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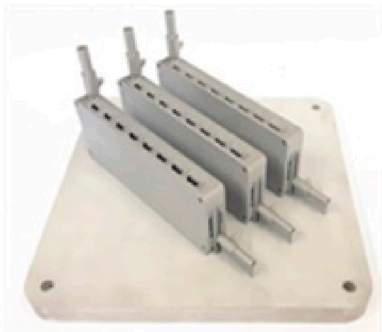
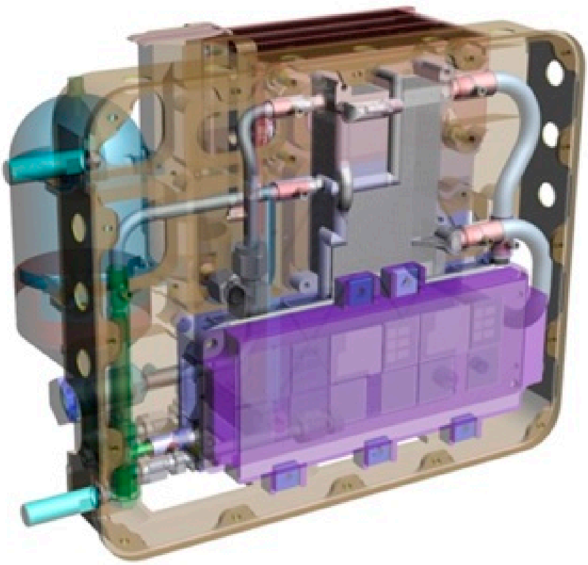
Material Selection and Component Optimization for a Pumped Two-Phase Cooling System Using Additive Manufacturing

CUSTOMER: European Commission





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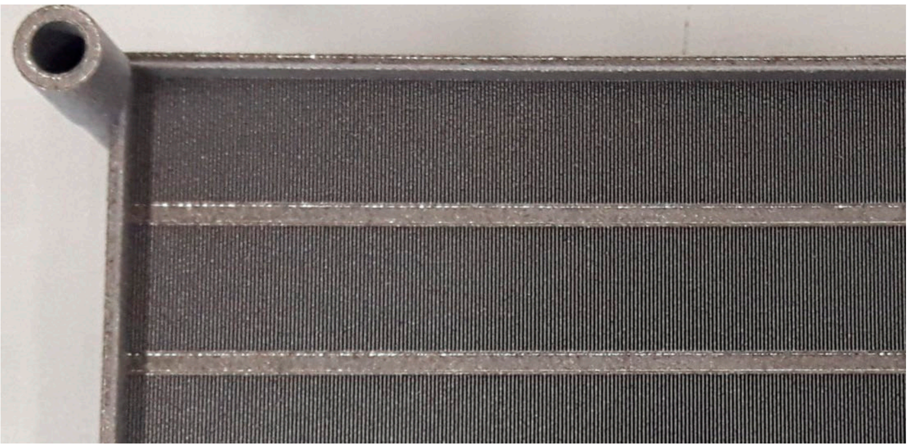

Problem area

Aeronautical power electronics are traditionally cooled with liquid and/or air forced cooling systems. These cooling systems are proven, reliable and robust but generally have high weight and limited efficiency.

Description of work

A thermal control system is being developed based on pumped two-phase technique. Two-phase heat transport systems are especially suitable for high-heat flux applications because the large two-phase heat transfer coefficient. Small tubing diameters and compact components can be applied because a small mass flow is required in a two-phase heat transport system. Additive manufacturing offers high potential for production of these components due to the large freedom of design and the ability to create complex internal structures.

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Results and conclusions

A preliminary design has been made based on the results of the present study. This design for the complete system will be further refined during the critical design phase and refined components will be tested. Three demonstrators will be built and extensively tested. These tests include mechanical (e.g. vibration), thermal, and electromagnetic tests.

Applicability

Additive manufacturing offers high potential for production of components in order to drastically reduce thermal constraints, weight and dimensions of power electronics modules. This cooling technique, initially developed for space application, becomes a promising solution for the More Electric Aircraft (MEA) concept that allows for densification and growth of on-board power without overweight or thermal issues. The development of compact thermal control systems can have a strong impact in other markets as well where low weight and high performance are important. Examples of promising industrial applications are cooling of sensors in portable inspection equipment, or cooling of components that are subjected to high accelerations and decelerations during high-speed positioning.

GENERAL NOTE
This report is based on a presentation held at the Fraunhofer Direct Digital Manufacturing Conference 2018, Berlin, 14-03-2018.

