49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-01

Lightweight Two-Phase Pumped Cooling System with Aluminium Components produced with Additive Manufacturing

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The amount of waste heat that is generated in electronic components in aerospace application is increasing because of higher electrical power demands. As a result, conventional cooling methods are not able to maintain the electronic component below its maximum temperature. For this reason, a two-phase Mechanically Pumped Fluid Loop has been developed for high-power electronic components in a commercial aerospace application. These electronic components generate a waste heat of 1200 W that is divided over several hotspots while the temperature gradient over the component has to be kept to a minimum. The developed cooling system uses R245fa as refrigerant and is made from aluminum components produced with additive manufacturing. The use of this novel production technique results in an unprecedented low system mass (2.5 kg) and small system dimensions. Measurements show that the system has an excellent thermal performance and is able to cool 2400W.

Nomenclature

AM	- Additive Manufacturing
P	- Heat input/output (W)
SLS	- Selective Laser Sintering
T	- Temperature (°C)
T_{sat}	- Saturation temperature (°C)
R245fa	- Pentafluoropropane
2Φ-MPFL	- Two-phase Mechanically Pumped Fluid Loop

I. Introduction

Modern aircraft and spacecraft rely on growing numbers of electronic components onboard, which in turn are increasingly high-powered and compact. Conventional cooling methods have become too large and heavy and have thus become a bottle-neck in aerospace systems. In some instances, they cannot supply the required cooling performances and keep devices below their specified maximum temperatures. For this reason, a two-phase Mechanically Pumped Fluid Loop (2Φ-MPFL) is being developed for high-power electronic components in a commercial aerospace application in the TOPMOST project.

The key advantage of a two-phase system over a conventional single-phase system is that the required mass-flow for a 2Φ-MPFL is substantially less for a given heat load, allowing for smaller tubing diameter and component dimensions. As a result, 2Φ-MPFL tend to be both more compact and less heavy than their single-phase counterparts. Furthermore, due to phase change of the fluid (evaporation and condensation) the temperature of the liquid/vapor mixture is nearly the same in the entire system. This results in a uniform temperature of the electronic component's surface (whose temperature limit is 110°C).

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II. Layout of the cooling system

Figure 1 shows the layout of the TOPMOST cooling system. A pump circulates the fluid (also known as the refrigerant). The fluid flows through an evaporator downstream of the pump, which physically interfaces with the electronic component to be cooled. The heat from the component is conducted towards the circulating fluid, causing it to partly evaporate. The electronic component has three 'hot spots' where the heat flux is the highest. Each hot spot has a 4 cm x 4 cm area and produces up to 400W of waste heat (so 1200 W in total). The evaporator has 3 evaporator sections with parallel channels. Each evaporator section has a similar channel and manifold geometry as evaporator sample number 1 that was tested and discussed in paper[1].

From the evaporator, the vapour/liquid mixture flows to the condenser, where the vapour is condensed back into liquid. The condenser is cooled by an airflow. The saturation pressure (and thereby the saturation temperature) in the system is controlled by the accumulator. For this reason, the accumulator is equipped with an electrical heater at the bottom of the vessel. The accumulator has a pressure sensor located at the top and another pressure sensor is located just after the pump. The two pressure sensors are used to monitor the pressure difference over the pump. The system has an electrical preheater to maintain the system above a certain temperature under cold conditions without any heat load on the evaporator. This electrical preheater is not used in the tests described in this paper.

The 2Φ-MPFL system uses the refrigerant pentafluoropropane (R245fa) as heat carrier fluid and operates at a saturation temperature of 87°C. The fluid R245fa was selected by using the NLR fluid selection tool[7] and the system was designed with the NLR fluid solver tool[4].

Figure 2 and Figure 3 show CAD drawings of the cooling system while Figure 4 to Figure 8 show photos. The total mass of the system is 2.5 kg without fluid, and 2.75kg when the system is filled with R245fa.

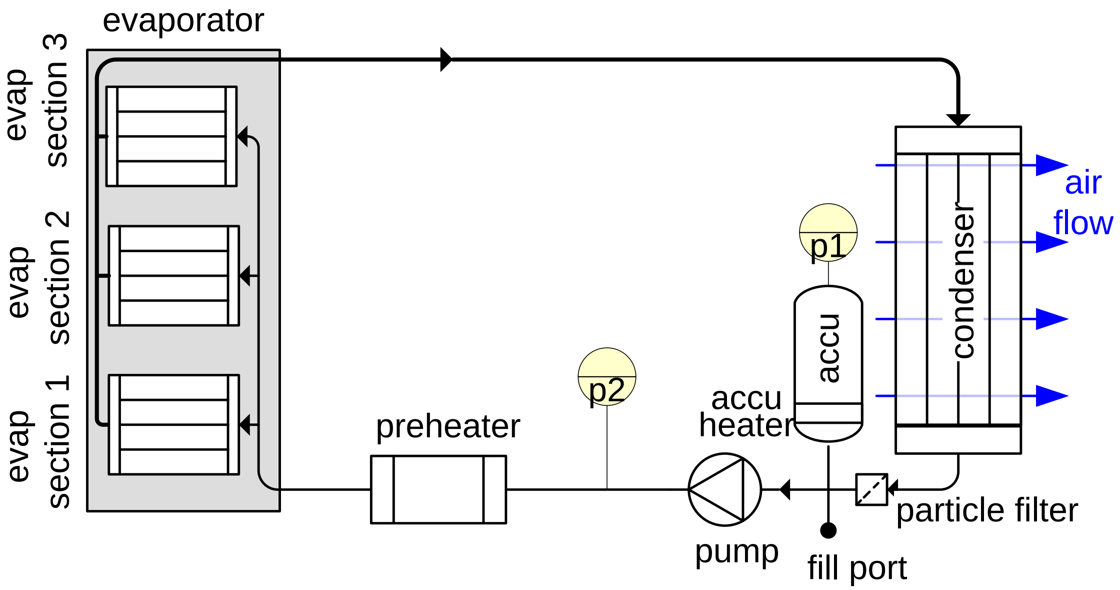

Figure 1 Schematic drawing of a basic 2Φ-MPFL

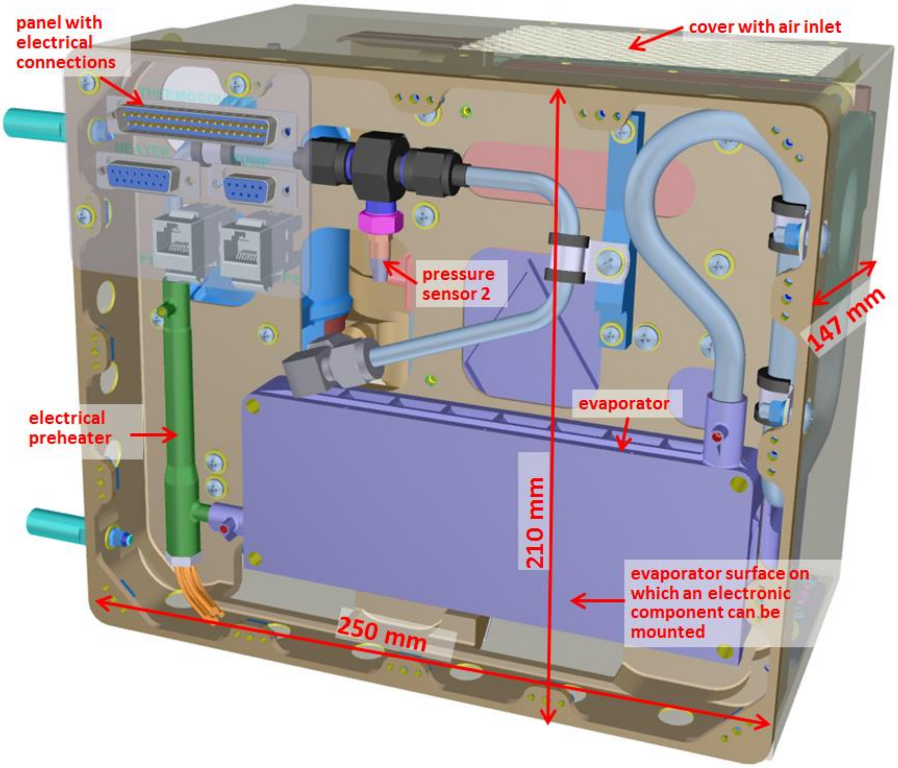

Figure 2 CAD drawing of the TOPMOST cooling system

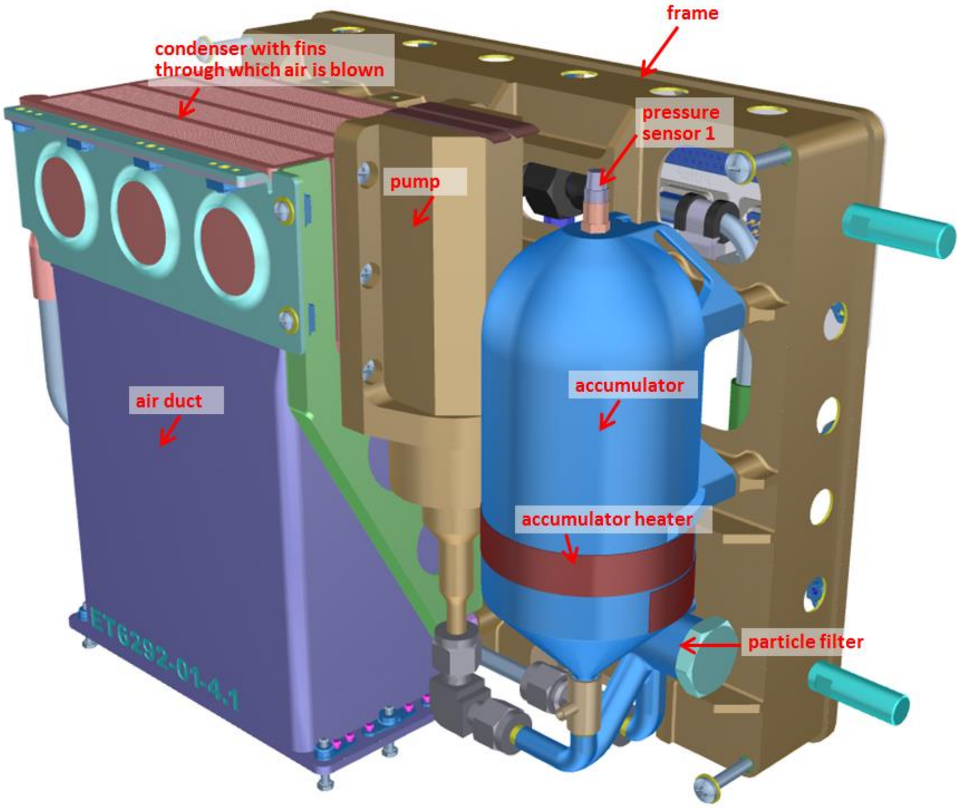

Figure 3 CAD drawing of the TOPMOST cooling system (without cover)

