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An introduction to additive manufactured heat pipe technology and advanced thermal management products

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A R T I C L E I N F O

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k-Core
Solid Conduction
Encapsulated Graphite

A B S T R A C T

This paper introduces additive manufactured (AM) two-phase heat pipe technology and advanced thermal management technologies, presented as a Keynote Lecture at the 16th UK Heat Transfer Conference at the University of Nottingham. AM heat pipes have been developed utilising laser powder bed fusion (LPBF) techniques to form titanium heat pipe vessels with integrated miniaturised lattice capillary wick structures. AM heat pipe technology developed in an European Space Agency (ESA) and an Innovate UK project are presented including a titanium-ammonia space mini-heat pipe assembly and a titanium-water two-phase heat pipe vapour chamber. In addition, various bespoke thermal management devices for high-end electronic applications in the space, aerospace and high-end automotive markets are introduced. Commercial examples of heat pipe technology, vacuum brazed liquid cold plate technology and k-Core encapsulated graphite technology are included.

Introduction

Aavid are global leaders in the design and manufacture of electronics thermal management technology across a broad market spectrum. Internationally Aavid offer a wide range of technologies including volume production of heat pipes and heat pipe assemblies for consumer electronics and automotive applications, through to high-end technologies such as refrigeration systems and loop heat pipes for military and aerospace applications.

Aavid UK focus on the development and manufacture of bespoke thermal management devices and have a strong research and development heritage. With the support of world leading academic and industrial partners Aavid UK have pioneered patented additive manufactured heat pipe technology [1], developed through European Space Agency and Innovate UK funded collaborative R&D projects. Titanium-ammonia heat pipes, Titanium-water heat pipes & vapour chambers, with integrated lattice capillary wick structures have achieved technology readiness level 4 (TRL) and are ready to progress to the TRL demonstration phase. This paper provides an introduction to AM heat pipe technology and presents examples of potential applications.

Commercial examples of Aavid UK's core technologies including advanced heat pipes, k-Core encapsulated graphite thermal spreader technology and vacuum brazed liquid cold plates, deployed in increasingly challenging electronics thermal management applications [2] are presented.

Additive manufactured heat pipe technology

In collaboration with the University of Liverpool (UoL) who pioneered laser powder bed fusion (LPBF) technology, Aavid UK have focused on the challenge of development of additive manufactured heat pipe technology, with integrated microscale lattice capillary wick structure and have been granted European Patent No. 2,715,265 [1], which is believed to be the first patent in this field. Additive manufacture utilising LPBF technique was identified by in the early stages of the LPBF technology development, by the author of this paper, as a

Abbreviations: **AM**, **Additive Manufacture**; **CTE**, **Coefficient of Thermal Expansion**; **ESA**, **European Space Agency**; **LHP**, **Loop Heat Pipe**; **LPBF**, **Laser Powder Bed Fusion**.

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candidate technology for manufacture of next generation thermal management systems. Early adopters of the technology are expected to be in high-tech, low volume applications in the aerospace sector, where both mass and thermal performance are critical specifications. As reliability of the technology is proven, the technology is expected to be deployed in space applications, such as telecom satellites and science missions. With advancements in AM LPBF capability, the technology will start to scale into high-end medium volume products [3].

An example of a titanium AM vapour chamber heat pipe being built vertically on a Renishaw AM 250 machine is shown in Fig. 1. The figure shows a cross-section (40 mm × 6 mm) through the vapour chamber shown. The solidified material shows the perimeter of the vapour chamber vessel and the internal lattice wick structure around the perimeter of the internal surface. Fig. 8 shows a sectioned version of the vapour chamber, showing the internal lattice structure.

The LPBF process constructs 3D metal components by laser fusion of 2D patterns in multiple-subsequent layers of powder material [4]. The major challenge in the technology development was miniaturisation of the lattice wick structure to enable functionality as a heat pipe capillary wick. To miniaturise the capillary pore size, laser parameter optimisation was completed on various titanium powder grades. A description of the optimisation process is published [5], therefore can be referred to for more details. However, to illustrate the process, examples of a lattice structure construction model and the achievable lattice size at the initiation of the development activity are shown in Fig. 2 and an example of a miniaturised characterisation test piece used for porosity and permeability testing is shown in Fig. 3. In a functional heat pipe, a vapour space is required to be added through the centre of the wick structure.

The preliminary work was followed by a European Space Agency (ESA) ARTES 5.1 activity [6] to investigate novel, 'gravity friendly' heat pipes that enable functionality on ground test and direct thermal management of the electronics, which is currently not possible with current aluminium-ammonia constant conduction heat pipes, with extruded grooved wicks.

LPBF laser parameter optimisation was completed in the ESA project to identify laser build parameters to construct lattice structures with minimised cell sizes achievable within the limits of the process, where the structure transitions from open cell to closed cell structures. Several hundred laser parameter sets were completed, examining two titanium material grades and a series of seven lattice cell sizes. The lattice cell sizes were selected based on calculated capillary lift heights of for candidate working fluids at temperatures of 0° and −35 °C. Ultimately ammonia was selected as the preferred working fluid for charging of the heat pipe test pieces. Characterisation testing (porosity, permeability and pore size measurement) enabled the optimised laser parameters to be identified for each lattice cell size, that were utilised to additive manufacture a series of representative test pieces (half-pipes) (Fig. 4), that enabled capillary lift height against gravity and mass flow rate of the fluid to be determined.