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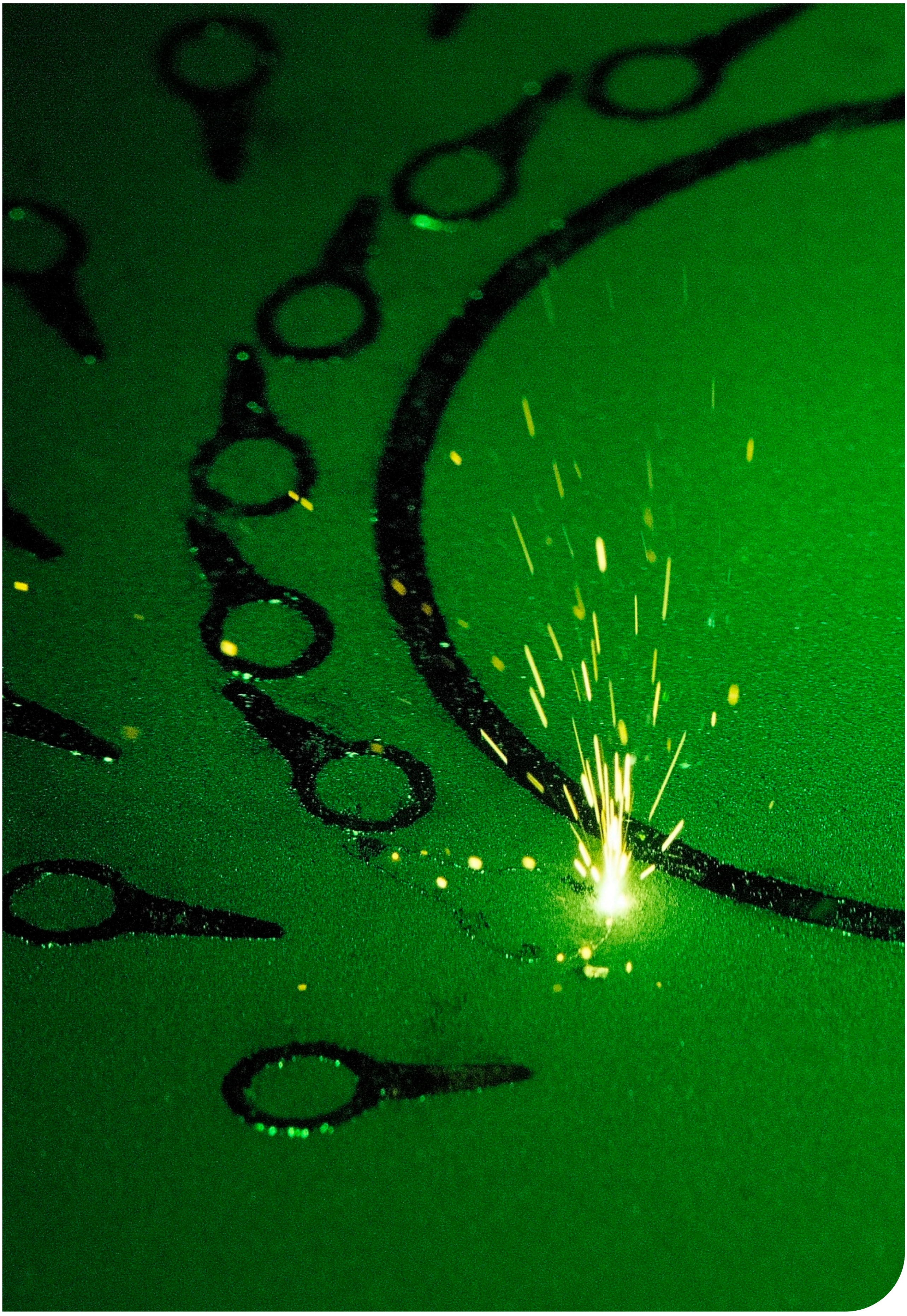
Abstract

Aeronautical power electronics are traditionally cooled with liquid and/or air forced cooling systems. These cooling systems are proven, reliable and robust but generally have high weight and limited efficiency. A thermal control system is being developed based on pumped two-phase technique. Two-phase heat transport systems are especially suitable for high-heat flux applications because the large two-phase heat transfer coefficient. Small tubing diameters and compact components can be applied because a small mass flow is required in a two-phase heat transport system. Additive manufacturing offers high potential for production of these components due to the large freedom of design and the ability to create complex internal structures. A material selection is made in this work based on criteria like thermal conductivity, corrosion resistance, mechanical performance, cost and ease of processing.



Contents

Abbreviations

ACRONYM	DESCRIPTION
ASTM	American Society for Testing and Materials
DNW	German-Dutch Wind Tunnels
LPBF	Laser Powder Bed Fusion
MEA	More Electric Aircraft
NLR	Netherlands Aerospace Centre

1 Introduction

Traditionally, aeronautical power electronics use liquid and/or air forced cooling systems. These techniques are proven, reliable and robust. Drawbacks are overweight and limited efficiency to extract heat flow generated in high power and dense converters.

The present paper describes the work done on the development of a thermal control system based on pumped two-phase technique. This cooling technique, initially developed for space application, becomes a promising solution for the More Electric Aircraft (MEA) concept that allows for densification and growth of on-board power without overweight or thermal issues.

Additive manufacturing offers high potential for optimisation of components in order to drastically reduce thermal constraints, weight and dimensions of power electronics modules.

The development of compact thermal control systems can have a strong impact in other markets as well where low weight and high performance are important. Examples of promising industrial applications are cooling of sensors in portable inspection equipment, or cooling of components that are subjected to high accelerations and decelerations during high-speed positioning.

2 What is a two-phase pumped loop?

Figure 1 shows a schematic drawing of a pumped two-phase thermal control system. A pump transports liquid to an evaporator that is mounted on e.g. a power converter. The heat from the power converter is absorbed in the evaporator and the liquid partly turns into vapour. The vapour/liquid mixture then flows to the condenser where the vapour condenses back into liquid. Two-phase heat transport systems have several advantages compared to single-phase heat transport systems:

1. The fluid temperature is independent of the heat load due to the isothermal evaporation process. This results in a uniform temperature of the cooled item.
2. A two-phase system requires a much (e.g. 10 to 100 times) smaller mass flow since the (latent) heat of evaporation of a fluid is much larger than the specific heat capacity of a fluid times the allowed temperature gradient. This results in much smaller tubing diameters and a more compact evaporator.
3. The two-phase heat transfer coefficient is generally much larger than the single-phase heat transfer coefficient. This larger heat transfer coefficient results in a smaller temperature difference between the fluid and the item that has to be cooled (i.e. power converter). This is especially relevant for high-heat flux applications.

