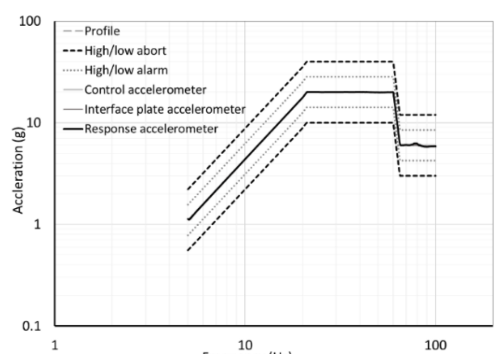

Figure 18: High-Sinusoidal Vibration Test (z-direction)

B. Heat Pipe Assembly Thermal Cycle Tests

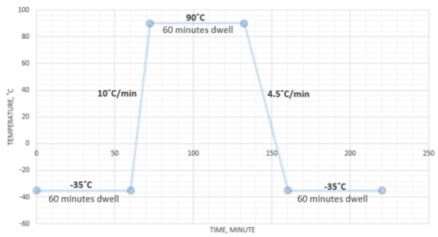

Figure 19: Thermal Cycle Test Profile

The AM-Titanium heat pipe assembly and stainless steel screen mesh assembly were subjected to eight thermal cycles between -35 °C and +90 °C, with a 1 hour hold at each temperature extreme. The thermal cycle profile is shown in

Figure 19. The tests aimed to observe mechanical failure due to thermal cycle induced mechanical failure, such as cracking of epoxy joints, delamination or damage to the wick and bulging of the heat pipe vessels. Degradation potentially is observed in the form of dimensional or thermal performance deviations versus the pre-thermal cycle condition. Mechanical degradation was not observed and post-cycle thermal performance test data did not indicate failure of the test pieces, therefore the test was successfully passed.

C. Heat Pipe Assembly Thermal Test Data and Test Assembly

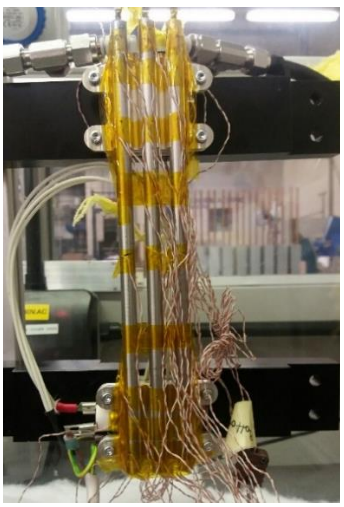
Figure 20: Stainless-Steel HP Assembly Test Section

The assembled test section for the stainless-steel-ammonia, screen mesh wicked heat pipe assembly is shown in Figure 20 (insulation removed). The test section consist of an electrical heater and liquid cold pate that interface with the evaporator and condenser saddles of the heat pipe assembly. The test section is mounted onto a rotating framework, allowing the test angle to be adjusted and measured using a digital inclinometer. As the tests were completed in ambient atmosphere, the electrical input power was elevated, to account for losses, to ensure the correct transport power was transferred by the test piece. The transport power was measured experimentally during each test by carrying out an energy balance on the fluid flow through the condenser end liquid cold plate. As the evaporator input power is elevated, this test method operates the heat pipe, beyond operational conditions in a vacuum.

Twenty-seven thermocouples were attached across the heat pipe assembly at the locations shown Figure 21. It can be seen that thermocouples were attached across the evaporator, adiabatic and condenser regions of each heat pipe and across the solid evaporator and condenser block materials to allow the heat pipe temperature differences and overall temperature difference for the assembly to be measured. Inlet and outlet thermocouples were inserted directly into the coolant flow to measure the the coolant temperature rise and a corriolis mass flow meter was utilised to measure the coolant mass flow rate.

A comparison of the thermal performance of the AM heat pipe assembly against the pre-mechanical tests condition is shown in Table 2 for a test angle of -0.3 °C to simulate the in-orbit performance. Tests were completed at power loads of 20, 25, 28 and 30 W at a constant heat pipe evaporaotor temperature of ≈ 90 °C, to observe the progression of the heat pipe performance data.

The temperature difference across each individual heat pipe was monitored as well as the overall heat pipe assembly temperature difference. Comparing the pre- and post-vibration test data, that the results are similar. At the maximum power load, the overall temperature difference observed was slightly reduced, but was within the thermocouple measurement accuracy.