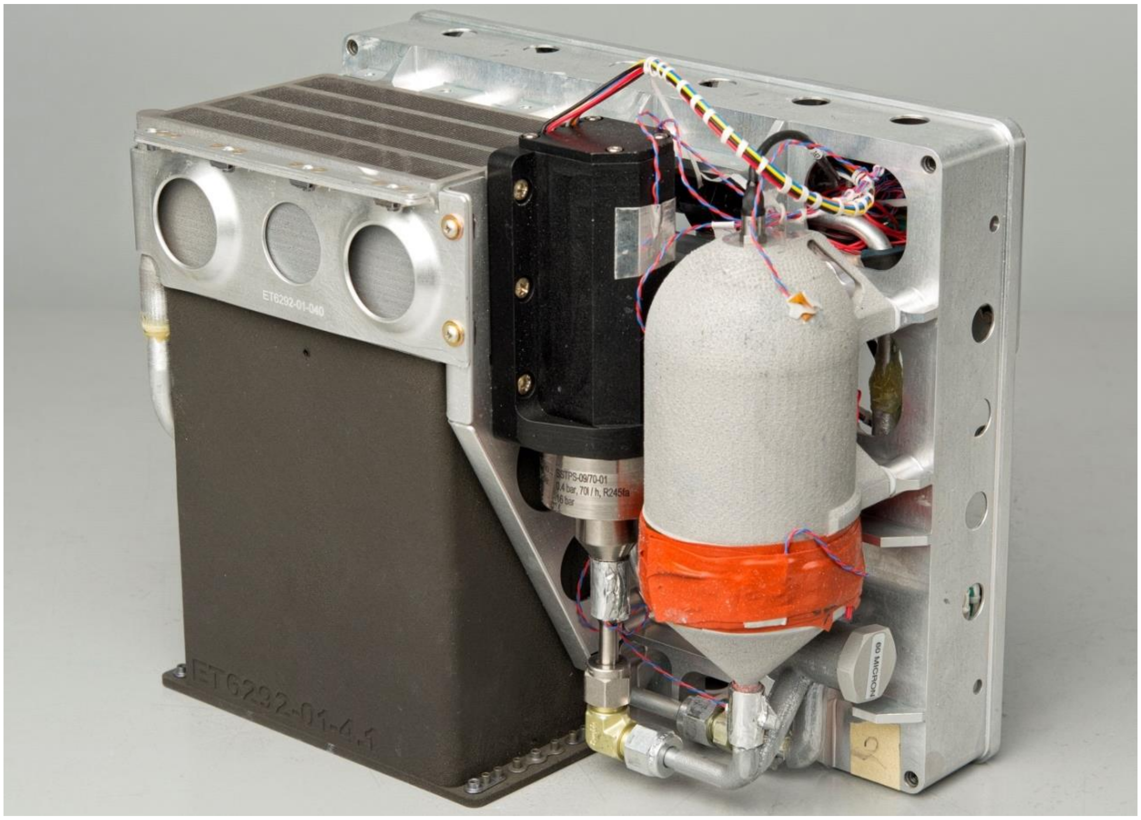

Figure 4 Photo of the TOPMOST cooling system (without cover)

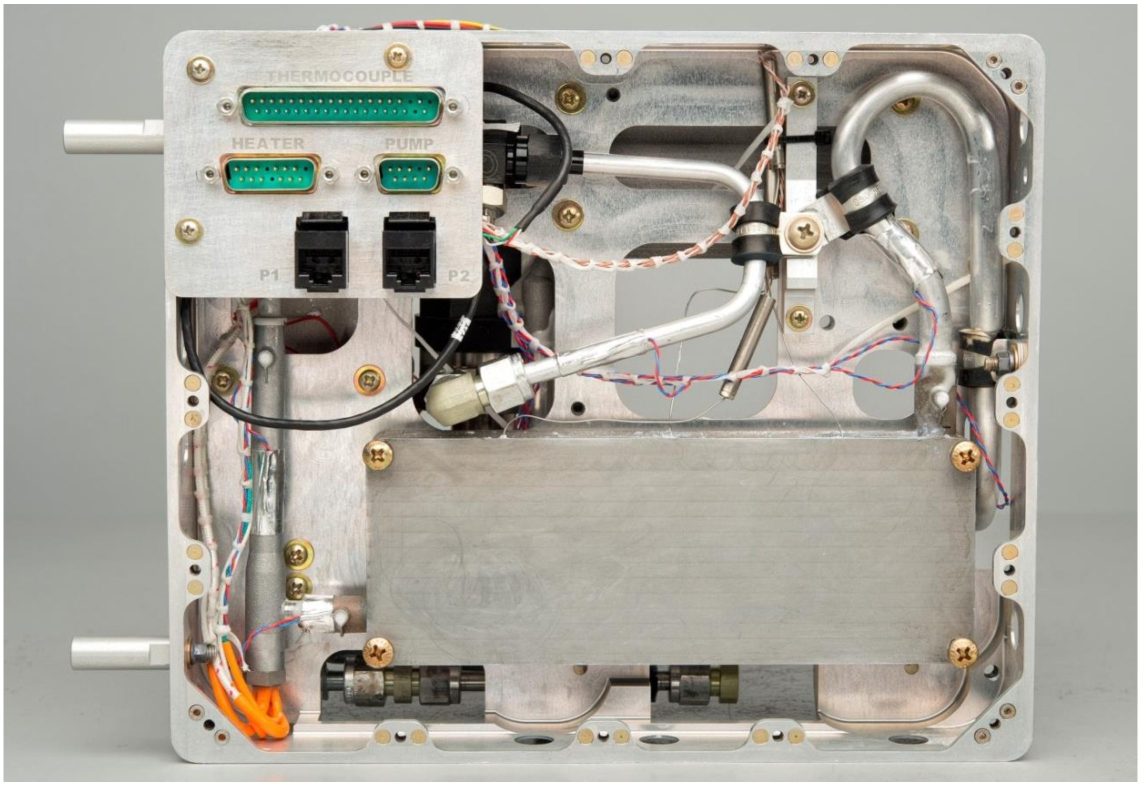

Figure 5 Front view of the TOPMOST cooling system (without cover and air duct)

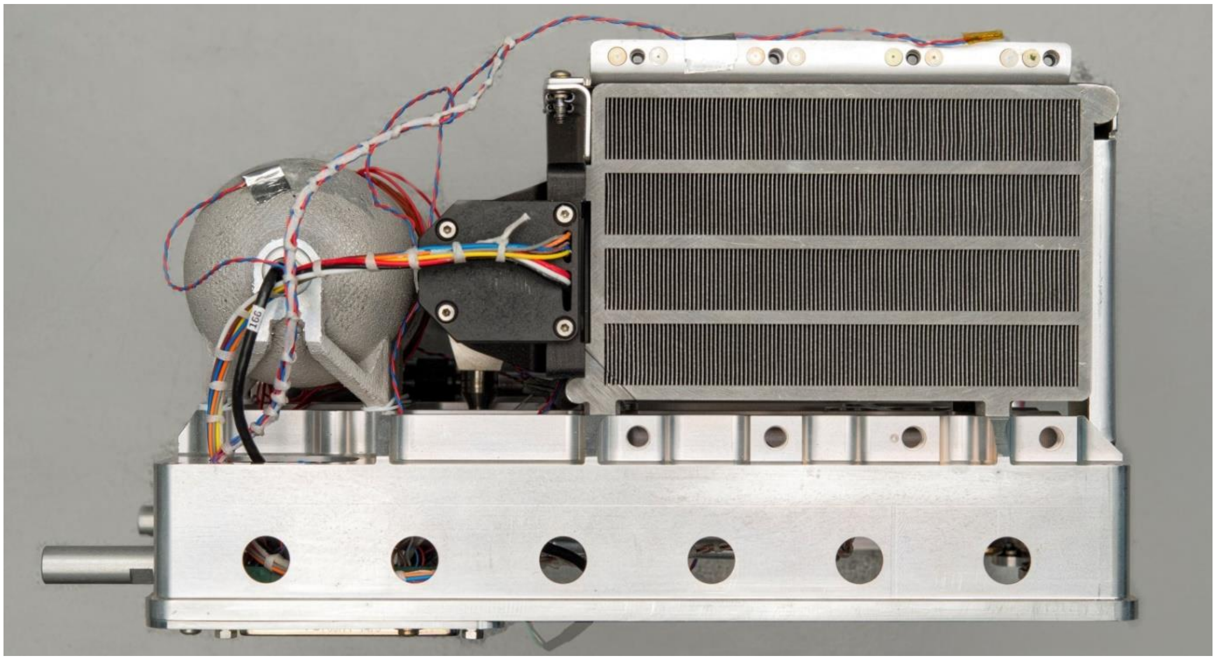

Figure 6 Top view of the TOPMOST cooling system (without cover and airduct)