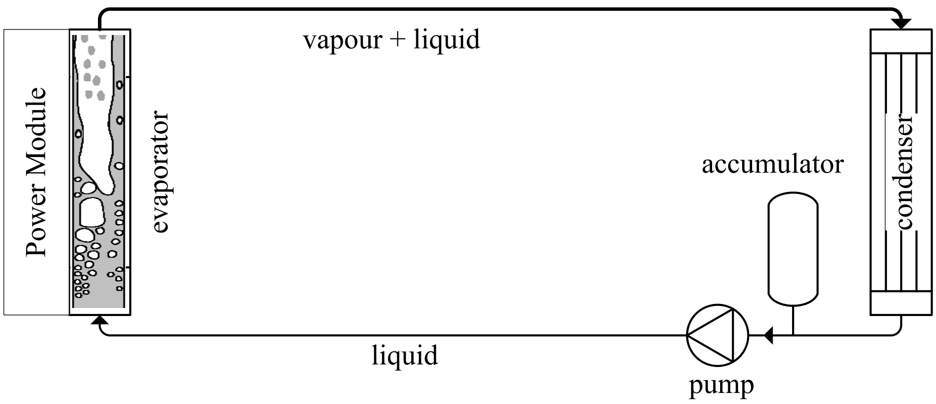


Figure 1 Simplified schematic drawing of a two-phase pumped loop

A drawback of a two-phase system is that it must be leak-tight for gas, which is more difficult to realize than leak tightness for liquid (as in a single-phase cooling system). Furthermore, the design of a two-phase system is more complex than the design of a single-phase system, e.g. because flow separation can occur in badly designed evaporators. When flow separation occurs, one part of the evaporator only receives liquid while another part only receives vapour. This can result in local overheating of a power converter.

3 Components that are made by additive manufacturing

3.1 Evaporator

The evaporator absorbs the waste heat from the power converter. This power converter generates a high heat flux in the range of 85 W/cm^2 and a total power of 1200W. Cooling such a high heat flux can be achieved with a microchannel evaporator. In a microchannel evaporator, many parallel small-diameter channels (typically 0.5 to 2 mm) are used. However, a microchannel heat exchanger is susceptible to 'dry-out', which means that locally the wall of the evaporator is not wetted by the liquid anymore. This results in a sudden drop in heat transfer coefficient and too high temperatures. Dry-out can be prevented by optimising the internal geometry of the evaporator. Metal additive manufacturing is very suitable for production of evaporators because it allows for complex internal geometries. New evaporator concepts were generated and evaluated in this study.

3.2 Condenser

The waste heat from the power converter is transferred to the condenser. A heat exchanger of the air cooled plate fin type is applied as shown in Figure 2. The hot fluid flows through channels that pass by cooling fins. A cold air flow is forced to pass by the fins that function as heat exchange surface areas. Optimisation of the fin configuration is required to obtain the required cooling capacity while staying below the maximum allowable air pressure drop. Important design parameters are fin thickness, height, length and distance between fins.

3.3 Accumulator

The accumulator is a pressure vessel that allows for density variations in the thermal control system due to changes in the heat load or temperature (see Figure 2). The pressure in a two-phase fluid loop is related to the temperature. The accumulator is used to control the temperature and pressure in the system with a small heater at the bottom of the accumulator. Commercially available accumulators are usually made out of stainless steel. The mass of the accumulator can be greatly reduced by making a dedicated aluminium accumulator by additive manufacturing.

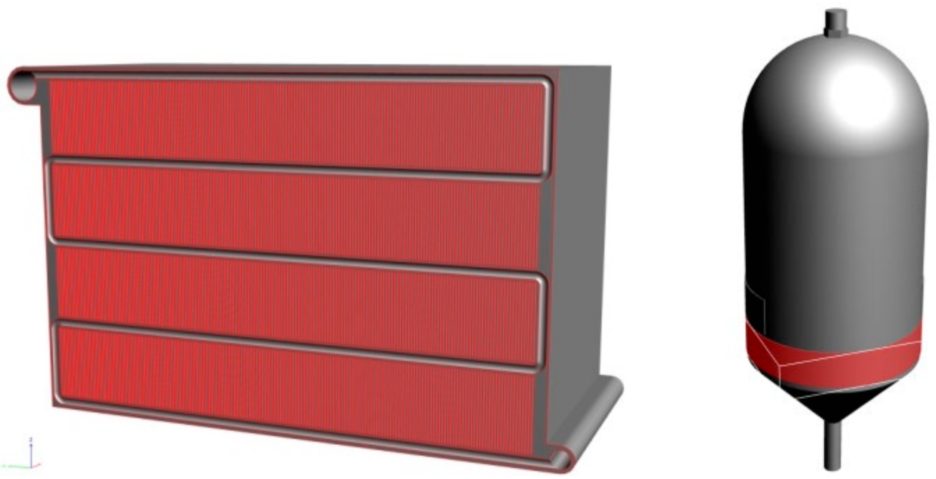


Figure 2 Concept designs of thin plate condenser heat exchanger and accumulator pressure vessel

3.4 Miscellaneous other components

Besides the above-mentioned components, several other parts will be produced by additive manufacturing. Examples are a filter housing, a cartridge heater housing, and several tubing sections. Also these components are made by additive manufacturing in aluminium because of additional weight reduction. The commercially available parts are generally made of stainless steel.

4 Criteria for alloy selection

An aluminium alloy is preferably used because of the low weight and good thermal conductivity. A selection is made of AlSi10Mg or Scalmalloy for each of the components based on criteria like thermal conductivity, corrosion resistance, mechanical performance, cost and ease of processing. AlSi10Mg is a typical casting alloy with a combination of good thermal properties and low weight. Scalmalloy is a high strength, corrosion resistant and protected aluminium-magnesium-scandium alloy (AlMgSc) developed for Additive Manufacturing by Airbus Group Innovations.