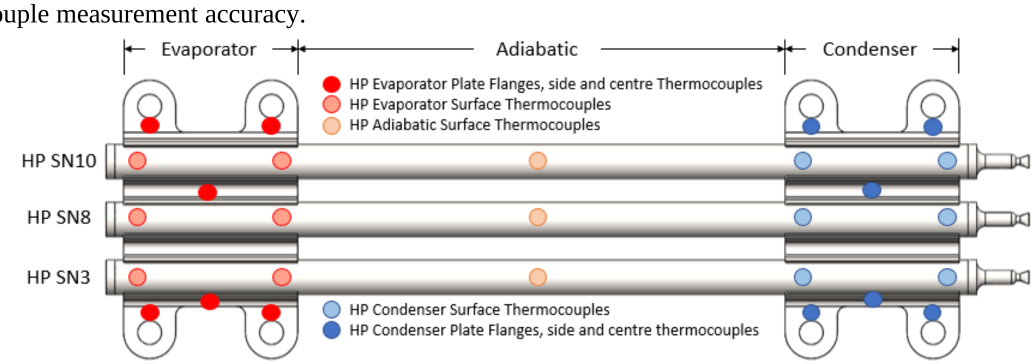

Figure 21: Thermocouple Locations Across the Heat Pipe Assembly Test Pieces

Comparing the pre- and post-vibration test, thermal test data with the post-thermal cycle test data, an increase in operating temperature was observed, however at the maximum transport power of 30 W, the overall temperature difference of the mini-heat pipe assembly was 8.94 °C. The temperature increase over the pre-vibration test condition of 0.54 °C was within the accuracy of the thermocouples, therefore no significant degradation in thermal performance was induced by exposure to vibration testing or thermal cycle temperature limits, indicating that the test piece have successfully passed the qualification test.

Table 2: Thermal Test Data for AM Heat Pipe Assembly, Pre- & Post-Vibration& Post-Thermal Cycle Tests

	Power Input (W)	Power Output (W)	Heat Loss	Target Power (W)	Evaporator Flange Average (°C)	SN3 ΔT (°C)	SN8 ΔT (°C)	SN10 ΔT (°C)	Assy. Ave ΔT (°C)
Pre-Vibration Test	28.5	20.33	28.67%	20	82.21	2.44	3.96	2.55	2.98
	33.2	24.91	24.98%	25	87.33	3.39	6.03	3.55	4.32
	36.7	27.75	24.38%	28	88.43	5.02	8.46	6.43	6.64
	38.8	30.45	21.51%	30	89.40	7.31	9.90	8.00	8.40
Post-Vibration Test	27.9	20.28	27.31%	20	82.76	4.32	3.55	3.01	3.63
	32.5	24.61	24.29%	25	89.10	5.48	5.42	4.75	5.22
	35.2	28.25	19.74%	28	88.16	6.15	6.81	6.41	6.46
	37.0	30.39	17.86%	30	91.33	7.59	8.55	8.13	8.09
Post-Thermal Cycling	29.0	20.92	27.87%	20	88.82	3.59	3.49	4.73	2.98
	30.8	22.43	27.18%	22	89.58	3.64	3.99	5.57	4.42
	34.9	25.58	26.71%	25	88.47	4.92	6.09	7.26	6.09
	36.9	28.43	22.96%	28	87.57	5.90	7.91	8.92	7.58
	38.0	29.96	21.16%	30	89.49	7.03	9.40	10.39	8.94

V. Conclusions & Recommendations

A first generation additive manufactured titanium-ammonia heat pipe technology, with integrated lattice wick structure has been developed and has successfully completed qualification testing to the ESA project (AO-6896) test specifications. The AM technology was benchmarked against an alternative stainless-steel screen-mesh wicked ammonia heat pipe technology, demonstrating enhanced performance of the additive manufactured heat pipes technology and transporting a total heat load of 30W at angles of -15° to -20° (1 x HP) against gravity, versus -2° for the screen mesh wicked heat pipes. The technology has achieved TRL 4 and is ready to transition into the TRL demonstration phase in representative applications and progress to a full qualification for space flight programme. Demonstration has been initiated through an Innovate UK project where an AM titanium heat pipe vapour chamber test piece, with a more complex, integrated mechanical design was constructed. The test piece demonstrated full functionality against gravity (100 mm lift height), utilising the AM wick laser parameters defined in this project.

Acknowledgments

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