Fig. 1. Manufacture of Aavid AM Titanium Vapour Chamber by Laser Powder Bed Fusion.

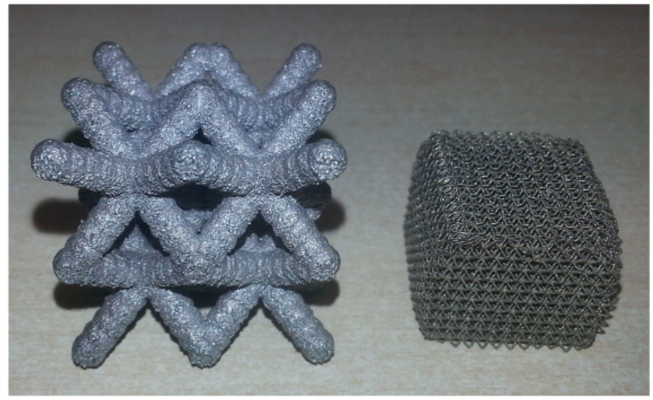

Fig. 2. 25 mm Lattice structure example & 20 mm lattice cube (UoL).

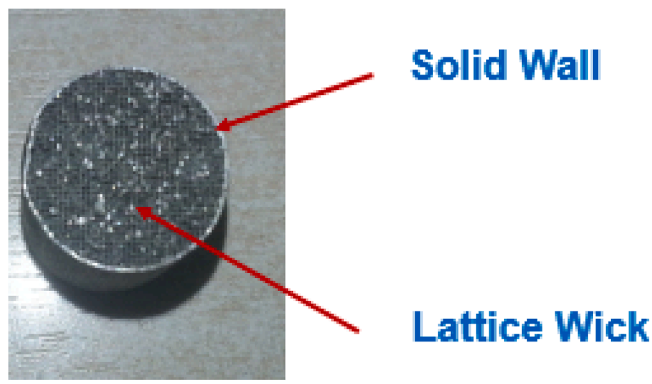

Fig. 3. Ø12.7 mm characterisation test piece with integrated solid tube wall (pore size < 700 μm) (UoL & Aavid UK).

Porosity was measured by mass balance of dry and saturated test pieces. Pore sizes were analysed by photogrammetry, following a method described by Evans et.al (2017) [7]. Permeability testing was conducted on porous samples with dimensions of 30 mm × 20 mm × 5 mm and the permeability was calculated using Forchheimer's equation. Capillary lift height was determined experimentally utilising an infrared camera to observe the transition of the progression through the test piece. In parallel a mass balance was completed, enabling the mass flow rate of the fluid (water) through the test piece to be measured.

Although decreasing the pore size increases capillary lift height / capillary pressure, it also reduces mass flow rate of liquid phase condensate to the evaporator, which limits the maximum transport power of the heat pipe, therefore pore sizes suitable to achieve the require transport power were selected to manufacture the ESA heat pipe test pieces.

A series of additive manufactured titanium heat pipes test pieces were constructed in the ESA project and charged & tested utilising Aavid UK's ammonia heat pipe facilities (Fig. 5). Preliminary development and testing activities were completed in alignment with the specific test requirements of the ESA activity, that were aligned with ESA standard ECSS-E-ST-31-02C. Tests included pneumatic proof pressure test(nitrogen) at 79.5 Bar, ammonia charge mass optimisation, helium leak detection, welding & sealing development, thermal performance testing ($T_{adiabatic}$ = 60 °C; Test Angles: +90°, −0.3° & increasing negative angles

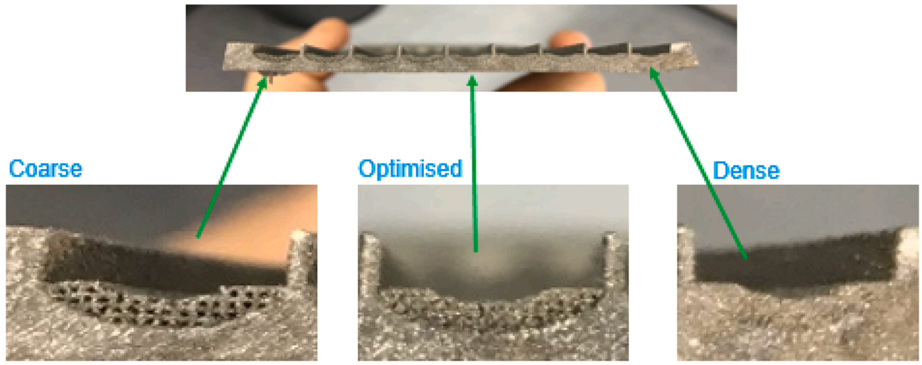

Fig. 4. Example of lift height and mass flow rate test pieces with coarse, optimised and closed cell lattice structures.