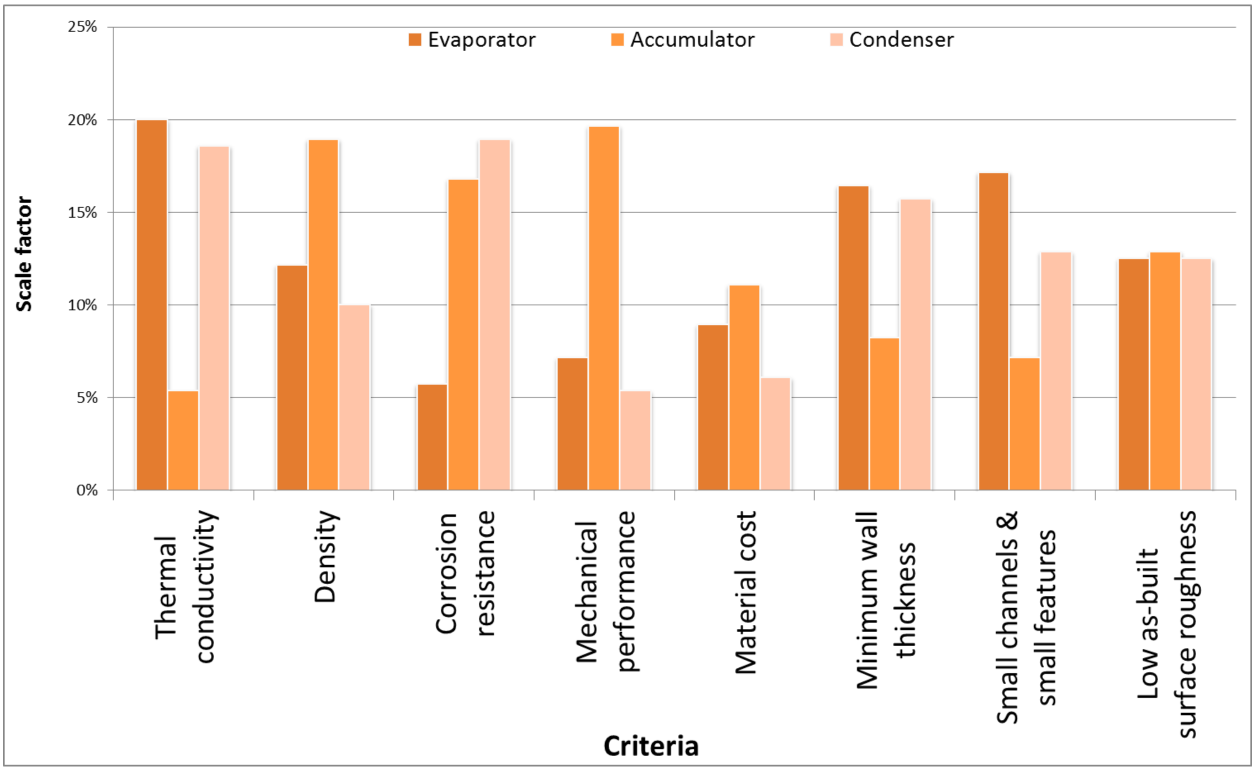


Figure 3 Scale factors of material selection criteria for the different pumped loop components

There are differences in the relevance of criteria for the components in the pumped loop. Scale factors are determined for material selection. These are shown in Figure 3. The next sections describe the performance evaluation of the two candidate aluminium alloys based on these criteria.

4.1 Thermal conductivity

High thermal conductivity is required for the evaporator and the condenser. The thermal conductivity has a substantial influence on the component design, the weight, and the performance. Thermal and electrical conductivity of a metal depends on how many free electrons are available in the metal and how freely these electrons can move. The conductivity of a metal is highest when it is pure. Alloying can be used to strengthen a metal but strained regions around solute atoms cause additional scattering of the electrons. Resistivity due to scattering of electrons from impurities increases nearly linearly with the concentration of the alloying elements in solid solution which is described by Nordheim's rule [1]. The conductivity of an alloy can be influenced significantly by the formation of precipitates during an ageing heat treatment. A competition occurs between two effects on the scattering of electrons:

1. Matrix purification: formation of precipitates removes solute atoms from the matrix which results in a reduction in electron scattering.
2. Precipitate characteristics: deformations in the crystal's lattice can increase reduction in electron scattering.

Grain boundaries cause scattering of the electron and therefore add to the resistivity [2]. Laser Powder Bed Fusion (LPBF) is known to produce a fine-grained microstructure. Grain growth commonly occurs at high temperature during the heat treatment which has a positive effect on the conductivity.
For AlSi10Mg, a thermal conductivity is expected between 103 W/(mK) and 175 W/(mK) depending on the heat treatment [3]. The influence of heat treatment parameters on the conductivity of AlSi10Mg was investigated by Uliasz et al. [4]. It was found that ageing improves the electrical conductivity of this alloy. Over-ageing results in the highest conductivity in combination with a reduction of the mechanical performance.
The thermal conductivity of Scalmalloy is ±100 W/(mK) [5]. $Al_3(Sc,Zr)$-, Al_6Mn-, and Mg-rich precipitates are formed during an ageing heat treatment of Scalmalloy. Similar effects of the heat treatment on the thermal conductivity of Scalmalloy can be expected.
Based on literature, AlSi10Mg appears to be the preferred material when a high thermal conductivity is required. Drawbacks of AlSi10Mg are the lower corrosion resistance (see §4.2) and mechanical performance (see §4.3) compared to Scalmalloy. It is not known if the conductivity of Scalmalloy can be substantially increased by a suitable heat treatment. For the present work, flat plate samples were produced by LPBF using AlSi10Mg and Scalmalloy as shown in Figure 4. Heat treatments were selected that promote the formation of precipitates and grain growth to improve conductivity (see Table 1).

Table 1 Selected heat treatments on samples for conductivity measurement

AlSi10Mg heat treatments	
H1:	Stress relief 300°C -2hr
H2:	Stress relief 300°C -2hr Solution 510 °C - 2hr + Water Quench + Ageing 160 °C - 8hr
H3:	Stress relief 300°C -2hr Solution 510 °C - 2hr + Water Quench + Over Ageing 200 °C - 10hr
Scalmalloy heat treatments	
H4:	Stress relief 180°C - 2 hr
H5:	Stress relief + Precipitation Hardening 325°C - 4hr
H6:	Stress relief + Over Ageing 380 °C - 12hr

Figure 4 Thermal conductivity evaluation samples

Accurate determination of thermal conductivity is challenging due to heat leaks and errors in measured temperatures. The thermal conductivity can also be calculated from the electrical conductivity using the Wiedemann-Franz law [6]. The electrical conductivity was measured using the eddy current method.