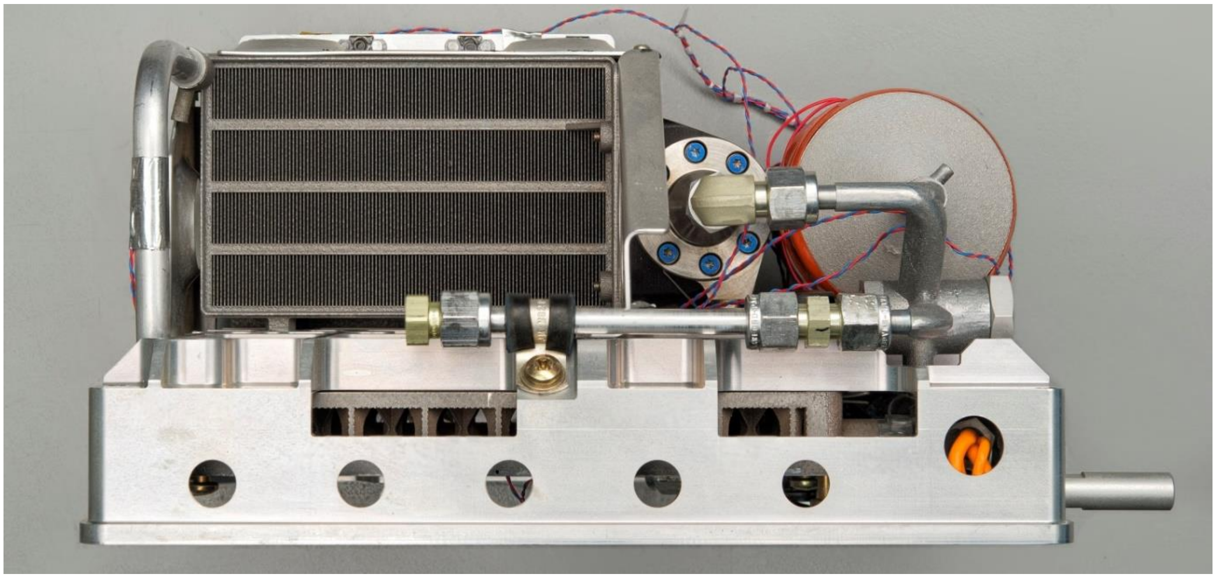

Figure 7 Bottom view of the TOPMOST cooling system (without cover and airduct)

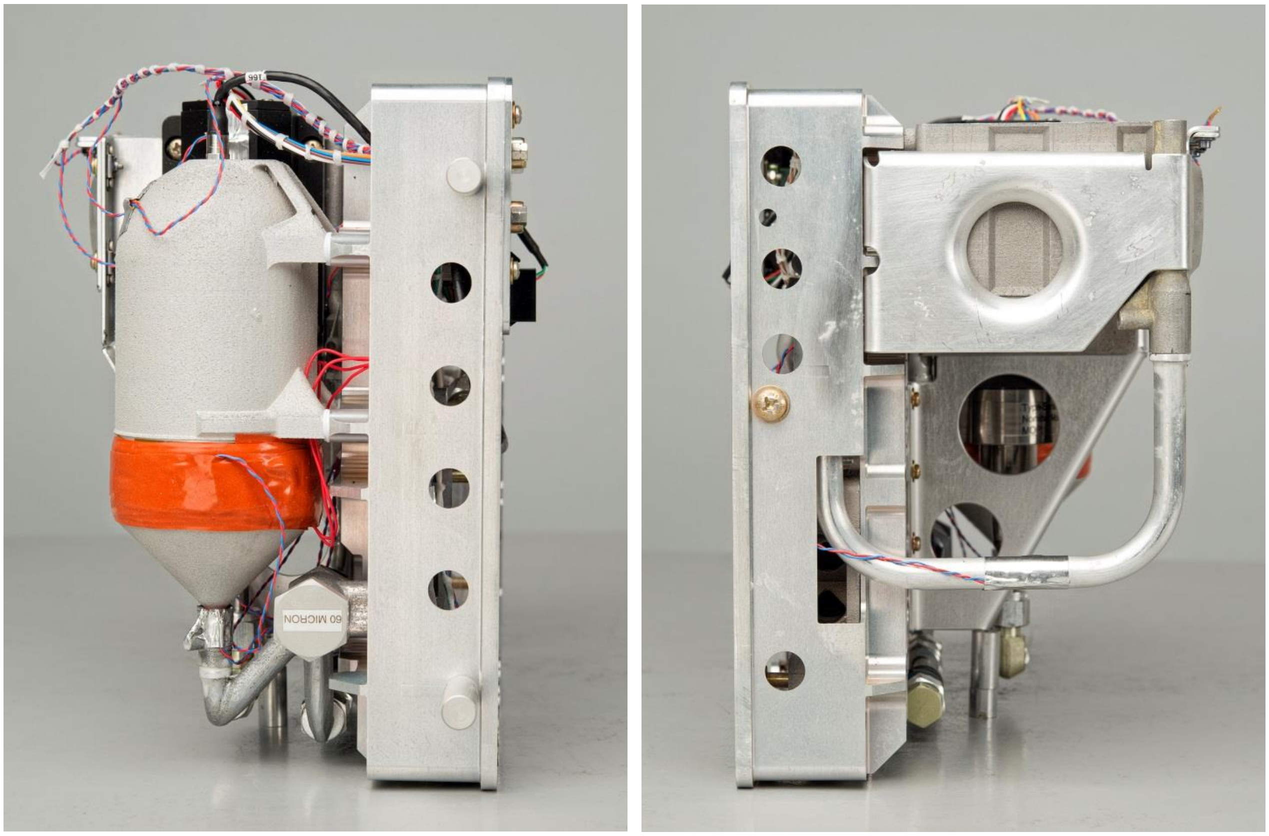

Figure 8 Side views of the TOPMOST cooling system (without cover and airduct)

III. Main components of the cooling system

The main components of the cooling system are discussed in the next sections. Many of the components have been manufactured with Additive Manufacturing (AM). The details on the manufacturing process and aluminium alloy selection for this system can be found in reference[3].

A. Centrifugal pump

Most liquid pumps have a shaft between the motor and the pump section, and the seal of this shaft is very prone to leaking of a two-phase fluid. For this reason, standard liquid pumps with a shaft between motor and pump section are not suitable for a two-phase pumped system. For the TOPMOST cooling system, a modified version of the Realtechnologie AG SSTPS centrifugal pump is used[5]. This pump is hermetically-sealed and uses a magnetic coupling between the motor and pump section. The pump has contactless gas bearings, which should not be susceptible to wear. Lifetime tests with similar pumps have been running for 10 and 14 years[5], but no lifetime test for this pump has been carried out. A CAD drawing of the pump is shown in Figure 9. The specifications of this pump are listed below:

- Fluid: R245fa
- Max. operating pressure: 17 barA
- Fluid temperature range: -40°C to 95°C
- Environment temperature range: -40°C to 70°C
- Tube interface: ¼ inch
- Pump housing material: Titanium
- Mass: 0.5 kg

Before the pump was installed in the cooling system, its pump characteristics were measured with R245fa. The measured pump curve is shown in Figure 10. The saturation temperature for this measurement was 95°C at pump inlet while the liquid temperature was 85°C (so the liquid before the pump was subcooled with 10°C). Another measurement with 75°C liquid temperature was also carried out, with very similar results. A pump cavitation test was carried out at a pump speed of 21 kRPM and a Δp over the pump of 0.4 bar. No pump cavitation was observed with a saturation temperature at pump inlet of 95°C and a liquid temperature of 92.5°C (so 2.5°C sub-cooling for the pump). In the actual cooling system, the software will shut down the pump and evaporator heaters when the pump sub-cooling is less than 5°C.

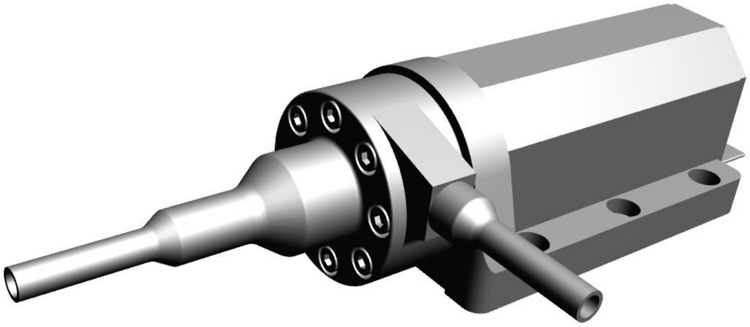

Figure 9 CAD drawing of the TOPMOST pump

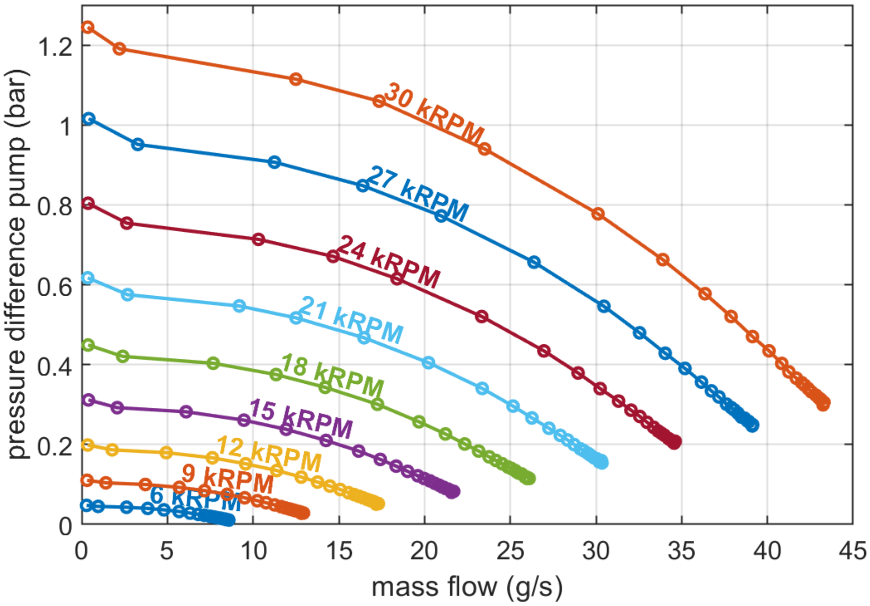

Figure 10 Measured pump curve, which shows the pressure difference versus the massflow for different pump rotational velocities (which are expressed in kRPM)