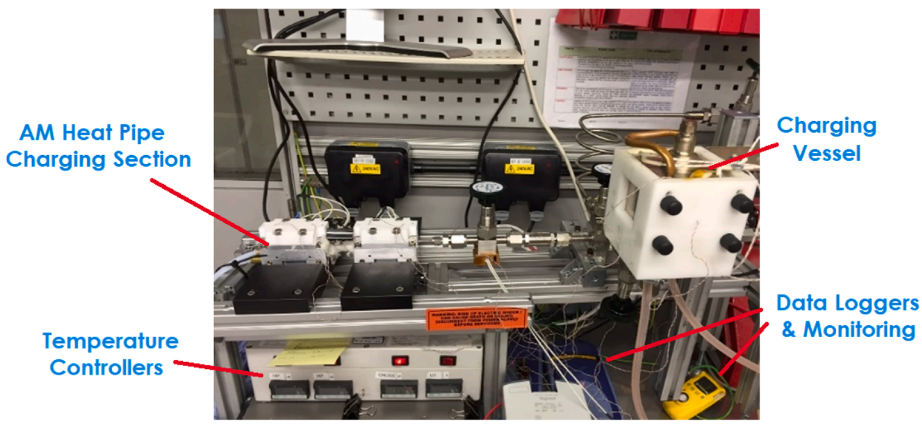

Fig. 5. Lab-scale ammonia charging facility (Aavid UK).

until dry-out occurred; transport power, 2 W to 11 W). Completion of these tests enabled the successful manufacture of functional titanium-ammonia heat pipes, with circular design (Ø8 mm × 200 mm long). The heat pipes were then integrated by epoxy bonding with two aluminium saddles to form the final heat pipe assembly test piece (Fig. 6).

The individual heat pipes and heat pipe assembly successfully completed a series of qualification tests to the ESA project test specification, including ageing and non-condensable gas tests (T = -35 °C), proof pressure at temperature testing, preliminary accelerated life test (burn-in) at temperature test (300 h at 100 °C to 105 °C, equivalent to 2 years accelerated lifetime, full test = 8000 h), thermal cycle test and vibration testing to simulate launch conditions. Thermal characterisation testing was completed at the pre-test stage and after significant qualification tests, to observe any variations in performance. The heat pipe assembly achieved the transport power requirement of 30 W and was functional at an angle of −20° against gravity, versus a maximum functional angle of −2° for screen-mesh wicked ammonia heat pipe reference test pieces.

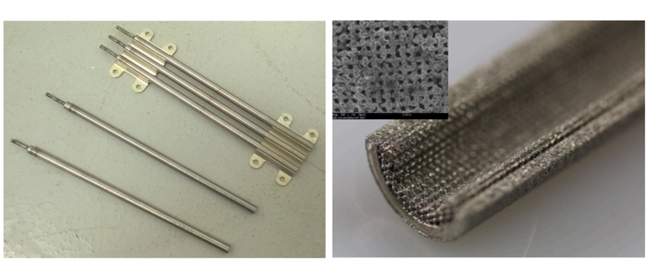

Fig. 6. ESA activity titanium-ammonia additive manufactured heat pipes and heat pipe assembly (Aavid, Thermal Division of Boyd Corp. / UoL).

To highlight the potential benefits of AM heat pipe technology, various demonstrators have been designed and manufactured. Loop heat pipes enable thermal transport against high gravitational acceleration loads and over long distances by deploying a primary and secondary wick arrangement that is challenging to manufacture [8]. An innovative loop heat pipe evaporator with integrated primary wick is shown in Fig. 7. The component dimensions are Ø20mm × 45 mm long and it incorporates a solid outer vessel, integrated primary wick and vapour passage network, secondary wick representation and solid bulkhead seal. The loop heat pipe component is a good example of innovation in two-phase technology, however further work on minimisation of the wick pore size is required to realise this technology.

An example of an additive manufactured titanium-water vapour chamber heat pipe, developed in an Innovate UK collaborative R&D 'CLASS' project [9], is shown in Fig. 8. Lift height testing demonstrated capillary pumping, vertically against gravity, up to a lift height of 100 mm (top of the component) for the AM wick. An example of how the vapour chamber can be integrated into a lightweight aerospace electronics chassis (≈20% mass reduction) is shown in Fig. 9. Three discrete heat sources with heat dissipation requirements of 50 W to 100 W each, potentially can be thermally managed by the technology in the example.

In summary Aavid's patented additive manufactured heat pipe technology has achieved technology readiness level (TRL 4) and is ready for demonstration in commercial applications. Functionality against gravity and high power transport has been demonstrated, that can be deployed in commercial applications. To progress towards commercialisation, collaborations with early adopters are required to progress from lab-scale to a pilot production capability. Further innovations in the capillary wick construction techniques and processes to convert the AM vessels into functional heat pipes can be made. Qualification of the processes and products to the end user specifications is required.

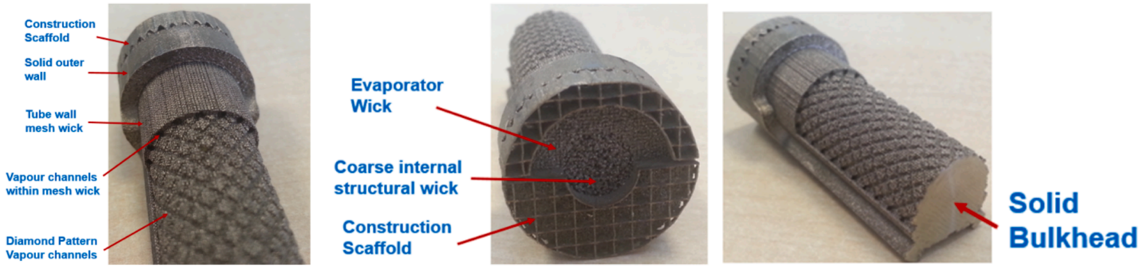

Fig. 7. Additive Manufactured Loop Heat Pipe Evaporator Demonstrator, Incorporating Various Innovative Features (Aavid, Thermal Division of Boyd Corp.)