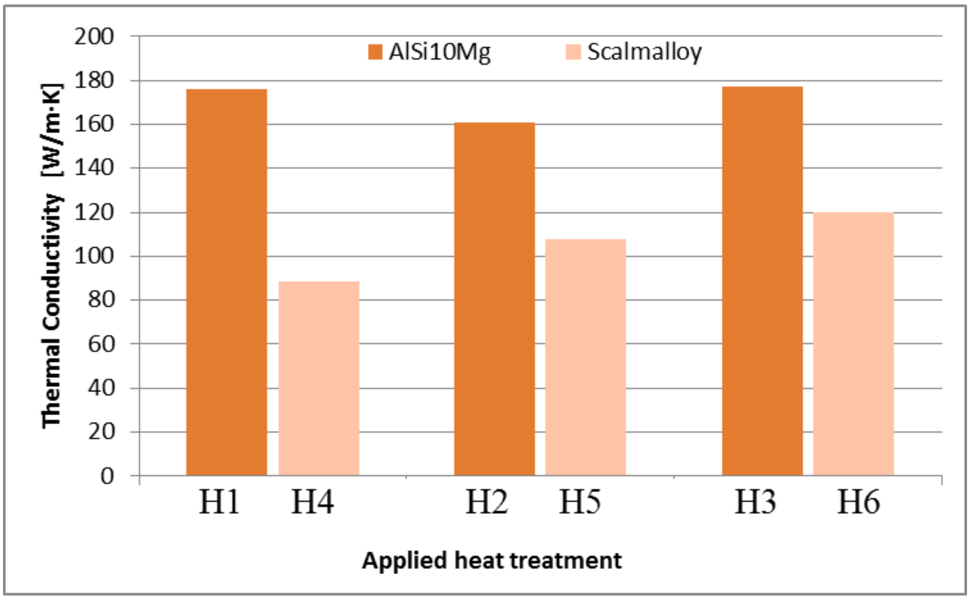


Figure 5 Thermal conductivity calculated from electrical conductivity measurements

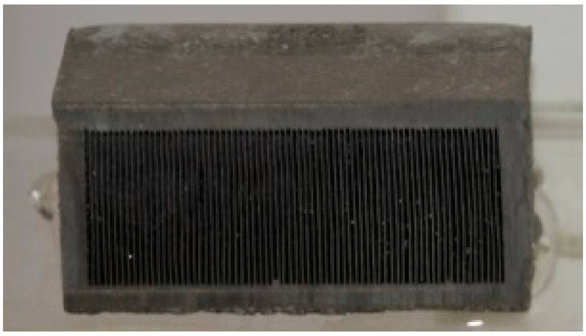
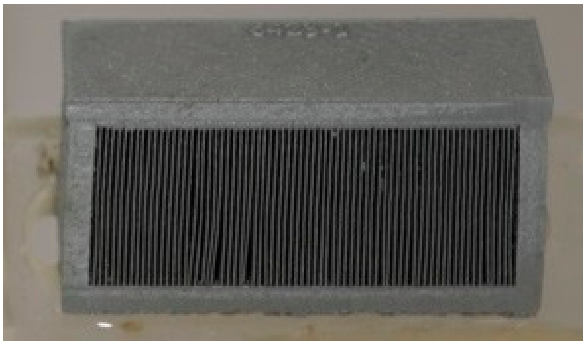
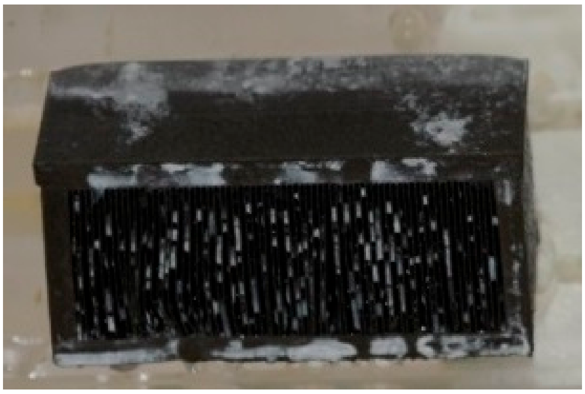
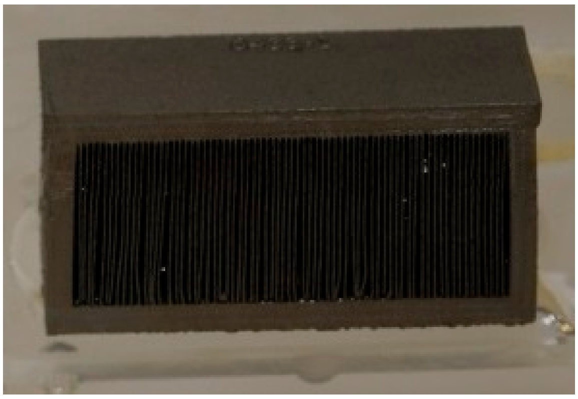
Measurement results are shown in Figure 5. It can be seen that an ageing and solution heat treatment decreased the conductivity of the AlSi10Mg samples after the stress relief. Over-ageing did increase the conductivity of AlSi10Mg slightly. The conductivity of Scalmalloy is increased after the precipitation hardening treatment. It is further increased after over ageing. The conductivity of Scalmalloy remains considerably lower than that of AlSi10Mg. Based on these results it is recommended to use AlSi10Mg in combination with a stress relief heat treatment for applications that require high heat conductivity.