B. Evaporator

Figure 11 shows a cross section of the evaporator design. The evaporator has been manufactured from aluminium (AlSi10Mg) with AM. The mass of the evaporator is 0.25 kg. The electronic component that has to be cooled has three ‘hot spots’ where the heat flux is the highest. For this reason, the evaporator has 3 evaporator sections with 33 parallel channels. The channels have a length of 45 mm and a diameter of 1 mm. Each section has its own inlet manifold and the three sections share a single outlet manifold. Each inlet manifold has a flow restriction. This ensures that each section receives the same amount of fluid, independent of the heat input.

In a typical evaporator, the channels are located as close to the interface as possible in order to minimize the temperature gradient through the aluminium. A typical distance between the channels and interface is 0.3 mm, which would result in a 0.9°C temperature gradient with a heat flux of 50 W/cm^2. However, it is required that the evaporator surface temperature is below 110°C, and in order to verify this requirement, temperature sensors have to be inserted between the channels and the interface. In order to drill a hole for these sensors, a 2 mm thick aluminium layer has to be present between the interface and the channels (Figure 12). This 2 mm thick layer will result in a 5.8°C temperature difference with a heat flux of 50 W/cm^2. This means that in theory, the electronic component temperature can be 4.9°C lower when the system is not equipped with temperature sensors near the evaporator surface. However, this project is not intended as a final product, but as a demonstrator for two-phase cooling which is used to obtain measurement data. For this reason, it was decided to locate these temperature sensors between the fluid and the evaporator surface, despite the associated higher temperature difference between the fluid and the electronic component.

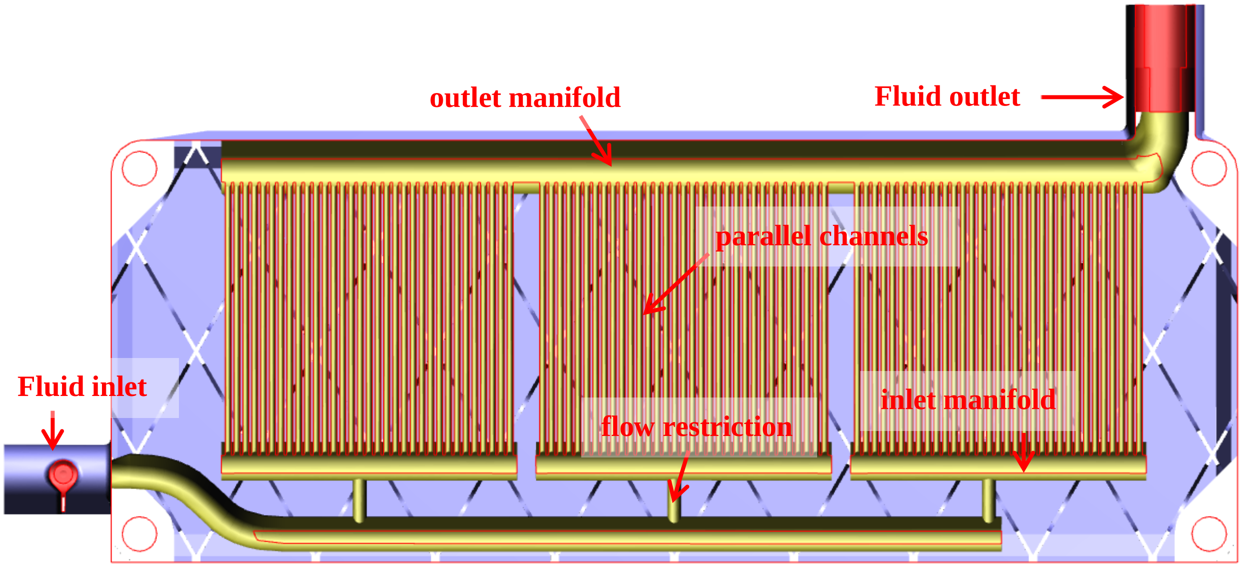

Figure 11 Cross-section of the evaporator

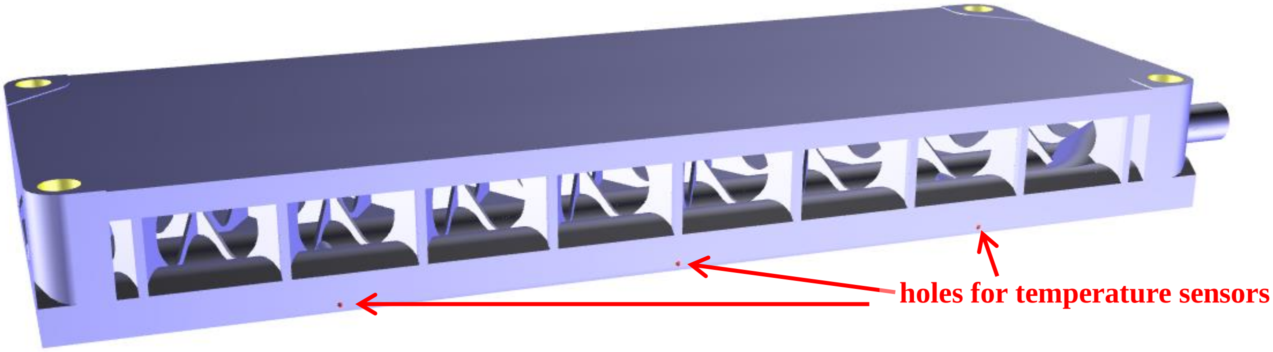

Figure 12 Evaporator with temperature sensor locations

C. Condenser

Figure 13 shows a CAD drawing of the condenser. The condenser is manufactured from aluminium (AlSi10Mg) with AM. The mass of the condenser is 0.56 kg. The two-phase fluid enters the inlet manifold, and then flows through 19 parallel channels with 2 mm diameter through the fluid plates in the condenser. Perpendicular to the fluid plates are fins with a thickness of just 0.25 mm and 0.75 mm distance between the fins. The thermal energy in the fluid is transferred to the air and the vapour in the fluid is turned into liquid. This liquid then flows to the pump.