Fig. 8. Titanium-Water AM Vapour Chamber Heat Pipe Capillary Wick Test Piece with Integrated Lattice Structure (Aavid, Thermal Division of Boyd Corp.)

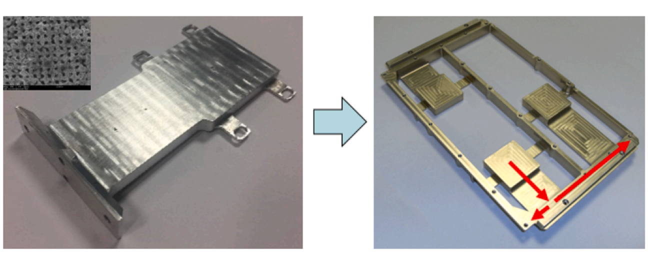

Fig. 9. Integration of AM Vapour Chamber Heat Pipe Technology into Aerospace Electronics Chassis Example (Aavid, Thermal Division of Boyd Corp.)

Radio telescope heat pipe application

Typically, radio telescopes are deployed in remote low population regions to minimise the impact of human activity on the functionality of the telescope. The Australian Square Kilometre Array Pathfinder (ASKAP) radio-telescope constructed by the Commonwealth Science and Industrial Research Organization (CSIRO) [10] has 36 twelve-meter reflector antennas, located in a severe environment with low night time temperatures and daytime ambient temperature up to 55 °C. Each radio telescope has an advanced phased array feed (PAF) receiver module (Fig. 10) that incorporates a Ø1.2 m heat pipe chassis disc (Fig. 11) [11], that was designed and manufactured by Aavid UK. The disc [12] incorporates 117 customised heat pipes that transport heat from the 188 individual receiver components to the disc perimeter, where it is dissipated by eight secondary cooling systems consisting of perpendicular heat pipe thermal links and heat pipe forced convection fin stacks (Fig. 12). To enable functionality in a 55 °C ambient, the secondary cooling system incorporates thermo-electric coolers (TEC) that sub-cool the disc perimeter to 20 °C preventing thermal failure of the electronics. The TEC's add an additional heat dissipation requirement of 560 W to the system.

Ultra-Thin vapour chamber technology

Transport and spreading of heat from discrete electronic components within confined spaces or narrow gaps, conventionally can be achieved by flattening of circular heat pipes to thicknesses of 1.0 to 1.5 mm or by deploying similar thickness, two-phase vapour chamber heat pipes, to spread the waste heat over a larger surface area. However, the rapid evolution of smaller, thinner, light weight mobile electronic devices requires higher performance thermal solutions, to handle high heat fluxes generated by the miniaturised electronic components.

Ultra-thin vapour chambers [13] enable a thickness reduction and high thermal performance with the ability to handle high heat flux bursts and high-performance modes of the mobile devices (Fig. 13). Titanium ultra-thin vapour chambers offer a thickness range of 0.3 mm to 0.5 mm and a mass reduction of > 50% versus equivalent copper (0.4 mm) and stainless-steel (approaching 0.3 mm) ultra-thin vapour chambers variants.

The technology incorporates customised wick structure designs that are performance matched to the application. Fig. 14 compares the thermal conductance of various ultra-thin vapour chambers against 0.3 mm thick graphene (1300 W/mK), for a typical mobile phone application (100 mm × 50 mm; at 60 °C). The 0.4 mm thickness stainless steel

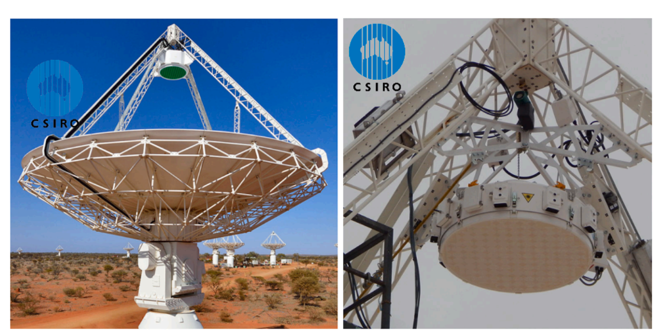

Fig. 10. Photographs of an ASKAP radio-telescope with and close-up view of the PAF receiver module with integrated Aavid UK heat pipe receiver disc (CSIRO).

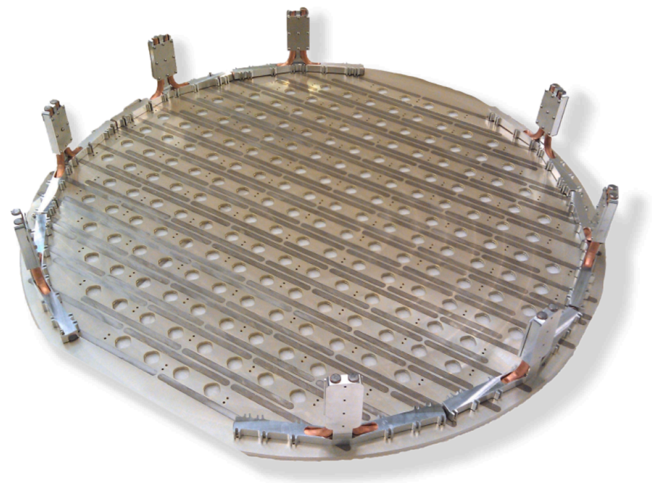

Fig. 11. Heat pipe receiver disc (Ø1.2 m) for ASKAP radio telescope (Aavid UK).