4.2 Corrosion resistance

The thermal control system needs to pass a salt fog test in order to demonstrate sufficient corrosion resistance. Corrosion resistance is especially relevant for the air cooled condenser with its larger number of thin closely spaced fins. Therefore the corrosion behaviour of AlSi10Mg and Scalmalloy was investigated in the present work.
Al-Mg alloys are known to provide excellent corrosion resistance compared to other aluminium alloys. Combined with scandium as alloying element, the corrosion resistance of these alloys further improves due to grain refinement which increases resistance against pitting corrosion [7]. From a corrosion point of view, Scalmalloy (AlMgSc) is therefore preferred over AlSi10Mg.
Also the applicability of a thin coating was part of the study. Several different types of coating are available to provide improved corrosion resistance to aluminium alloys. A thin coating is preferred because a thick coating may influence the heat transfer properties and cannot be applied in small spaces between fins. Anodising coatings also cannot be applied on closely spaced fins. Chromate based conversion coatings can easily be applied by immersion. These coatings are known to strongly improve corrosion resistance of aluminium alloys. The SurTec 650 conversion coating was selected for testing in the present study. Two samples with closely spaced fins were made of Scalmalloy and two were made of AlSi10Mg. One sample of each alloy was provided with a SurTec 650 conversion coating. These four specimens were exposed to an ASTM B117 salt fog test. The exposure consisted of a continuous salt fog exposure at a temperature of 35°C for a period of 168 hours. The test solution was a 5% NaCl solution with a pH between 6.5 and 7.2.
The coated specimens performed better than the uncoated specimens with respect to corrosion resistance. A discoloration of the uncoated AlSi10Mg specimen was already observed in the early stages of the exposure. Corrosion commenced from the start of the test on this specimen. After 168 hours of exposure, some of the gaps between the

condenser fins were clogged with corrosion products. The effectiveness of the coating is apparent from the comparison between the coated and uncoated AlSi10Mg specimens. Even though the application of the coating resulted in a brownish discoloration of the AlSi10Mg specimen, no significant corrosion was observed after 168 hours of exposure.
Little corrosion was observed on the uncoated Scalmalloy specimen. Scalmalloy coated with SurTec 650 did not show any signs of corrosion after 168 hours of exposure (see Table 2).

Table 2 Specimens after 168 hours of salt fog exposure

	Uncoated	Coated with SurTec 650
Scalmalloy		
AlSi10Mg		

4.3 Mechanical performance

The thermal control system to be developed must be able to withstand vibrations and mechanical loads. The internal working pressure introduces stresses in the components. The internal pressure will result in very low stresses where small diameter channels are applied. The mechanical performance of the selected alloy can however be relevant for the accumulator because this pressure vessel has a larger diameter.
The pressure in the two-phase pumped loop depends on the selected fluid and temperature. Mechanical properties at elevated temperature must be considered as the system operates at a temperature in the range of 100°C. The tensile strength of aluminium alloys depends on temperature. Creep must be considered as the system continuously works under pressure at an elevated temperature [8].
A calculation of the minimum wall thickness of an accumulator vessel was made based on conservative values for the material strength at elevated temperature as no exact test data are available. From this calculation it can be concluded that selection of Scalmalloy instead of AlSi10Mg for the accumulator can result in a weight reduction of approximately 25%.

4.4 Minimum wall thickness

Optimisation of the evaporator and condenser designs requires a small wall thickness in the range of 0.2-0.3 mm. The minimum wall thickness in LPBF depends on the combination of layer thickness, laser power and scan speed. A layer thickness of 50µm is selected. The dependence of the single track wall thickness on the combination of laser power and scan speed is investigated for AlSi10Mg and Scalmalloy. Cross sections have been made of the samples and these cross sections were analysed on thickness and roughness (see §4.6). Examples of thin wall cross sections are added in Figure 6. The average wall thickness as function of laser intensity is shown in Figure 7.