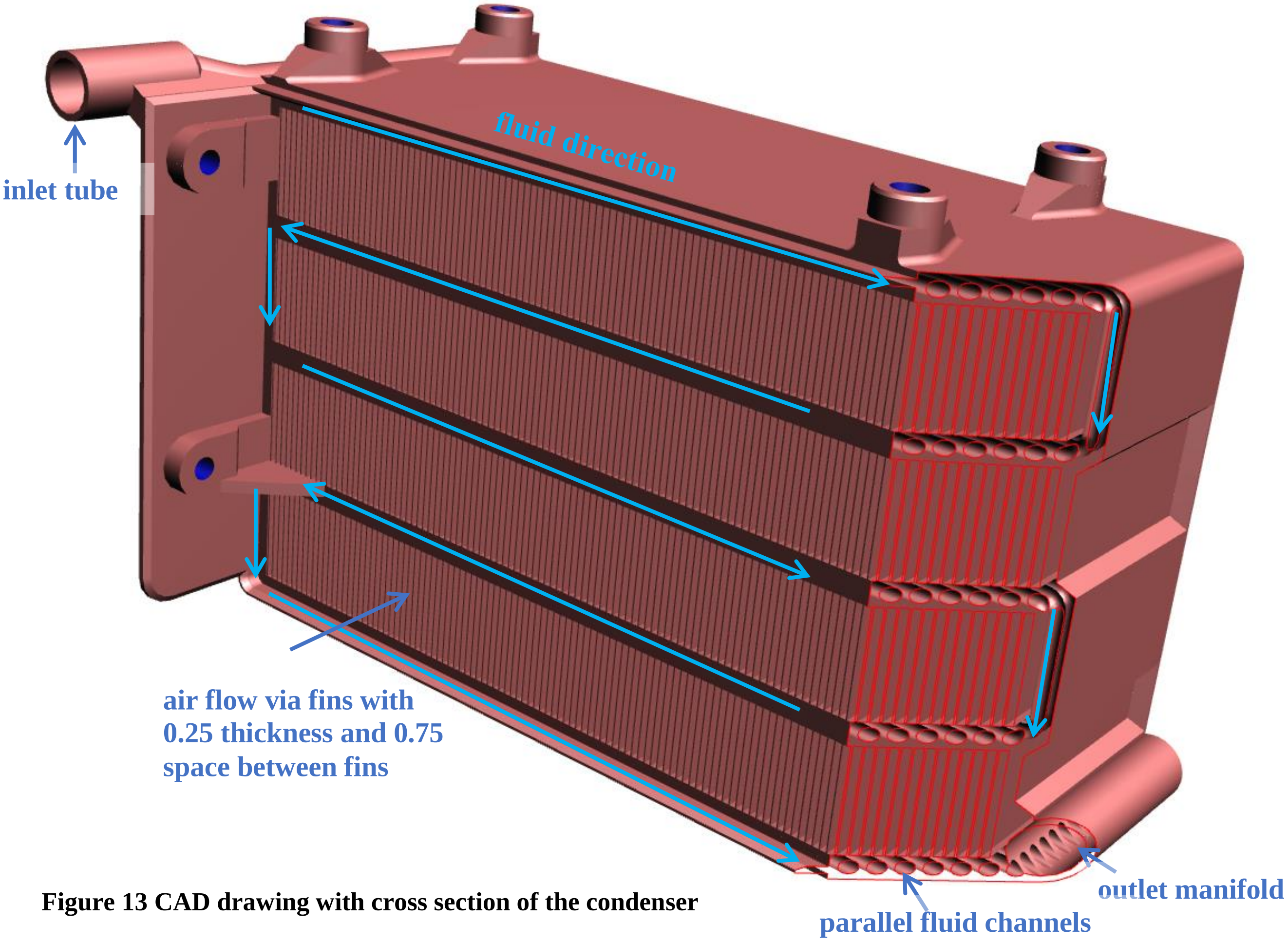

Figure 13 CAD drawing with cross section of the condenser

D. Accumulator

Figure 14 shows a drawing of the accumulator. The accumulator has an outer diameter of 62 mm, a height of approximately 135 mm, and a volume of 330 ml. It is made from aluminium (Scalmalloy) with AM. The mass of the accumulator is 0.08 kg.

The accumulator has two Minco HAP6946 Thermofoil heaters which can provide a maximum heating power of 40W. These foil heaters are used to control the temperature of the accumulator. The pressure sensor is located at the top of the accumulator. In the tests described in this report, the liquid outlet of the accumulator is located at the bottom of the vessel (i.e. the system has the orientation as in Figure 4). In this orientation, gravity ensures that liquid is located at the bottom of the vessel.

For a space application, capillary wicking structures can be used to ensure that liquid is always present at the inlet/outlet tube of the accumulator and near the heaters. For example, the accumulator of the two-phase pumped thermal control system of the AMS02 instrument[6] contains such wicking structures. AMS02 is a particle detector that has been launched with the space shuttle in May 2011, after which it was mounted on the International Space Station[6]. Since then, the two-phase thermal control system keeps the AMS02 particle detector at a very stable temperature (variations less than 0.3°C) in a strongly fluctuating thermal environment.

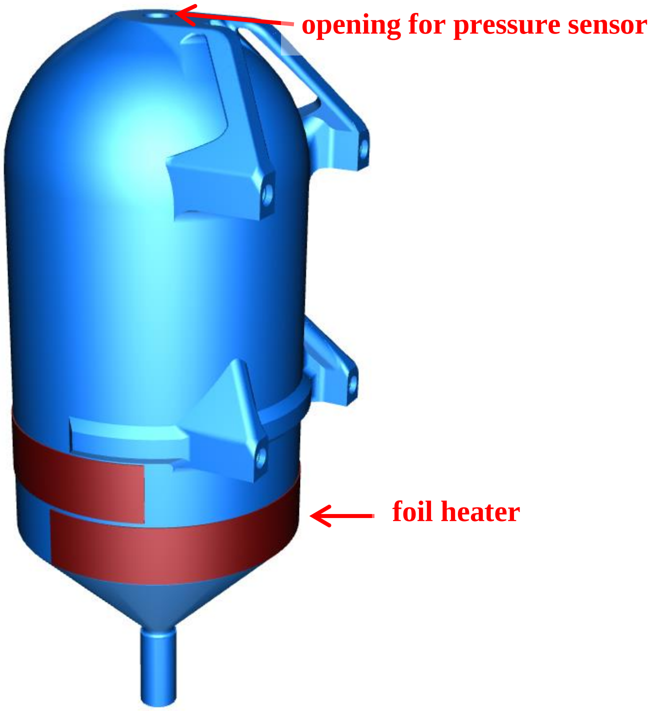

Figure 14 CAD drawing of the accumulator

E. Sensors

Two Kulite XTL-193-190 with a 17 bar absolute pressure range are used in the system. These pressure sensors are not compatible to an external vacuum, so for a space application, other sensors would have to be used. The temperatures are measured with type T thermocouples.

F. Copper heater block

The TOPMOST cooling system is intended to cool an electronic component. However, since this electronic component is not yet available for testing, a copper heater block (Figure 15) is used to simulate the heat load of this electronic component. The copper heater block is designed to produce a similar heat flux and heat spreading as the actual electronic component. The copper heater block has 3 heating sections. Four 200W cartridge heaters are inserted in each heater section and the heater block can generate a heat load of 3 x 800W. Each heating section contains a temperature sensor which is connected to the safety relay. Near the evaporator interface, there are also 3 temperature sensors to measure the temperature near this interface. These three temperature sensors in the copper heat block are adjacent to three temperature sensors in the evaporator, see also Figure 17. The base plate of the copper heater block has a thickness of 4 mm.

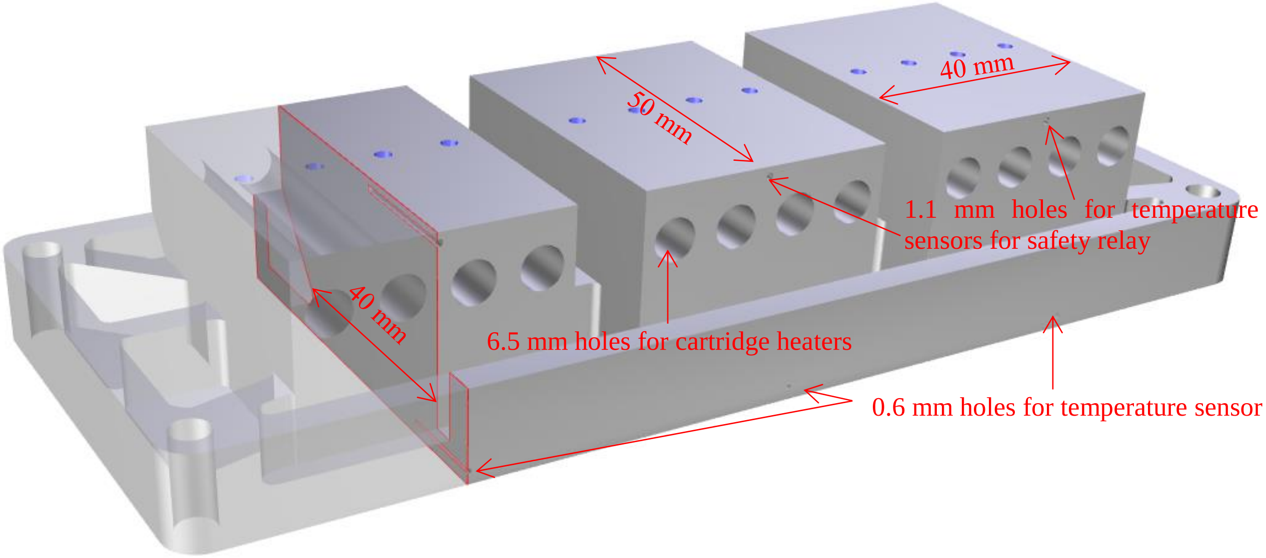

Figure 15 CAD drawing of the copper heater block

G. Fluid

R245fa has no ozone depletion potential, a low toxicity, and is non-flammable (ASHRAE Safety Group (2013) A1). It does have a high global warming potential of 950 (950 times the global warming effect of CO_2). R245fa is compatible with most common seal materials, like PTFE, Nylon, Butyl rubber, and viton. It is also compatible with stainless steel and aluminium. Some relevant fluid properties are shown in Table 1. The properties are obtained from REFPROP[8].

Table 1 Fluid properties of R245fa

property	value
Chemical description	1,1,1,3,3-pentafluoropropane
Saturation pressure at 20°C	1.23 bar
Saturation pressure at 87°C	9.4 bar
Triple point temperature (freezing point)	-102.1 °C
Critical temperature	154°C
liquid density ρ_l at 87°C	1145 kg/m^3
vapour density ρ_v at 87°C	52.6 kg/m^3
heat of evaporation h_{lv} at 87°C	147 kJ/kg
specific heat c_p at 87°C	1.5 kJ/(kg K)
Joule-Thomson coefficient $\partial T_{sat}/\partial p_{sat}$ at 87°C	4.4 °C/bar
Thermal conductivity k_l	0.068 W/m K

H. Pressure in the system

The TOPMOST system is filled with R245fa. The pressure in the system is related to the temperature of the fluid in the system. At room temperature, the absolute pressure of R245fa is 1.2 bar. The maximum normal operating temperature of the system is 95°C, and at this temperature, the pressure in the system is 11 bar. The maximum temperature in the system is 110°C, which corresponds to a maximum system pressure of 17 bar. The system is protected by an independent safety relay, which shuts down all the heaters if the pressure rises above 17 bar. However, the software already shuts downs all heaters when the pressure rises above 15 bar. The pressures in the system are summarized in Table 2. The system is designed by using the certification specification for large aeroplanes CS-25. Section "CS 25.1435 Hydraulic Systems"[2]. The proof and ultimate pressures that are derived from this specification are shown in Table 3. The maximum system pressure of 17.3 bar is used for the value of the Design Operating Pressure (DOP). All the hydraulic components of the TOPMOST system have been subjected to the ultimate pressures in Table 3 to verify that they can withstand these pressures. Fatigue strength has not been tested. For the evaporator and condenser, the stresses due to fluid pressure are small, because the diameter of the fluid channels is small. Only for the accumulator is the fatigue stress due to pressure variations relevant. The pressure in the accumulator is actively controlled, and for a space application, the pressure can be kept at a constant level.