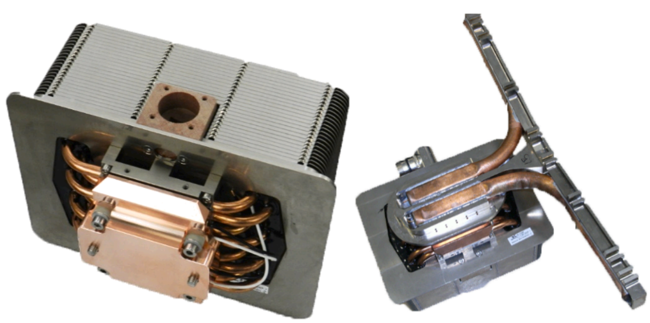

Fig. 12. Secondary cooling system: heat pipe assembly and forced convection heat pipe fin stack for ASKAP radio telescope (AAVID UK).

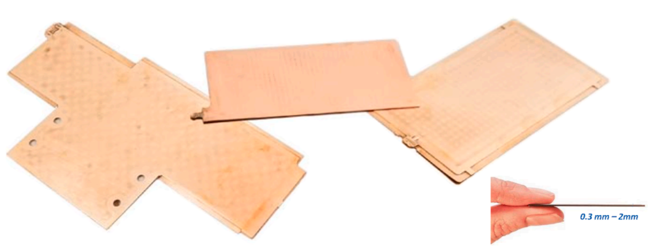

Fig. 13. Ultra-Thin Vapour Chamber Examples for Miniaturised Electronics Applications.

and Copper vapour chambers have similar thermal conductance up to 5700 W/mK and 6000 W/mK respectively. The 0.3 mm thick titanium ultra-thin vapour chamber is comparable, with thermal conductance in the range of ≈2000 to 4500 W/mK. The 0.4 mm thickness titanium ultra-thin vapour chamber offers up to five times higher thermal conductance, ranging from ≈16,000 upto 24,000 W/mK in the mobile phone application.

Ultra-thin vapour chambers offer the potential benefits of increased reliability & lifetime, mass reduction, thickness reduction and enhanced handling of short burst, high power usage modes. The technology also enables reduced touch temperatures, which is an important factor in wearable electronics. An additional benefit of the titanium and stainless-steel ultrathin vapour chambers is that high strength allows them to be incorporated as a structural component, potentially enabling further size and mass reductions of the electronics devices. Titanium has a further benefit of a low coefficient of thermal expansion, potentially enabling an

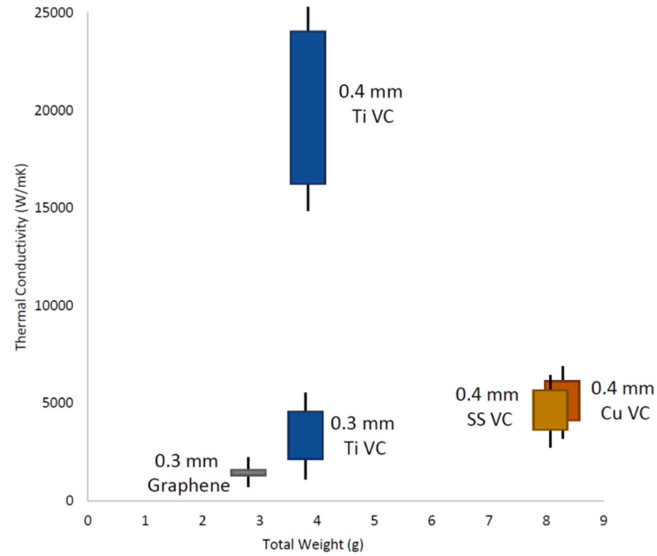

Fig. 14. Thermal Conductance and Mass Comparison of Various Ultra-Thin Vapour Chambers vs. Graphene, for a representative vapour chamber temperature typical in mobile phones at 60 °C.

increased level of integration with the electronics ($CTE_{Ti} = 4.8\text{x}10^{-6}$ m/m.°C; $CTE_{SS} = 8.8\ \text{x}10^{-6}$ m/m.°C; $CTE_{Cu} = 9.8\ \text{x}10^{-6}$ m/m.°C).

Vacuum brazed liquid cold plate technology

The vacuum brazing manufacturing processes produces high cleanliness, high quality braze joints that enables a step-increase in the complexity and thermal performance of the liquid cold plate technology versus conventional volume manufacturing techniques, such as controlled atmosphere brazing (CAB). Typically Aavid UK custom design and manufacture bespoke vacuum brazed liquid cold plates, that externally may appear simplistic in design, but internally incorporate labyrinth style flow passages, with customised fin inserts that target individual heat sources. The cold plates are optimised utilising CFD analysis to minimise pressure drop and maximise thermal performance. Typically applications include mass optimised high-end motorsport applications, aerospace chassis thermal management and ruggedized transmitter applications. Examples of a labyrinth style flow passage (280 mm × 40 mm × 6 mm) and a vacuum brazed folded fin insert (≈ 45 mm × 4 mm) are shown in Fig. 15 & Fig. 16.