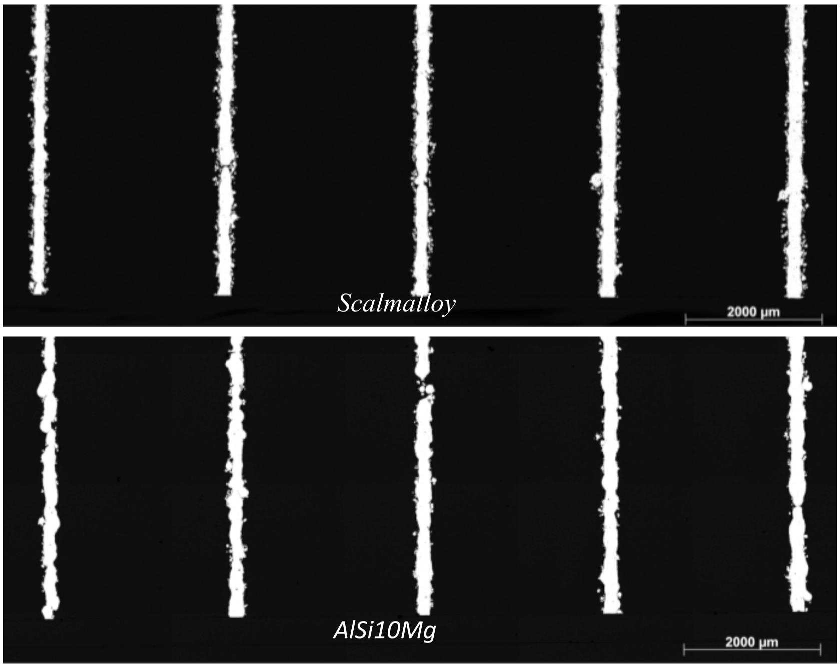


Figure 6 Cross sections thin wall samples

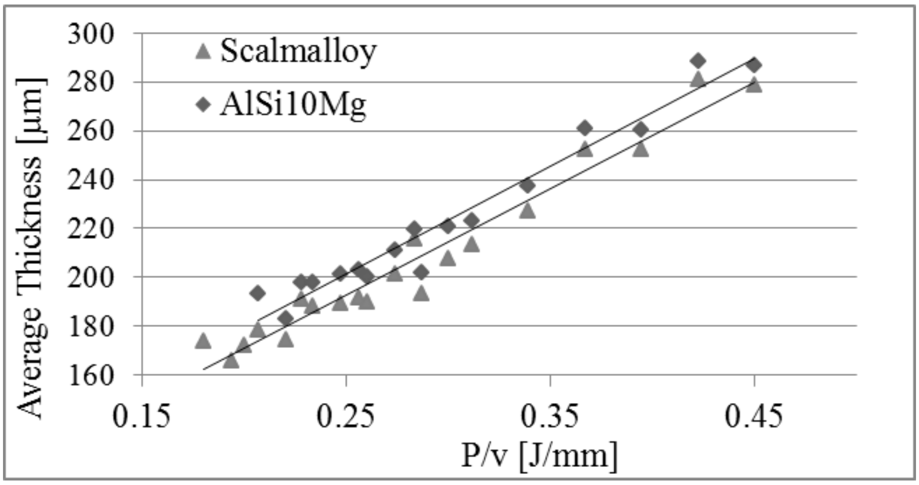


Figure 7 Measured average wall thickness as function of Laser intensity P/v [J/mm]

The thickness appears to be linearly dependent on the laser intensity. The same intensity results in a smaller thickness of the Scalmalloy wall compared to the AlSi10Mg wall. It is concluded that a smaller thickness can be achieved with Scalmalloy.

4.5 Small channels and features

Complex geometries and small-diameter channels are required for production of optimised evaporator and condenser concepts. Building blocks for these concepts are for example small channels, holes and rods in various directions. A study was carried out to investigate the ability to produce these small features.
The ability to produce small rods and holes is investigated by producing samples with rods or holes in the diameter range of Ø 0.1 to 0.6 mm under 0°, 45°, and 90° relative to the build direction.
The ability to produce small channels is investigated by producing a large number of samples with channels in the diameter range of Ø0.4 to 1.5mm. Also these samples were produced under 0°, 45°, and 90° relative to the build direction with and without down skin parameters. The channels were evaluated on diameter and roundness.

Figure 8 Samples with small rods, holes and channels

It is observed that the quality of small features produced in AlSi10Mg is better than that of the Scalmalloy features. Features produced in z-direction have the best quality. The smallest possible rod diameter is 0.2mm in XY-direction and 0.4mm in Z- and 45°-direction. Very small channels with a diameter in the range of 0.2 mm can be made in vertical direction. Horizontal channels with a diameter smaller than 1.2 mm are difficult to make. Application of dedicated process parameters in down facing areas can improve the quality of horizontal features. Limited work has been carried out on the application of down-skin parameters. However, no significant improvement was observed. A more extensive study on optimisation of down-skin parameters is required.

4.6 As-built surface roughness

The as-built surface roughness of parts that are produced by LPBF is usually high. This roughness depends on surface orientation, applied layer thickness and on the applied process parameters. The roughness on the vertical thin walls is calculated from the contour of the cross sections. These roughness values are shown in Figure 9. There is no big difference between the roughness values measured on Scalmalloy and AlSi10Mg samples. The type of roughness is different though. The Scalmalloy samples have much more very small particles on the surface.

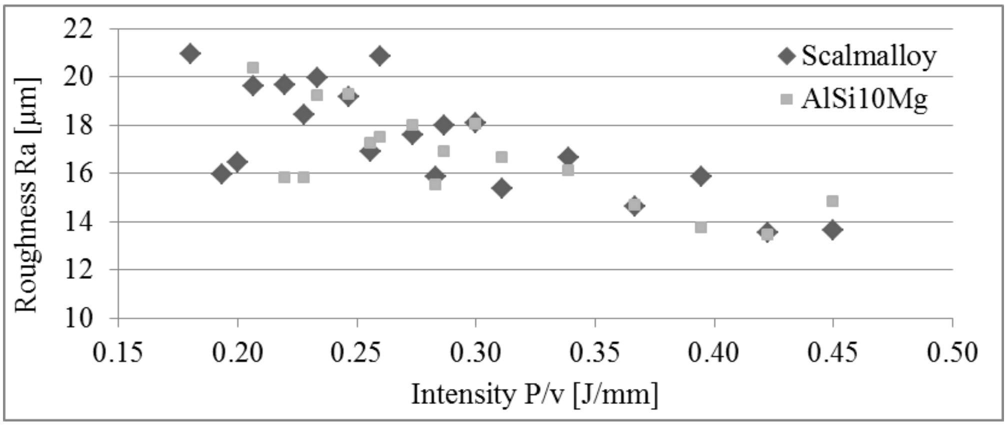


Figure 9 Roughness as function of Laser intensity P/v

4.7 Material selection

A material selection is made for each of the components based on criteria like thermal conductivity, corrosion resistance, mechanical performance, cost and ease of processing. AlSi10Mg is the preferred alloy for the evaporator and the condenser, mainly because of the highest thermal conductivity. A coating must be applied to provide sufficient corrosion resistance. Scalmalloy is preferred for the accumulator because of the better mechanical performance.