Table 2 Pressures in the system

	Pressure [bar]	Temperature [°C]
System pressure at room temperature	1.2	20°C
Maximum normal operating pressure	11	95°C
Maximum system pressure	17	110°C

Table 3 Proof and ultimate pressures for the TOPMOST system

	Factor (x DOP)		Pressure [bar]		Temperature [°C]
	proof	ultimate	Proof	ultimate	
tubes and fittings	1.5	3	26.0	51.9	110°C
accumulator	3	4	51.9	69.2	110°C
all other elements (heat exchangers, pump)	1.5	2	26.0	34.6	110°C

IV. Thermal test setup

Figure 16 shows photos of the test setup. The TOPMOST cooling system is mounted on an air duct that can deliver an air flow with a specified temperature through the condenser. The air flow pressure difference over the condenser is also measured.

Figure 17 shows a CAD drawing of the copper heater block that is used to simulate the heat load of an electronic component. The copper heater block has three heater sections that can deliver a heat load of 800W each. Near the heat exchange surface, there are three 17 mm deep holes with 0.6 mm diameter in which temperature sensors (with a diameter of 0.5 mm) are inserted. In the evaporator are also 3 holes in which temperature sensors are inserted. Besides the temperature sensors in the evaporator and copper heater block, there are also 12 other temperature sensors located e.g. on the evaporator exit and the air duct inlet and outlet. The results of several tests are described in the next sections

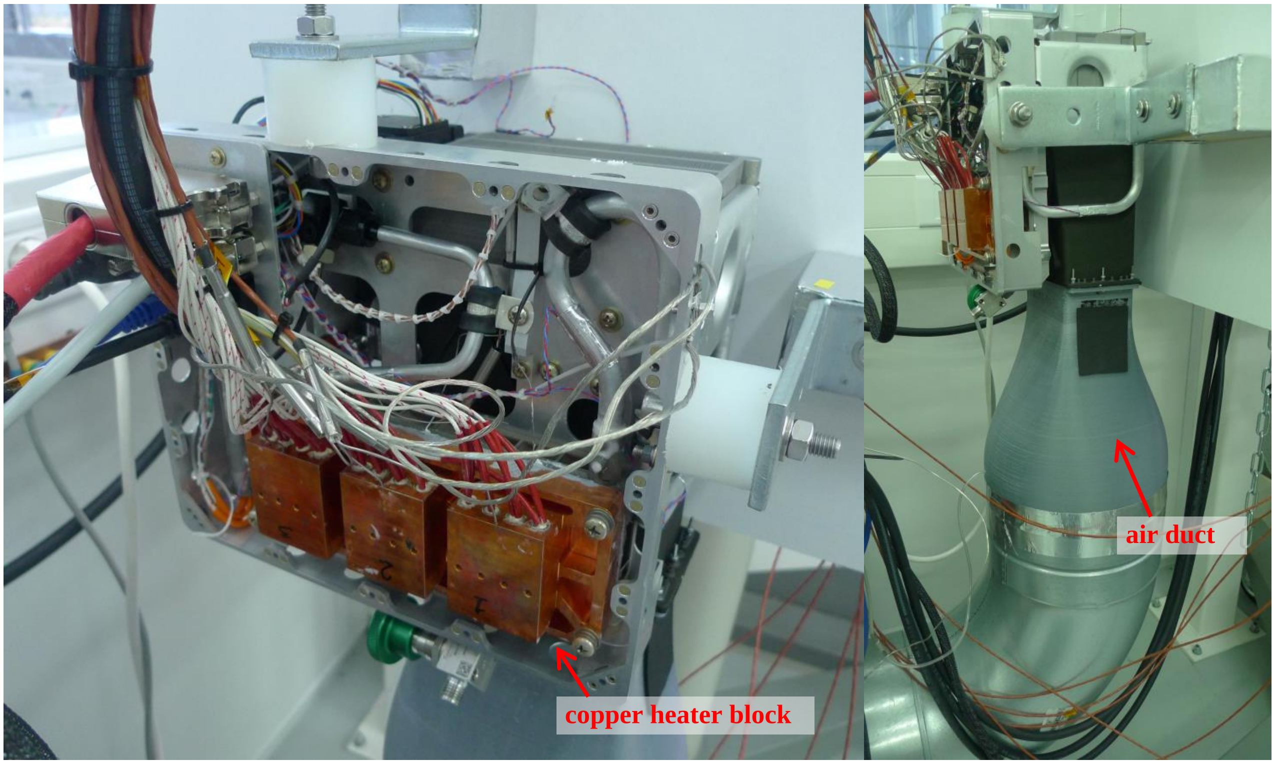

Figure 16 Photo of the test setup

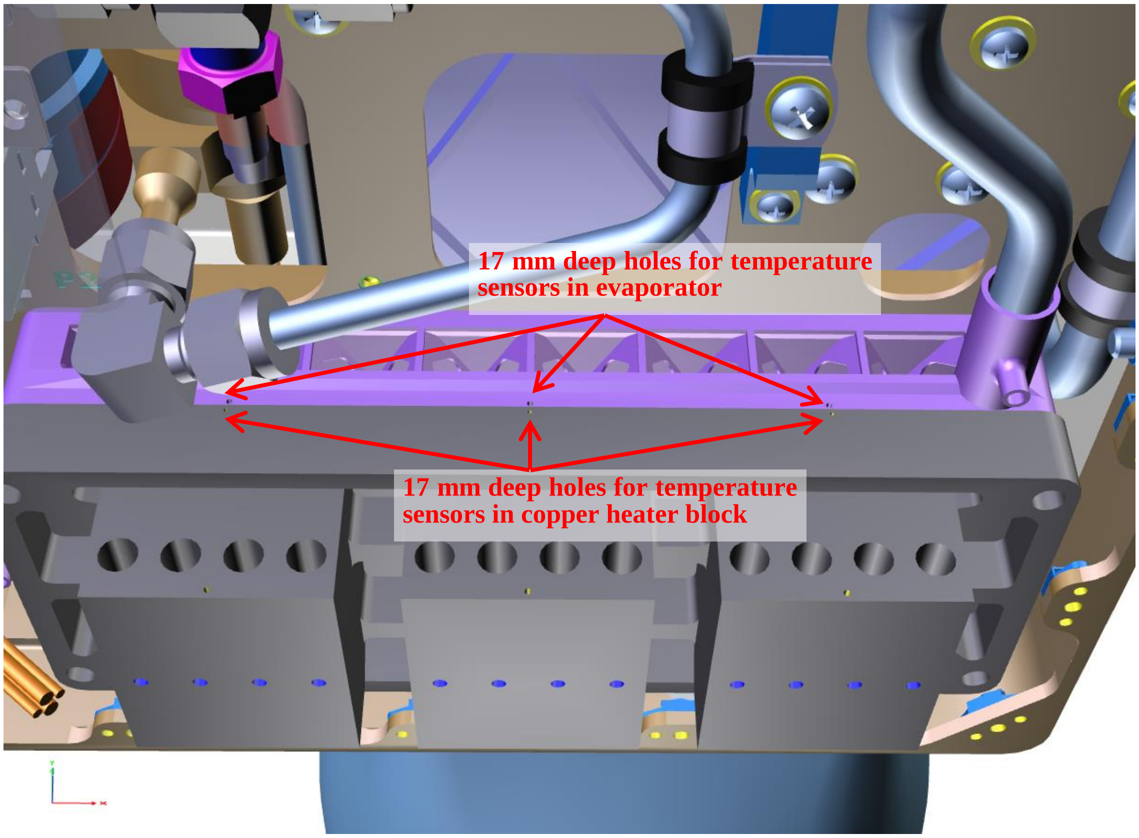

Figure 17 CAD drawing of the copper heater block mounted on the evaporator

V. Thermal test results

A. 600W heat load including imbalance in heat load

According to the requirements, the maximum steady-state heat input of the heat source that has to be cooled by the cooling system is 600W (200W for each heated section). It is possible that there is an imbalance between the three sections of ±10%. For this reason, a test was carried out with the following heater powers:

- 5 minutes with 0W evaporator heater power
- 10 minutes with 200W of heater power for each section of the copper heater block (so 600W in total)
- 5 minutes with 180W on heat block section 1, 200W on section 2, and 220W on section 3 (so 600W in total)
- 5 minutes with 220W on heat block section 1, 200W on section 2, and 180W on section 3
- 5 minutes with 220W on heat block section 1, 180W on section 2, and 200W on section 3
- 5 minutes with 200W of heater power for each section
- 10 minutes with 0W evaporator heater power

During the measurement, the following airflow was blown through the condenser:

- Air mass flow of 40 g/s
- Airflow temperature of 70°C at condenser air inlet

This 40 g/s of air flow results in an air pressure difference over the condenser of 195 Pa.

The saturation temperature was set to 87°C during the measurement. Figure 19 shows the measured temperatures in the three evaporator sections (indicated with solid line in red, green, and blue) and in the three heater sections (indicated with dashed lines in red, green, and blue). The temperature of the air inlet and outlet of the condenser is indicated with purple lines (solid for air inlet, dashed for air outlet). The system saturation temperature is indicated with a grey line, while the R245fa temperature at the outlet of the evaporator is indicated with a black line. After the heat load of 600W is applied at t=80 minutes, the temperature quickly starts to rise. At t=83 minutes, the liquid temperature has reached the saturation temperature and the liquid starts to evaporate. The temperatures of the heater block and evaporator now no longer rise, but remain around a temperature of 94°C, which is well below the requirement of 110°C.