An example of an ATR avionics electronics chassis with integrated vacuum brazed liquid cold plate sidewalls is shown in Fig. 17 [14]. Externally the mechanical design is simplistic, with a flat external surface that forms the chassis wall and internal CNC machined

Fig. 15. Labyrinth Style Flow Passage Example (Aavid, Thermal Division of Boyd Corp.)

Fig. 16. Vacuum Brazed Folded Fin Insert Example (Aavid, Thermal Division of Boyd Corp.)

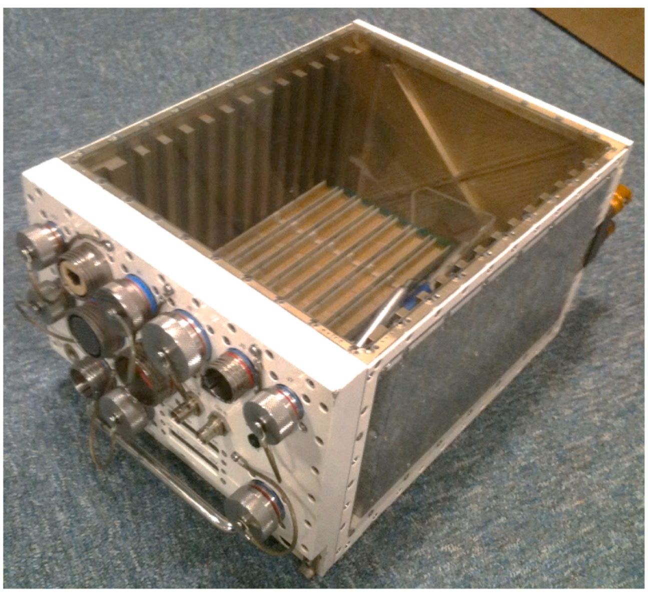

Fig. 17. ATR electronics chassis with optimised vacuum brazed liquid cold plate sidewalls (Elma & Aavid, Thermal Division of Boyd Corp.)

castellation's that that locate multiple electronics cards. Internally the component is optimised to thermally manage selected high heat dissipation electronics cards positioned in specific card slots. Low pressure drop channels are deployed across low heat dissipation slots to maximise the coolant flowrate through the cold plate.

An example of a complex vacuum brazed liquid cold plate for a terrestrial radio telescope application is shown in Fig. 18. The component has a circular design with multiple machined fixing holes within the fluid flow regions that must be avoided by the flow passages and fourteen ports machined ports that interface with the receiver electronics. The internal flow passages are complex and integrate multiple folded fin inserts.

k-Core encapsulated graphite technology

k-Core is a novel, advanced solid conduction technology that consists of an encapsulated annealed pyrolytic graphite (APG) within an external encapsulating material. K-Core is available in multiple encapsulating materials including kapton film, aluminium & copper foils and carbon fibre, however in the majority of applications, the APG is encapsulated within solid bulk aluminium that is highly machined to create a functional electronics chassis or thermal spreader (Fig. 19).

APG has high in-plane thermal conductivity (1450 W/mK at 100 °C), but low through-plane thermal conductivity (6–10 W/mK), that is accommodated by the integration of metal thermal via's / thermal bridges, in strategic locations. Typically the aluminium skin thickness is 0.75 mm, minimising the impact of the much lower thermal conductivity of aluminium (180 W/mK). The APG inserts are 3D CAD designed to fully integrate with the electronics whilst providing ports to accommodate thermal vias and machined features (e.g. tapped fixing points) in the aluminium body. The function of the thermal via is to introduce a higher thermal conductivity conduction path that overcomes the low through-plane thermal conductivity of the APG. The 'equivalent' thermal conductivity of the integrated k-Core component is typically in the region of 600 to 1000 W/mK (3 to 5 times higher than solid aluminium). Potentially a mass reduction in the region of 5% is achievable over solid aluminium due to the slightly lower density of APG. An example of a sectioned k-Core thermal spreader chassis, sectioned to reveal the internal APG core is shown in Fig. 20.

An X-ray showing the location of APG within an avionics electronics chassis is shown in Fig. 21. A central aluminium spline within the component acts as a thermal via that interfaces with two 125 W microprocessors mounted centrally on the external surface of the component. The heat is transferred by conduction to the card guides that interface with the electronics chassis (e.g. similar to Fig. 17). By incorporating customised APG inserts within the chassis, the maximum temperature difference between the heat input surfaces and card guides was reduced from ≈ 56.9 °C for a solid aluminium chassis to ≈ 17.5 °C for a k-Core advanced conduction chassis (Fig. 22).