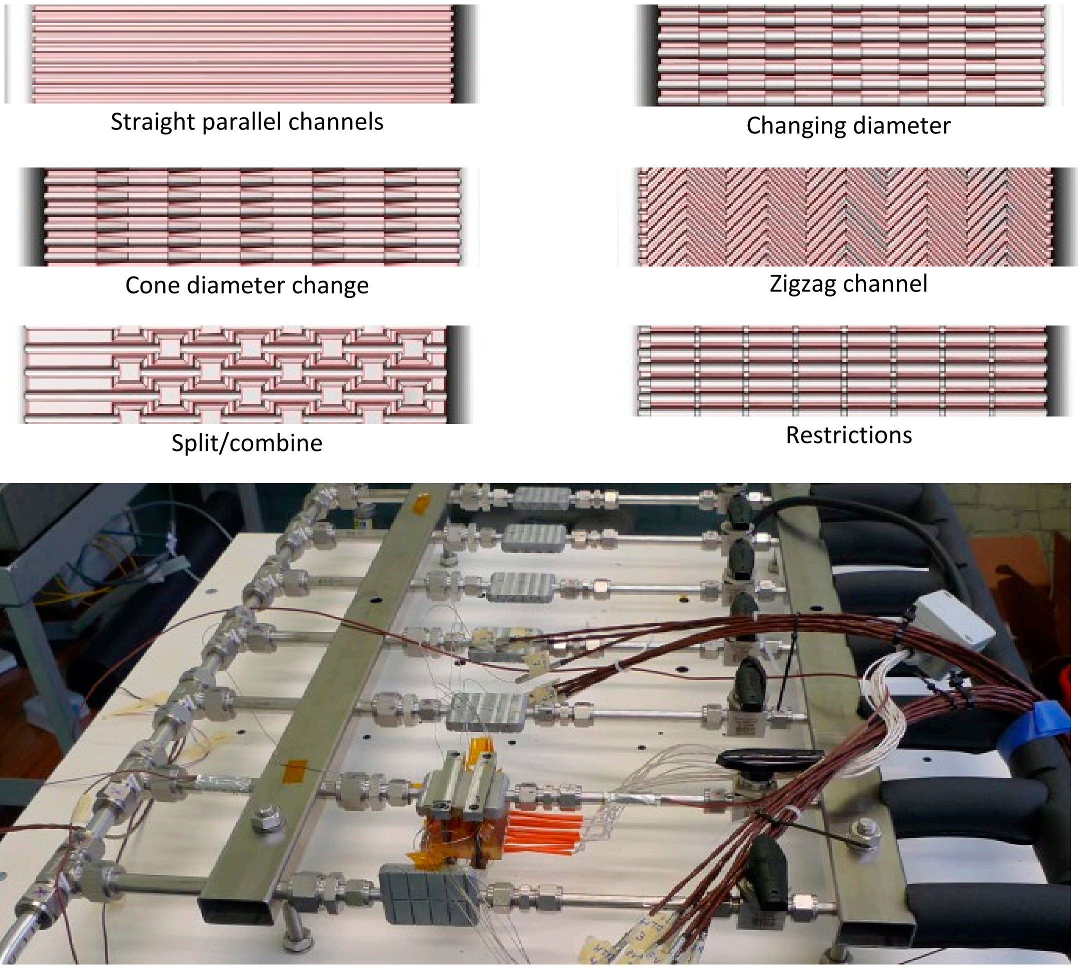


Figure 10 Evaporator concept designs and test set-up

5 Evaporator design

The evaporator is a critical component in the thermal control system that is developed in this study. A study was carried out to generate evaporator concept designs. Several modelling tools are used to design various different complex internal geometries for optimum performance of the two-phase pumped cooling system (see Figure 10).
A selection of concepts is produced by LPBF.
Component performance tests are carried out for final concept selection. The measurements showed that no dry-out occurs. The first concept with straight parallel channels was selected because it showed the highest heat transfer coefficient. This concept is also the most suitable for prediction of the expected pressure drop due to the relatively simple design.

6 Conclusions

A preliminary design has been made based on the results of the present study. This design for the complete system will be further refined during the critical design phase and refined components will be tested. Three demonstrators will be built and extensively tested. These tests include mechanical (e.g. vibration), thermal, and electromagnetic tests.

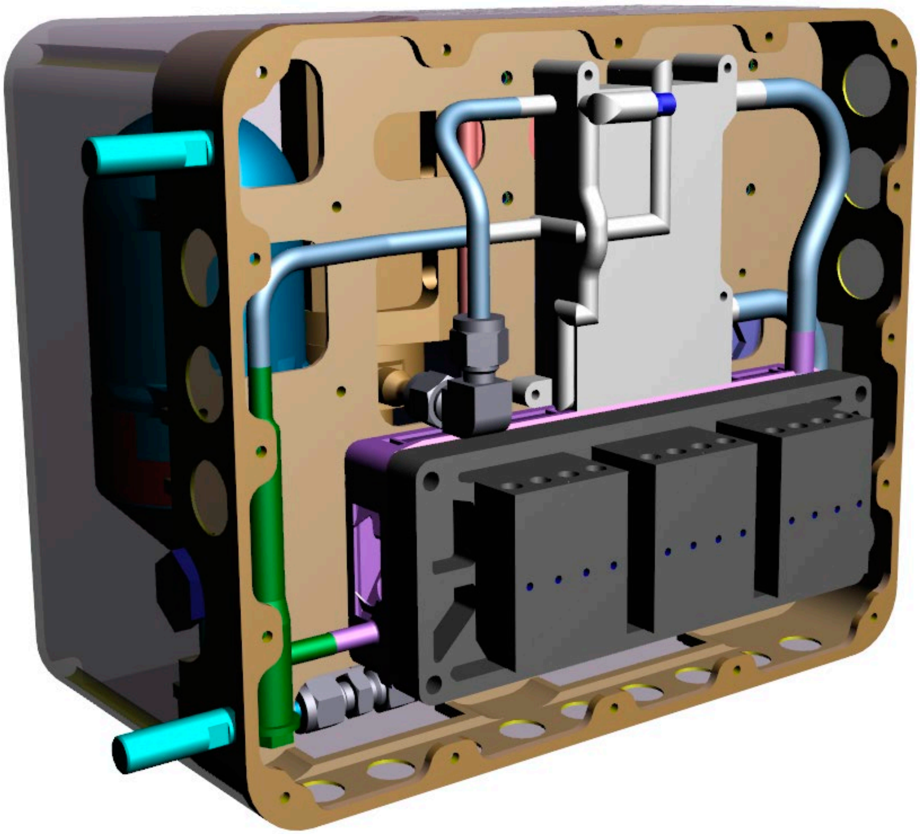


Figure 11 Design of a thermal control system based on pumped two-phase technique

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