The cooling air that enters the condenser has a mass flow of 40 g/s and a temperature of 70°C. In the condenser, the heat from the R245fa is transferred to the air, and as a result, the air temperature is increased to 82°C when it leaves the condenser. This is less than the theoretical air outlet temperature of 85°C, but this is likely because the system is not thermally insulated and some heat leaks to the ambient environment.

During the test, the pump rotational speed was set to 18 kRPM (Figure 20). The pump speed is kept at the desired value by the pump controller. Figure 21 shows the measured pressure in the accumulator and just after the pump. As a result of the R245fa flow in the system, the pressure after the pump is 0.25 bar higher than in the accumulator. The pressure difference over the pump is independent of the heat load on the evaporator, since the pressure drop in the system is dominated by the parts in the system that always have a liquid flow (i.e. no two-phase flow), e.g. the restrictions in the evaporator sections (see section III.B) and the particle filter. When evaporation starts at t=83 minutes, there is a short spike in the pressure (and therefore saturation temperature, see Figure 19). This short spike is caused by the inflow of liquid into the accumulator when liquid in the tubing and components after the evaporator is replaced with vapour. This liquid inflow compresses the vapour in the accumulator, which results in the short pressure spike. The liquid that flows into the accumulator is relative cold, which results in a reduction in the pressure immediately after this spike. When the evaporator power is turned off at t=110 minutes, there is a sudden drop in the pressure due to flow of liquid out of the accumulator. The accumulator heater regulates the pressure back to its desired value via a PID controller. More details on the transient behavior as a result of heat load variations can be found in reference[1].

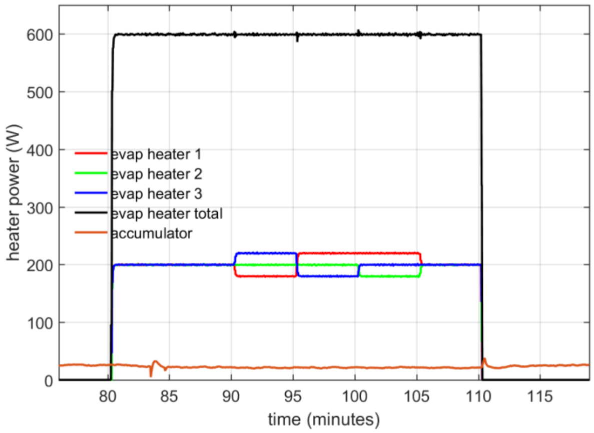

Figure 18 Applied heater powers

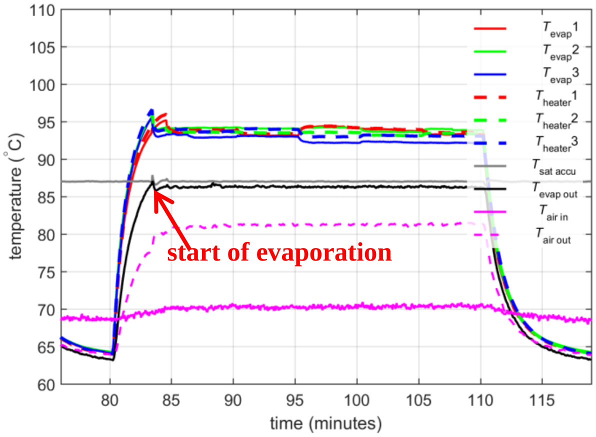

Figure 19 Measured temperature in the evaporator and heater block

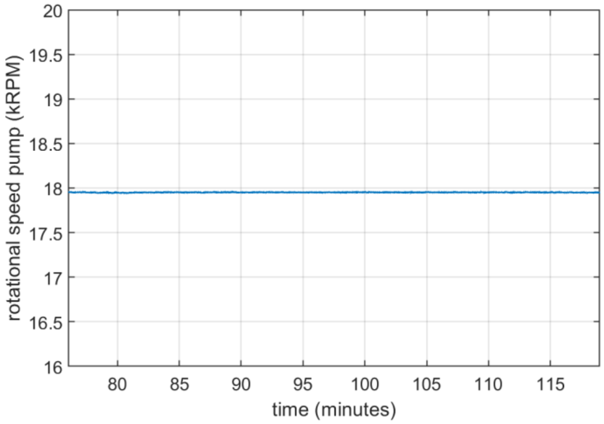

Figure 20 Measured rotational speed of the pump

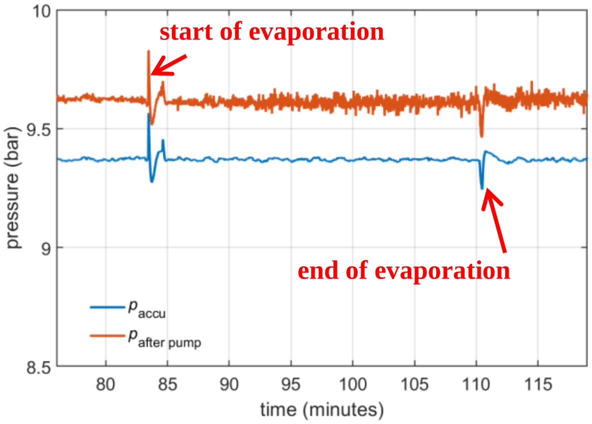

Figure 21 Measured pressures

B. 1200W heat load

According to the requirements, the electronic component can have a maximum heat load of 1200W in a transient case of 4 cycles of a 1200W heat load for 1 minute followed by two minutes of 0W heat load. Figure 22 shows the applied heater powers during a test that was carried out to test this requirement. Between *t*=125 minutes and *t*=135 minutes, 4 cycles of a 1 minute 1200W (3 x 400W) heat load followed by 2 minutes of 0W heat load are applied on the evaporator. At *t*=136 minute, a continuous heat load of 1200W is applied for 10 minutes. Figure 23 shows the measured temperatures. When the heat load of 1200W is only applied for 1 minute, the fluid does not rise above the saturation temperature, and no evaporation occurs. When the heat load of 1200W is applied for a longer duration, the fluid temperature reaches the saturation temperature and the liquid starts to evaporate. This measurement shows that the system can not only cool a short transient heat load of 1200W, but also a steady-state heat load of 1200W.

During the measurements, the pump rotational speed was 15 kRPM (Figure 24). The pressure difference over the pump is 0.17 bar (Figure 25). The airflow that is used to extract 600W heat load from the evaporator is not sufficient to extract 1200W, and the airflow through the condenser in this test was set to 65 g/s and the air pressure drop was 350 Pa. The air inlet temperature was 52°C.