Technology application areas

The technologies presented in this paper are targeted at high-end electronics thermal management applications, with challenging thermal and mechanical specifications that require a high level of

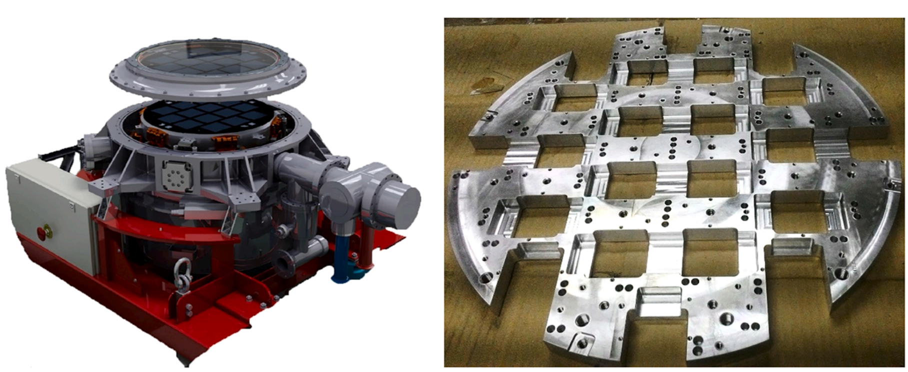

Fig. 18. Terrestrial Radio Telescope Vacuum Brazed Liquid Cold Plate Application (Aavid, Thermal Division of Boyd Corp.)

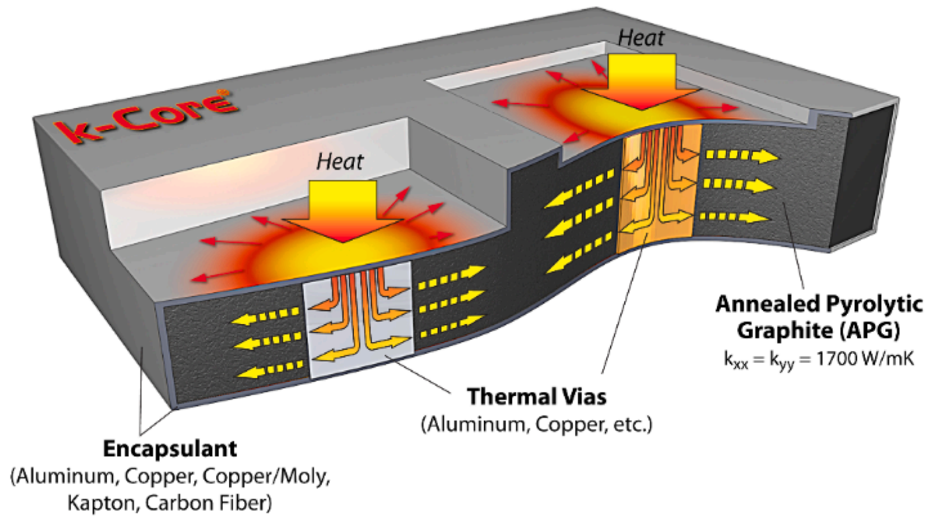

Fig. 19. k-Core thermal spreader construction (Aavid, Thermal Division of Boyd Corp.)

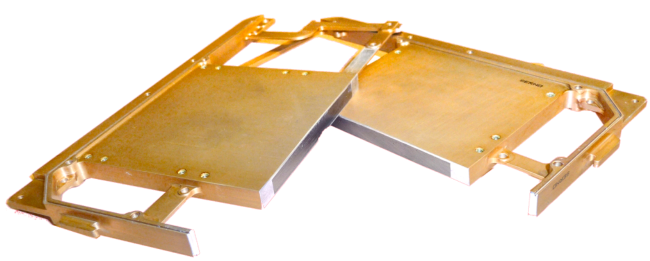

Fig. 20. Sectioned k-Core chassis revealing internal annealed pyrolytic graphite core (Aavid, Thermal Division of Boyd Corp.)

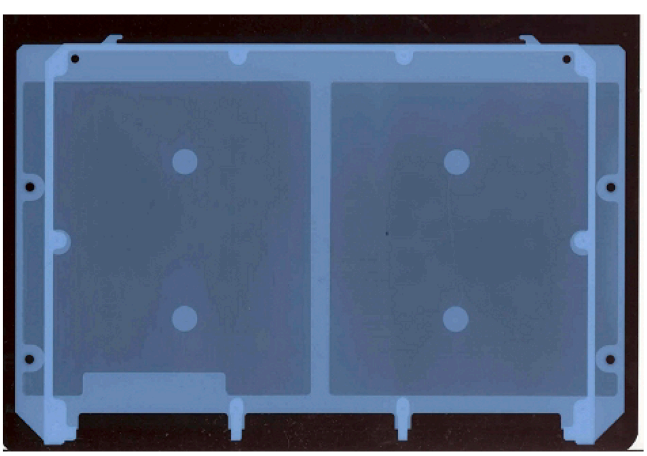

Fig. 21. X-Ray revealing APG internal location within avionics electronics chassis (Aavid, Thermal Division of Boyd Corp.)

engineering development and qualification testing to realise a qualified product. Each design is bespoke to the application and the appropriate thermal technology is selected based on the application's specifications.