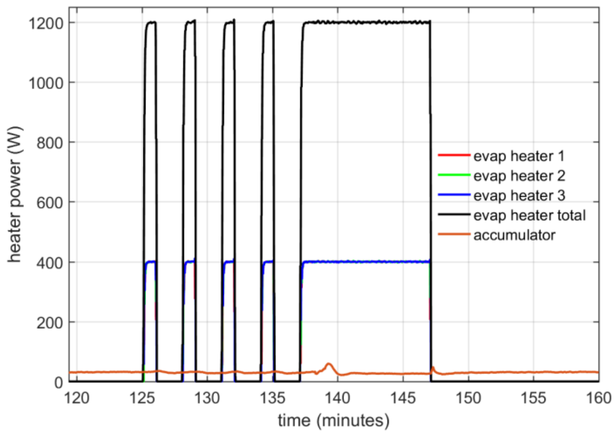

Figure 22 Applied heater powers

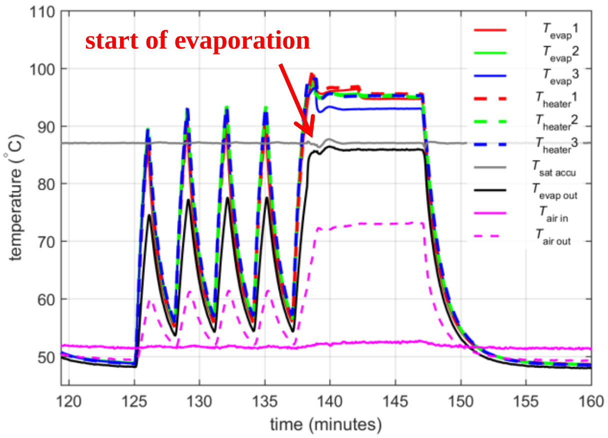

Figure 23 Measured temperatures

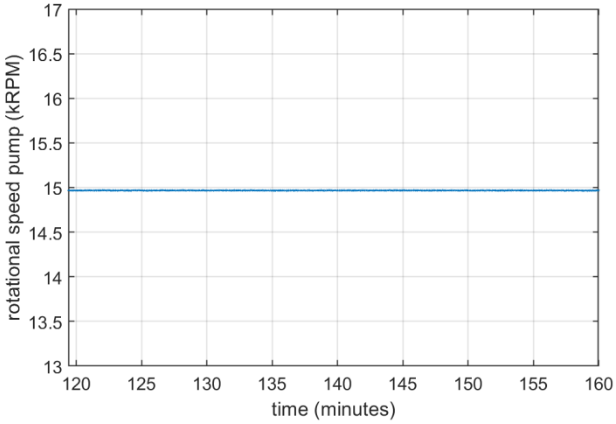

Figure 24 Measured rotational speed of the pump

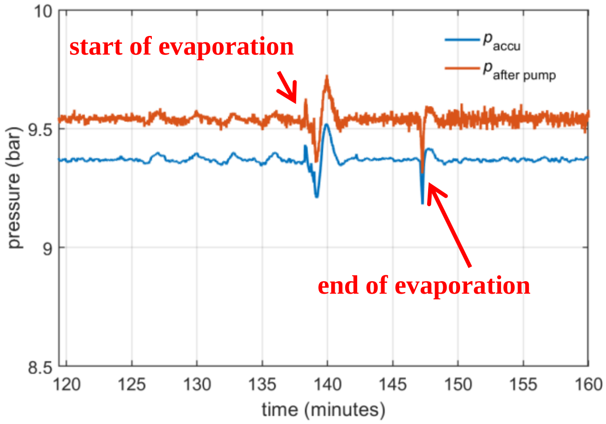

Figure 25 Measured pressures

C. 2400W heat load

According to the requirements, the TOPMOST cooling system has to be able to remove a steady-state heat load of 600W. However, for future applications the heat load will be much higher. For this reason, tests were carried out with higher heat loads. Figure 26 shows the applied heat load during such a test. At t=226 minutes, the heat load is increased to 1200W. At this heat load, no evaporation takes place. After 10 minutes, the heat load is increased to 1800W and after another 10 minutes it is increased to 2400W. The heat load is then decreased in steps to 1800W, 1200W and 0W. At a heat load of 1800W, evaporation starts. Even with a heat load of 2400W, the temperature is well below the maximum temperature of 110°C. Furthermore, even with a heat load of 2400W, the temperature difference between the different evaporator sections is smaller than 2°C. With a heat load of 2400W, the heat flux is 50W/cm^2. Despite this high heat flux, the temperature difference between the fluid and the copper heater block is just 13°C. Approximately 5°C of this temperature difference is due to the 2 mm thick layer of aluminum between the fluid channels and the interface (see section III.B), so in an actual application, the temperature difference between the fluid and the heater block can be approximately 5°C smaller. This effect is discussed in more detail in[1].

When the heat load is increased to 2400W, a 6.5°C temperature overshoot can be observed. This overshoot is caused by superheating of liquid before it starts to boil and is not uncommon for two-phase cooling systems. For this application, this overshoot is not an issue, but it could be for more critical applications. A method to reduce this overshoot is by creating more boiling nucleation sites. It was expected that the relative rough surface created by the AM process would already provide sufficient nucleation sites, but apparently, this is not sufficient. The overshoot can also be reduced by using a recuperator and preheater to warm the liquid close to the saturation temperature before it enters the evaporator. For example, in the evaporator sample tests that were carried out in this project[1], a recuperator was used and no overshoot was observed[1]. In fact, it was originally planned to also use a recuperator in the system described in this paper, but this recuperator was later removed from the design because it was considered not to be strictly necessary for this application.

During the measurements, the pump rotational speed was 20 kRPM (Figure 28). The pressure difference over the pump is 0.36 bar (Figure 29). The condenser was designed to cool a 600W steady-state heat load with a 40 g/s of airflow with an inlet temperature of 70°C. This 40 g/s airflow is not sufficient to absorb 2400W of heat and for this test, the air flow is increased to 96 g/s, resulting in an air pressure drop of 615 Pa. The air inlet temperature was 44°C.

This test shows that the TOPMOST cooling system can cool a heat load of 2400W, which is four times the maximum steady-state heat load from the requirements. In fact, it is expected that the cooling capacity of this system is even higher since the pump is only set to a rotational speed of 20 kRPM, which is well below the maximum speed of this pump (see Figure 10). However, the heater block is not able to generate a higher heat load than 2400W, so this could not be tested.

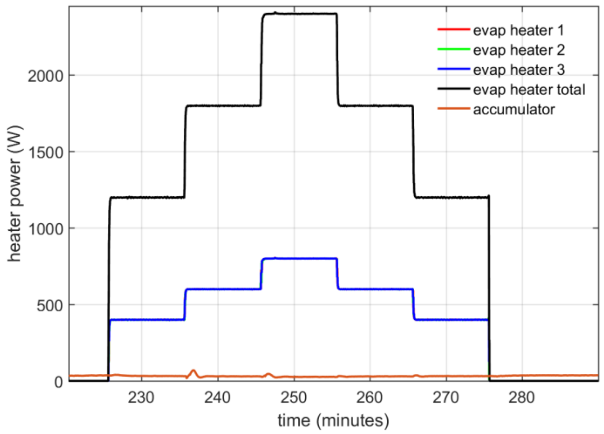

Figure 26 Applied heater powers

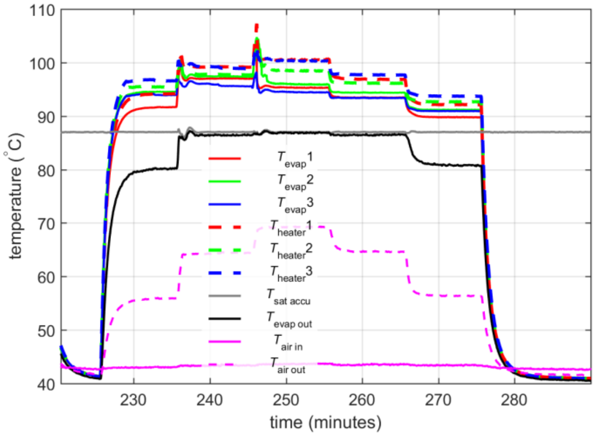

Figure 27 Measured temperatures

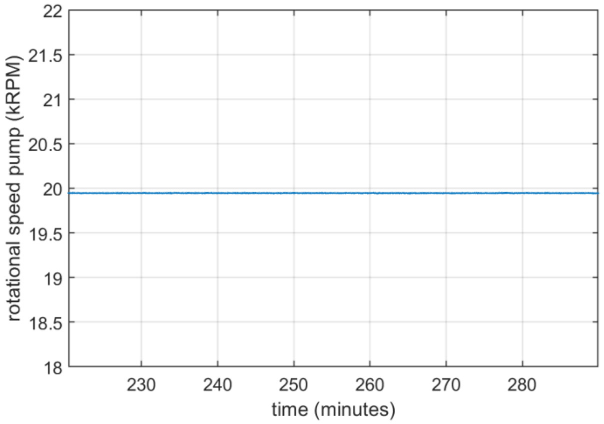

Figure 28 Measured rotational speed of the pump

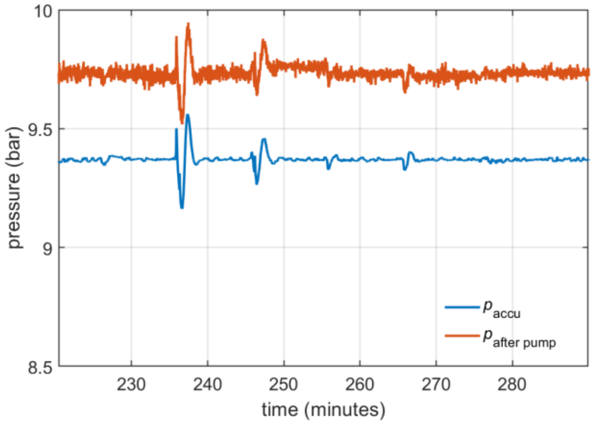

Figure 29 Measured pressures

VI. Conclusions and outlook

The thermal tests show that the TOPMOST cooling system is able to cool a heat load of 2400W. Thanks to the use of AM based on Selective Laser Melting (SLM)[3], it was possible to build a very compact system with an unprecedented low mass of 2.5 kg. In the next phase of the project, vibration, sand and dust, salt spray tests and tests in a climate chamber at -55°C will be carried out.

Although the TOPMOST cooling system has been developed for a commercial aircraft application, the technology that has been used and developed in this project (e.g. Additive Manufacturing[3], design tools[4,7]) can also be applied to develop thermal control systems for space applications. For example, the accumulator and recuperator of the AMS02 thermal control system[6] have been manufactured from machined stainless steel and mass and costs savings could be achieved if such components would be manufactured with AM. A drawback of the AM technology is that it is currently most suitable for manufacturing relative small components. For example the build envelope of the SLM Solutions SLM 280HL machine (which was used in this project) at the NLR AM facility is 280x280x360 mm^3. New machines have been developed in the recent years that have a larger build envelope. Examples are:

- Concept Laser X line: 800 x 400 x 500 mm^3
- EOS EOSINT M400: 400 x 400 x 400 mm^3
- Additive Industries, METALFAB1 420 x 420 x 400 mm^3
- SLM Solutions SLM 500HL: 280 x 500 x 360 mm^3

Also process qualification and component certification of AM for space and aircraft applications are important challenges that are currently being addressed. For example, a new Metal Additive Manufacturing program started in 2019 with the objective to enable the production of certifiable parts with predictable properties in a consistent way by implementing appropriate process monitoring and control systems. Certification of AM parts is difficult for aerospace applications due to a lack of acceptance criteria. Therefore, the development of acceptance and verification criteria of AM components has high priority in the AM community. New standards are under development. Examples are given below:

- ESA recently issued a call for proposals with the objective to define acceptance criteria for AM components based on in-situ process monitoring and NDI (Non-destructive-Inspection) methods (ESA Invitation To Tender AO9469, “Acceptance and verification criteria of AM components”)
- NASA/MSFC Technical Standard, EM20, ‘Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals’, Document No.: MSFC-STD-3716, Effective Date: October 18, 2017.
- SAE/AMS specifications AMS7001 - AMS 7003 are under development for powder acceptance/quality control and for establishing process controls for aerospace parts produced by Laser Powder Bed Fusion (L-PBF).

Acknowledgments

This project is carried out in cooperation with Thales Avionics Electrical Systems SAS. It has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation program under grant agreement No 738094. This publication reflects the author's view. The Clean Sky 2 Joint Undertaking is not responsible for any use that may be made of the information.

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