Heat Pipes: Copper-water heat pipes with sintered capillary will are low cost, volume manufactured and are heavily deployed in consumer electronics applications such as lap top and desk top PC's and in games consoles and telecom server applications. The function of the heat pipe is to transport heat from the high heat flux source to a region where it is more easily dissipated, such as a forced air convection fin stack or a heat sink. The equivalent thermal conductivity is application specific but is typically in the range of 8,000 to 30,000 W/mK. Progressing to high-tech applications, considerations such as sub-zero operation (e.g. −40 °C minimum operating temperature), and varying or high gravitational acceleration loads and operating angles, such as in fast jet applications, present challenges to the functionality of heat pipes, that must be overcome. To achieve low temperature functionality, water can be replaced with methanol or ethanol in copper heat pipes and in space applications, aluminium-ammonia heat pipes are heavily deployed. To achieve functionality against gravity customised capillary wicks can be deployed and to achieve functionality against high gravitational acceleration loads, loop heat pipes can be deployed, but at a cost premium.

k-Core aluminium encapsulated graphite thermal management components are deployed in applications that require optimised mass and thermal performance, such as enhanced electronics chassis or space radiator panels. Typically the equivalent thermal conductivity of k-Core components is in the range of 600 to 1,000 W/mK offering three to five times higher thermal performance than an equivalent solid aluminium component and significant mass saving over a solid copper component. Aavid's k-Core technology is heavily deployed in space and aerospace applications where mass is a premium consideration. Although k-Core has lower thermal performance that heat pipes, as heat transfer is by conduction through solid material, it's performance is not affected by operating angle or gravitational acceleration.

Ultra-thin vapour chambers are a new technology that are moving towards volume production. Potential opportunities that may benefit from the technology are future high performance mobile electronics such as mobile phones, laptops and tablets. Wearable electronics such as smart watches, virtual reality headsets, etc. where mass, compactness and touch temperature are key performance requirements, potentially will adopt the technology.

Vacuum brazed liquid cold plates typically form an electronics chassis that provides direct thermal management of the heat dissipating components, mounted to specific locations across the chassis surfaces. Vacuum brazing is carried out in a high purity atmosphere that enables the breakdown of oxide layers, resulting in high quality braze joints that have enhanced corrosion and vibration resistance over conventional brazing techniques, where fluxes can be retained within the braze joint, causing a reduction in joint quality and potential leading to corrosion and porosity in the joint after a period of operation in the end application. The construction of vacuum brazed liquid cold plates allows larger, low pressure drop CNC machined coolant supply passages that lead to high thermal performance heat input regions. Typically the heat input regions consist of close-packed folded fin or machined channels that provide a large heat transfer surface area and are tailored to the maximise thermal performance. For example, the fin design can be created to

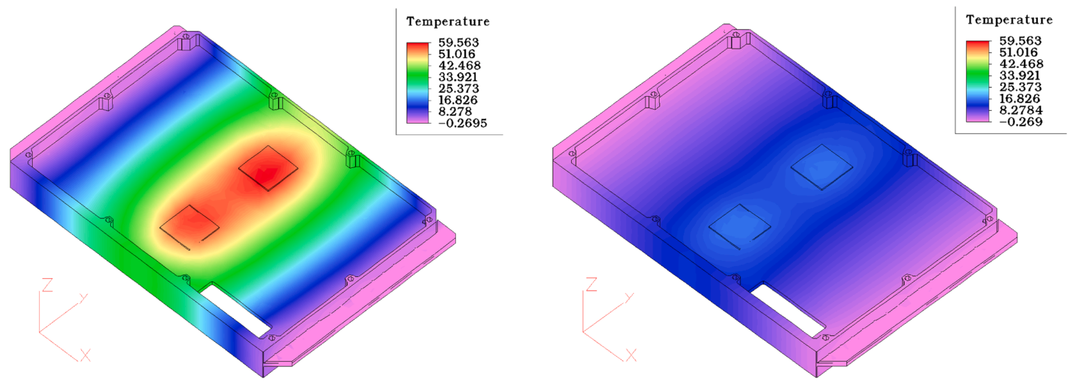

Fig. 22. CFD simulation comparing a solid aluminium chassis with a k-Core chassis, with a 250 W input power (Aavid, Thermal Division of Boyd Corp.)

break-up the boundary layer (wavy fin, louvered fin, etc.), giving a thermal enhancement over alternative cold plate technology such as CAB Brazing and extrusions.

In comparison to passive heat pipe and k-Core technology, liquid cold plates are part of an active liquid pumped loop system that requires a pump and electricity supply to function. Active systems require maintenance to maintain reliability of the overall system, however typically commercial vacuum brazed liquid cold plates transport heat loads in the region of 500 W to 10 kW, where commercial heat pipes and k-core applications typically transport between 1 W and 500 W.

Conclusions

This paper summarised advanced electronics thermal management technology, presented at the 16th UK National Heat Transfer Conference.

An overview of novel patented additive manufactured heat pipe technology, with integrated lattice wick structure is given. Water and ammonia charged titanium additive manufactured heat pipes and vapour chambers enable transport of high heat loads against gravity and a high level of integration into the electronics chassis. Demonstration activities are being pursued to commercialise the technology.

Potential future applications of the technology may include integration of AM heat pipe networks directly into chassis and structural components. For example, structural aerospace components may provide a dual function as a thermal conduit, without any mass penalty. A challenge in the future development of AM heat pipe technology is AM materials development, to enhance the heat pipe performance specifications and potentially enhance the heat pipe functionality against elevated gravitational acceleration loads. In parallel, working fluids compatibility with novel am material grades is a future challenge to address. Enhanced AM heat pipe technologies are expected to emerge.

An overview of various high performance thermal management technologies for high-tech applications is also presented. Technologies include encapsulated graphite advanced conduction technology, labyrinth style liquid cold plates and advanced heat pipe applications, including ultra-thin vapour chamber technology.

CRediT authorship contribution statement

Ryan J. M^{c}Glen: Conceptualization, Methodology, Supervision, Project administration, Writing - original draft, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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